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SESSION 1

Low temperature district heating for future energy systems

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LOW TEMPERATURE DISTRICT HEATING FOR FUTURE ENERGY SYSTEMS

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ABSTRACT

The building sector is responsible for more than one third of the end energy consumption of societies and produces the largest amount of greenhouse gas emissions (GHG) of all sectors. This is due to the utilisation of combustion processes of mainly fossil fuels to satisfy the heating demand of the building stock. District heating (DH) can contribute significantly to a more efficient use of energy resources as well as better integration of renewable energy into the heating sector (e.g. geothermal heat, solar heat and biomass from waste), and surplus heat (e.g. industrial waste heat). Low temperature district heating offers prospects for both the demand side (community building structure) and the generation side (properties of the networks as well as energy sources). Especially in connection with buildings that demand only low supply temperatures for space heating. The utilisation of lower temperatures reduces transportation losses in pipelines and can increase the overall efficiency of the total energy chains used in district heating. To optimise the exergy efficiency of a community supply systems the LowEx approach can be utilised, which entails matching the quality levels of energy supply and demand in order to optimise the utilisation of high-value energy resources, such as combustible fuels, and minimising energy losses and irreversible dissipation (internal losses).

The paper presents the international co-operative work in the framework of the International Energy Agency (IEA), the District Heating and Cooling including Combined Heat and Power (DHC|CHP) Annex TS1.

INTRODUCTION

The energy demand of communities for heating and cooling is responsible for more than one third of the final energy consumption in Europe and worldwide. Commonly this energy is provided by different fossil fuel based systems. These combustion processes cause greenhouse gas (GHG) emissions and are regarded one core challenge in fighting climate change and energy transition. National and international agreements (e.g. the European 20-20-20-targets or the Kyoto protocol) limit the GHG emissions of the industrialized countries respectively for climate protection. Country specific targets are meant to facilitate the practical implementation of measures. While much has already been achieved, especially regarding the share of renewables in the electricity system, there are still large potentials in the heating and cooling sector and on the community scale. Exploiting these potentials and synergies demands an overall analysis and holistic understanding of conversion processes within communities. Communities are characterized by a wide range of energy demands in different sectors, for instance heating and cooling demands, lighting and ventilation in the building stock. Different energy qualities (exergy) levels are required as heat or cold flows or as electricity and fuels.

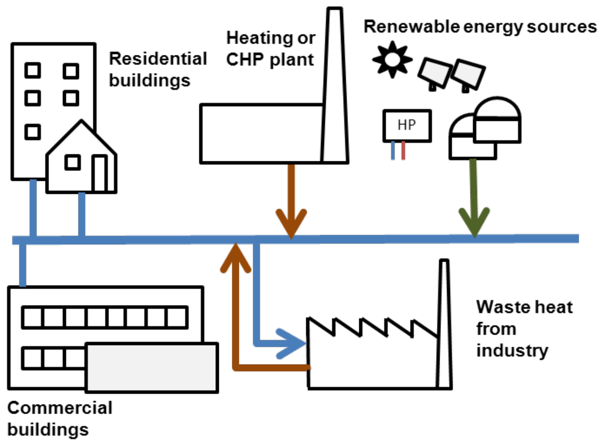

Fig. 1: Schematic district heating community supply system with multiple supply options [1].

On community scale especially low temperature district heating offers new possibilities for greater energy efficiency and lower fossil energy consumption. On the demand side, low temperature heat is commonly available as a basis for energy efficient space heating and domestic hot water (DHW) preparation. Low temperature heat can be integrated into district heating through e.g. the use of efficient large scale heat pumps, solar thermal collectors and biomass fired - combined heat and power plants.

Generally, the utilisation of lower temperatures reduces transportation losses in pipelines and can increase the overall efficiency of the total energy chains used in district heating. To achieve maximum efficiencies, not only the district heating and cooling networks and energy conversion need to be optimal, but also the demand side must be fitted to allow the use of low temperatures supplied by the network (e.g. via surface heating system). For this reason, the implementation of solutions based on large shares of renewable energies requires an adaptation of the technical and building infrastructure.

DESCRIPTION OF TECHNICAL SECTOR AND LOW TEMPERATURE DISTRICT HEATING

The application of low temperature district heating technology on a community level requires a comprehensive view of all process steps: from heat generation over distribution to consumption within the built environment. The approach includes taking primary, secondary, end and useful energy and exergy into account. This allows an overall optimization of energy and exergy performance of new district heating systems and the assessment of conversion measures (from high temperature DH to low temperature DH) for existing DH systems.

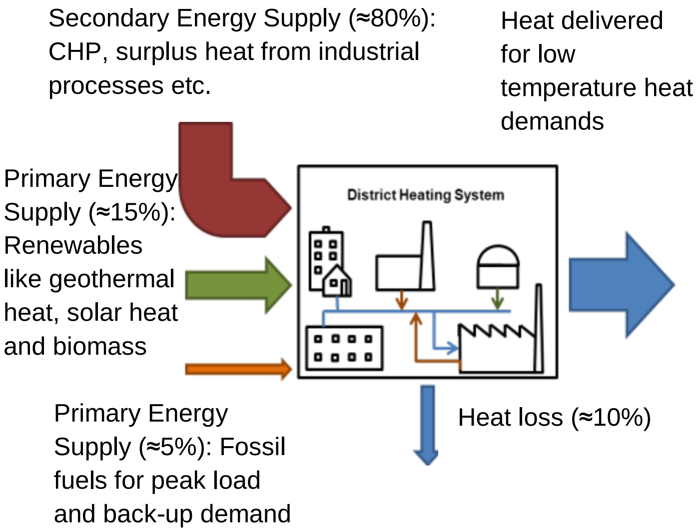

Fig. 2: Example of a district heating system which incorporates inputs from fossil and renewable energy sources, and utilises surplus heat sources [1].

The temperature levels required to heat and cool most building types (residential and non-residential buildings) are generally low (slightly above 23°C). In the case of the provision of domestic hot water, temperatures in the range of 50°C should principally be sufficient to avoid the risk from the legionella bacteria. Both renewable and surplus energy sources, which can be harvested very efficiently at low temperature levels, can fulfil this energy demand. On the community scale, synergies are maximised when buildings and building supply systems are regarded as integrated components of an energy system. A number of issues need to be addressed in regard to matching the demand created by space heating (SH) and domestic hot water (DHW) on the building side with the available energy from the supply side in order to develop advanced low temperature heating and high temperature cooling networks.

The LowEx Approach

Basically, the physical property “exergy” can be expressed as a product of energy and “energy quality” (Carnot Factor). The higher the temperature of a heat flow is above reference temperature, the higher the energy quality.

$$Ex_Q = Q \cdot \underbrace{\left(1 - \frac{T_0}{T}\right)}_{CarnotFactor} \qquad (1)$$

As a part of the considerations of this project, the following simplifications will be used: the lower the temperature of a thermal energy supply flow for heating, the lower its energy quality and, therefore, the associated exergy flow. This fact could be used to optimise the exergy efficiency of a community supply system and is known as the low exergy (LowEx) approach. The LowEx approach entails matching the quality levels of energy supply and demand in order to optimise the utilisation of high-value energy resources, such as combustible fuels, and minimising energy losses and irreversible dissipation (internal losses).

Benefits

The use and implementation of low temperature district heating networks offers various benefits.

Utility companies benefit from low temperature district heating by having lower heat losses in the DH networks. Also, they can use plastic piping, which can be more cost effective than conventional DH metal based pipes. The use of low temperature heat allows the integration of additional heat sources into the DH scheme, such as solar thermal collectors, deep geothermal wells and low temperature waste heat. If heat is generated by advanced CHP plants, such as combined-cycle plants, the low temperature of the used heat can lead to a higher electricity generation and therefore improved revenues from energy sales.

Customers benefit in various ways. First of all, the use of district heating ensures a good comfort level and a secure supply. Customers do not have to worry about maintenance, fuel supply and optimal operation of heating systems. In the case of low-temperature DHW supply, the use of systems without DHW storage and pipes with small volume from heat exchanger to taps could allow the safe use of DHW at supply temperatures in the range of 50ºC. In this way, the risk of legionella growth may be minimised without having to resort to higher temperatures.

From an economical point of view, relatively high price stability can be expected due to the use of locally available, renewable, or surplus heat energy sources. An additional advantage of this is a lower dependency on foreign fuel supplies. The high overall system performance that can be achieved by using low temperature DH would lead to reduced resource consumption and therefore lower costs for fuels. This would also increase price stability and could potentially provide heat at very competitive prices.

STRUCTURE OF THE DHC ANNEX TS1 ACTIVITY

To work on the field of low temperature district heating the IEA DHC activity Annex TS1 is covering work items ranging from the assessment and further development of planning tools, via the collection of suitable DHC technologies and the engagement on the field of the interfaces between the community, the DHC network and the buildings to the analyses of various case studies. Furthermore, dissemination in form of workshops and publications is also covered by the project participants [2].

RESULTS FROM INVOLVED RESEARCH PROJECTS

The goal of the research activities are primary reducing resource consumption (including primary energy) and GHG emissions through overall system optimization and developing new ways of bringing knowledge into practice.

First of all identification, demonstration and collection of innovative low temperature district heating systems is in foreground. Here advanced technologies and the interaction between system components are to be demonstrated. Following the collection and identification of promising technologies to meet the goals of future renewable based community energy systems is accomplished. In this case interfaces between an advanced generation and supply of thermal energy on one hand, and, on the other hand, the optimised demand management within the community have to be identified. The holistic systematic approach is the key issue to prevent the introduction sub-optimal systems. An overview of methodology for assessing and analysing procedures in order to optimise local energy systems is presented.

The development of appropriate solutions can help to reduce fossil energy consumption and, thus, emissions. The improvement areas are new methodologies, concepts, and technologies in the field of DH. This includes an improved integration of renewable and surplus heat as well as the adaption of energy and exergy demand.

Example: Network topologies

Within several research national projects different network topologies for DH supply were compared by using of simulation studies. One research project showed that in case of new development areas the usage of ring networks as well as house to house network is the most appropriate way for delivering heat.

The differences and advantages of a ring network topology in comparison to a traditional network topology that the required length of pipes are about the same, but smaller pressure gradients occur. The advantages are shorter service lines which lead to reduction of losses, network investments and pumping costs.

Example: Mass flow control

Especially in combination with ring networks mass flow control systems are a further technology for improving the efficiency of DH supply. The goal of this technology is to archive equal mass flow rates. Suitable mass flow can be archived by usage of inverter-controlled pumps. These pumps are placed in both the primary and the secondary side. The secondary side pump is controlled on the basis of the return temperature from the radiators. The primary side pump is controlled on the basis of the supply temperature of the district heating water. The advantages of this technology are lower pressure losses in customers' substations and that primary side control valves are replaced by inverter-controlled pumps. Furthermore, it will lead to generally decreased pressure losses throughout DH-pipes.

Example: Cascading

On the community scale, different types of heating systems require different supply temperatures. To obtain the maximum output from a given primary energy flow, different temperature levels can be cascaded according to the requirements of the building typology and technology. This demands an intelligent arrangement and management of the temperature levels and flows within the system. Bi-directional concepts and short term storage can be elements of a system which is not only energy efficient, but also exergy efficient.

Case studies

While requirements to energy performance of buildings are introduced generally on European and on national levels heat demands of buildings are decreased by applying improved building envelopes and more efficient heat recovery for ventilation systems. Nonetheless low temperature district heating offers a way to supply heat to buildings in an economical feasible and environmental friendly way. The case studies displayed in the following are show cases where a successful application of new and innovative district heating concepts has been shown. Low temperature district heating system usually means that supply temperature below 65 °C or even 50°C are used without any need of additional heating on side of district heating or customer side [3].

Reduced temperature level results besides reduced heat losses from district heating network in many benefits as e.g. comparable easy implementation of renewable energy sources with higher efficiency, but on the other hand in some cases there are challenges connected mainly to the issue of the hygienic preparation of domestic hot water (DHW).

Example: Hyvinkää (FI)

The project at the housing fair area Hyvinkää is based on the connection of a number of very low energy buildings and so-called passive houses to a district heating connection.

The particular goal for this project is the estimation of the long term performance of innovative district heating systems. So the long-term goal extends to the year 2020 and beyond. A life-cycle analyses on the community-level is carried out. Consequently, an influence of solutions on the community life-cycle emissions can be shown based on these analyses. The aim is also to explore in Finnish climate the boundary conditions and opportunities for the district heating solutions for so-called "nearly zero-energy houses".

During the course of the project energy consumption in the connected single-family houses and on the DH-system level will be monitored for several years. The results from the measurements will be used to explore short- and long-term fluctuations of power and energy consumption in buildings and to assess their impact on operation of electricity and district heating networks [4].

Fig. 3: The map of the Hyvinkää housing fair area (FI)

The project aims at the development of special district heating solutions for single-family houses with 2012- and 2021-level (Finish energy standards) of heat consumption. The approach is based on the life-cycle analysis of the entire energy system (i.e. extending from the indoor space services, through the new district heating network solutions up to the community level energy generation). The potential of using communal waste in energy generation will be assessed, too.

Based on that analyses a number of new business and service models for district heating in single-family houses will be developed and assessed. For the utility companies not only the economic issues are of interest, the short- and long-term variations and power peaks in district heating consumption will be examined to optimise the entire energy system. For this last point the proper sizing of on-site energy production (e.g. solar thermal) for own use in the houses are of interest as well.

The housing fair area in Hyvinkää opened in 2013 and is a place for demonstrations. On a long term perspective also opportunities to expand the use of district heat to replace heating function in some household's electrical equipment (laundry- and dish-washing, sauna, etc.) will be examined, and thus to optimise the local use of electricity. Finally a contribution to the development of national building code is in focus, since the energy consumption dynamics are actually not accounted for in the codes. Here the project is demonstrating compliance with the regulation.

The project considers the following working items:

- Life-cycle-costing for improving the competitiveness of district heating in small houses (LCC)
- Life-cycle analysis for DH-solutions in small house districts (LCA)
- Design criteria for new small houses according to 2012- and 2021 regulations
- Solutions for new 2012- and 2021 standards in small house districts
- New business and pricing models
- Pilots and monitoring measurements
- Information, recommendations and dissemination

Example: Lystrup (DK)

A key challenge for achieving a competitive district heating system of today and in the future is to reduce heat loss in network while today's building regulations demand reduction of heat consumption. So, the ratio between network heat loss and heat consumption in the connected buildings is a main issue. Low temperature district heating offers a solution and is implemented and evaluated in real scale in Lystrup close to Aarhus in Denmark. The goal of this project is to reduce district heating temperature delivered to consumers to 50°C and connect the buildings in a manner that no reheating is needed to be applied - neither at consumer site nor at district heating site. For the Lystrup project, two types of low-temperature district heating substations and new district heating twin pipes with reduced diameter were developed and tested.

The project consists out of 7 row houses with totally 40 flats where two different sizes of flats are being realised: 89 m^2 and 109 m^2 (gross area) with a resulting design heat demand for space heating of 2.2 kW and 2.6 kW respectively. All rooms - except bathrooms – are equipped with low-temperature radiators with a design supply temperature of 50°C and a return temperature of 25°C. The bathrooms are supplied with floor heating. To keep the very low supply temperatures district heating water is supplied directly into the building's heating system, no heat exchanger between building heating system and district heating system has been applied [5,6]

Fig. 4: The row houses at the Lystrup project (DK)

The project is a show case that demonstrated that low temperature district heating can be used even in areas with low energy demand while being economical feasible and giving high comfort levels for the connected users.

Overall heat loss from the new low temperature district heating network was reduced to a quarter (¼) compared to traditional district heating system designed with temperatures of 80/40°C. Besides good economy, reduced heat loss of the heating grid there is a contribution of savings equal to about 21 tons of CO_2/a just by satisfying the heating needs of the 40 houses via a district heating network. Further benefits of low temperature district heating can be seen from earlier implementation of renewable energy sources into the heating sector being one of the main goals of European Union Energy Policy. The concept of low temperature district heating has also been investigated to include existing buildings representing much larger perspectives for its application than newly erected buildings [7].

Example: Ludwigsburg (GER)

The urban planning concept for the city quarter of Ludwigsburg entails the design of the local energy supply system by the extension of the main district heating network of the quarter "Sonnenberg" with the aim the use innovative network technology, a so-called low exergy (LowEx) sub grid, and to integrate of thermal solar energy into the new grid section.

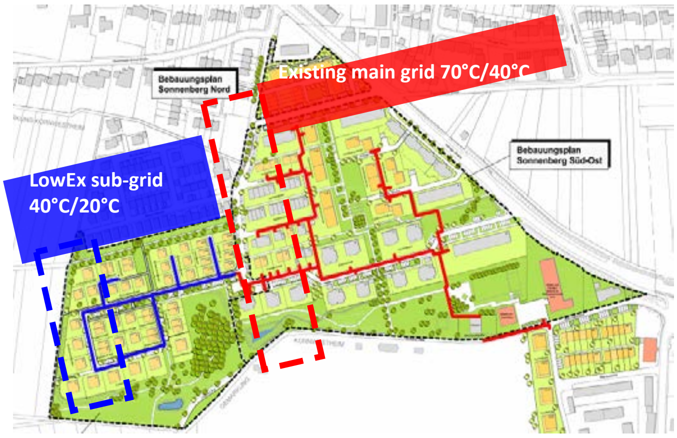

Fig. 5 the Sonnenberg quarter of the city of Ludwigsburg (GER)

The project goals for the city of Ludwigsburg are to realise an energy supply concept with a gas-fired cogeneration plant (CHP) of 700 kW_{th} and with a geothermal driven heat pump of 200 kW_{th}. The decentralised heat storages are planned to be located inside the buildings and operated via a smart metering concept with a central control unit [8].

The LowEx network extension is operated with supply temperature at 40°C from the return temperature of existing network of the city quarter Sonnenberg. This new district heating network, which represents about 30% of the total network length, is going to be connected to low energy/passive standard buildings. The research project focuses on the demand side management and structure (energy standard of buildings, operation of heaters), the network structure, on the chosen supply concepts and on the storage management.

Example: Kassel Feldlager (GER)

An innovative heat supply concept for the new housing area „Zum Feldlager" of the city of Kassel in Germany with about 140 houses has been set up. The main Objectives and challenges with this particular project are the minimization of primary energy consumption, the reduction of CO_2 emissions compared to common supply systems, the reduction of transmission heat losses and the usage of a high share of renewable energy sources for the supply of the about 500 persons living there in near future.

Fig. 6: The housing area “Zum Feldlager” (GER)

In order to identify the best possible system solution, different supply strategies are investigated and compared. Main objective is the development of an innovative and optimised heat supply concept based on renewable energies and low temperature district heating. Central challenge in achieving this objectives is the identification of the most promising and efficient technical solutions for practical implementation. Furthermore aspects of future network management as well as business models for distribution and operation will be considered [9].

The buildings are designed in a low energy house standard witha low heating energy demand (< 50 kWh/m²a). The specific heat demands for the buildings turned out to be 45 kWh/m²a, the specific domestic hot water heat demand has been estimated to be 730 kWh/pers*a.

So, the heat supply concept has been set up with regard to realise the supply to the entire development area without fossil fuels, such as oil (expensive, water protection area), natural gas (no gas network) or fire wood (fine dust emissions). Use of renewable energy sources such as geothermal and solar energy for low temperature supply has been elaborated. The supply to the different houses has been planned to be a low temperature heat supply with by implementation of intelligent storage systems and thermal load shifting concepts.

For the realisation of the project two different supply concepts are investigated in more detail: a centralised and a decentralised concept.

For the decentralised supply variant of the low energy buildings both an air to water heat pump system and a condensing boiler system have been investigated. The domestic hot water preparation is planned to be realised by solar thermal collectors and a small photovoltaic system delivers a share of the electricity for the pumps.

For the centralised concept the houses are supplied by a low temperature district heating grid. For the heat generation both a renewable gas powered combined CHP plant and a low temperature heat generation via a ground coupled (boreholes) central heat pump are investigated separately. In both cases the use of a large heat storage to realise a demand-oriented power generation is foreseen. Here the operation as a seasonal or a short-term geothermal storage for the entire supply areas is investigated. The use of excess electricity from wind / PV by electric heater is also considered. For the domestic hot water preparation solar thermal systems with an additional electrical backup heater are planned.

The supply temperatures of the low temperature district heating grid is designed to be 40°C, the heat supply for space heating is preferably done directly via floor heating systems or via low temperature radiators. To increase the efficiency of the heating systems and to optimise the hydraulic integration of the heat generation systems the use of smaller water storage tanks in all buildings are intended. A hygienic preparation of domestic hot water is realised by fresh water stations.

- The key advantages of the analysed system layout are: Low heat losses through the low water temperatures in the district heating network
- High efficiency of heat pumps due to the low temperature lift ($\Delta T \approx 20K$)
- Low investment by using plastic tubes, quick and flexible installation
- Efficient operation of the solar system through a direct connection to the heat storage
- Easy and convenient implementation of large storage volumes by using unpressurized storage
- Hygienic hot water preparation via fresh water stations. (legionella problem)

EXPECTED OUTCOME AND RESULTS FROM THE PROJECT

The primary deliverable of the presented activities within the annex is an easy to understand and practical, applicable future low temperature district heating design guidebook for key people in communities. It is to contain an executive summary for decision makers. Some key questions for the targeted group of people are:

- What are arguments for taking action in regards to a possible change of the energy system within the community?
- What shall be done with regard to the community's energy system?
- And, what should not be done?
- Does our community fulfil the conditions for the implementation of low temperature district heating and, if not, what could we improve to allow for this in the future?

These questions will be answered in the guidebook, which is to be focussed at low temperature district heating from a communal, decision makers' point of view. This will cover issues on how to implement advanced low temperature district heating technology at a community level and how to optimise supply structures to ensure reduced costs for the system solution, while providing a high standard of comfort to the occupants of the buildings.

This brochure will be published preferably both as a book via a publisher, and as an electronic publication. More detailed results, which will be published as appendices or separate reports via the project homepage [2] are intended to cover topics such as:

- Analysis concept and design guidelines with regard to the overall performance. This could include a possible classification of technologies in terms of performance, improvement potential and innovation prospects.
- Analysis framework and open-platform software and tools for community energy system design and performance assessment.
- A collection of best-practice examples and technologies.
- Dissemination of information on demonstration projects.
- Guidelines on how to achieve innovative low temperature systems design, based on analysis and optimisation methods, and derived from scientific studies.

The dissemination of documents and other information is to be focussed at transferring the research results to practitioners. Methods of information dissemination include conventional means such as presentations at workshops and practice articles. The project homepage is used extensively to spread information [2]. Publications may be written in English and in the languages of the participants' countries. However, the translation of the key findings into English will allow for a broader distribution of knowledge. A communication platform will be developed using local networks and energy related associations. Regular workshops will be organised in all participating countries to show the latest project results and to provide an exchange platform for the target audience. Some of the workshops might be organised within the framework of national or international conferences or symposia of the district heating community/industry.

SUMMARY

The IEA DHC Annex TS1 is a framework that promotes the discussion of future heating networks with an international group of experts. The goal is to obtain a common development direction for the wide application of low temperature district heating systems in the near future. The gathered research which is to be collected within this Annex should contribute to establishing DH as a significant factor for the development of 100% renewable energy based communal energy systems in international research communities and in practice. The Annex TS1 is intended to provide solutions for both expanding and rebuilding existing networks and new DH networks. It is strongly targeted at DH technologies and the economic boundary conditions of this field of technology. The area of application under consideration is the usage of low temperature district heating technology on a community level. In connecting the demand side (community/building stock) and the generation side (different energy sources which are suitable to be fed in the DH grids), this technology provides benefits and challenges at various levels. The scientific basis for the development of assessment methods provides the low exergy (LowEx) approach. This approach promotes the efficient and demand adapted supply (e.g. at different temperature levels) and the use of renewable energy sources. The project will be realised based on selected case studies. As Annex TS1 is a task-shared annex, there will be no individual, separate research projects started within the Annex. The Annex TS1 provides a framework for the exchange of research results from international initiatives and national research projects and allows, in a novel way, the gathering, compiling and presenting of information concerning low temperature district heating. Currently 12 research institutions from 12 countries are participating [2].

ACKNOWLEDGEMENT

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TOWARD 4th GENERATION DISTRICT HEATING: EXPERIENCE AND POTENTIAL OF LOW-TEMPERATURE DISTRICT HEATING

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ABSTRACT

In many countries, district heating (DH) has a key role in the national strategic energy planning. However, tighter legislation on new and future buildings requires much less heating demand which subsequently causes relative high network heat loss. This will make current DH system uneconomical comparing with other local heat generation units. The design and operation of DH systems therefore needs to be re-examined, part of the solution being low operational temperature. The 3-years IEA DHC Annex X project 'Towards 4th Generation District Heating: Experience and Potential of Low-Temperature District Heating (LTDH)' aims to document experiences gained in mature DH countries with low temperature systems serving highly energy-efficient new buildings and existing buildings. The potential to supply DHW at temperature close to 50°C without the risk of Legionella was investigated. Information on optimal DH network design and decentralized heating supply has been reported. The technical and economic feasibility to supply LTDH in different countries/regions was reported.

INTRODUCTION

The evolution of DH has gone through three generations since the first commercial DH system was emerged in 1870s. The concept novelty and technique advance brought the generation replacement for every 40-50 years. Typically, the classification of different generation DH systems can be characterized with the type of transport media and the network temperature levels: the 1st generation DH is steam-based system (1880s-1930s), the 2nd generation DH uses high network supply temperature above 100°C (1930s-1970s), and the 3rd generation DH uses medium network supply temperature between 80°C to 100°C (1970s-now). Up until now, the LTDH is emerging as the 4th generation DH system. Figure 1shows the evolution of the four generation district heating systems.

The major impetus to develop LTDH is mainly due to two aspects: increase current DH market share and maintain competitive advantages in the future heating market. In mature DH countries, the current DH market is saturated. Further market penetration requires the engagement of the region on the peripheral of urban areas where normally have low heat density and traditionally supplied with individual heating units like natural gas-oil boilers, or individual heat pumps. Future DH development faces the challenge of drastically decreased heating demand. The energy demand in low energy building drops to one-quarter of current level. The nowadays economically feasible regions supplied with DH may become un-profitable in the future due to the reduced heat density. Connecting DH to such area will incur large network heat loss if the current DH technologies were continuously used.

LTDH reduces the network temperature down to around 55°C, which closes to the minimum required DHW supply temperature. This brings the advantages in heat distribution with respect to reduced network heat loss, improved quality match between heat supply and heat demand, reduced pipeline thermal stress, reduced risk of boiling and scalding. In particular, comparing with current 3rd generation DH system, LTDH with well-designed network and better insulation reduces the network heat loss down to ¼ of current network heat loss [1]. This makes DH economically competitive to low heat density area when compares with local heat generation units.

The goal for the 3-year IEA DHC project aims to bring experience, knowledge and solutions for 4th generation district heating systems to a level where they are ready to be implemented widely [2]. It comprises two phases.

- Phase I: document experiences in mature DH countries with very low temperature systems serving highly energy-efficient new-build developments
- Phase II: analyze and extend the scope of lessons arising from early examples of low-temperature systems, in order to improve the cost-effectiveness and environmental benefits, effectively formulating a blueprint for a new generation of district heating.

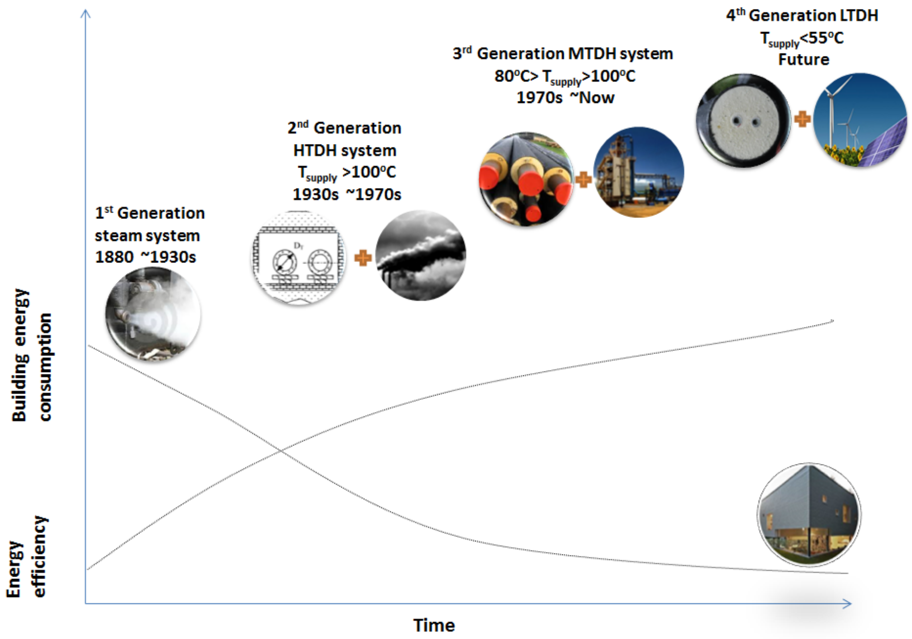

Figure 1 Evolution of four generations district heating system

THE RESEARCH APPROACH IN 4TH GENERATION DISTRICT HEATING

Traditionally DH utilities benefit from selling more heat to the consumers and in favor of short-term fossil-fuel based small investment. The evaluation of a DH system often focuses on the production/supply aspect and the operation of DH system is realized to supply sufficient high temperature and available pressure head. The 4th generation DH concept switches this perspective. As shown in Figure 2, it starts from energy savings in buildings, end-user thermal comfort and quality match between energy supply and energy demand, then moves to energy efficient and cost effective network design and operation and finally considers environmental friendly heat production techniques. It stimulates a paradigm shift from selling more heat is good for business to selling less heat is good for business. The corresponding financing mechanism will be in favor of investment for capital-intensive, low operational costs and long lifetime renewable based heat generation systems.

The development of the next generation DH system requires a coordinated effort for building energy reduction and wide exploitation of renewable energy and waste heat. Building energy reduction not only reduces the annual energy consumption but also levels out the peak heating demand. Therefore, the investment for building energy conservation measures should go hand in hand and preferably prior to the investment on new installed capacity for renewable heat generation. The level of building energy reduction and the sequence and magnitude to invest in different renewable heating technologies requires a strategic long term energy planning approach to evaluate the entire energy chain.

SAFETY SUPPLY DOMESTIC HOT WATER

The building DHW installation provides hot water for shower, kitchen and hand wash use. A well-designed and functioning domestic hot water installation should fulfill the requirements for hygiene, thermal comfort, effective cooling and better energy efficiency.

For low-temperature network operation, the bottleneck lies in DHW supply as the SH system can operate with a temperature close to room temperature with low-temperature radiant heating system. The minimum DHW temperature is defined from the perspective of hygiene. To avoid the risk of Legionella bacteria and other microorganism growth in potable water systems, the minimum DHW temperature should be above 50°C.

Legionella is a pathogenic group of gram-negative bacteria that thrive in the aquatic circumstance. The growth of Legionella is influenced by multiple factors: water temperature, water stagnation, size of DHW installations, sediment, sludge and biofilm. Among

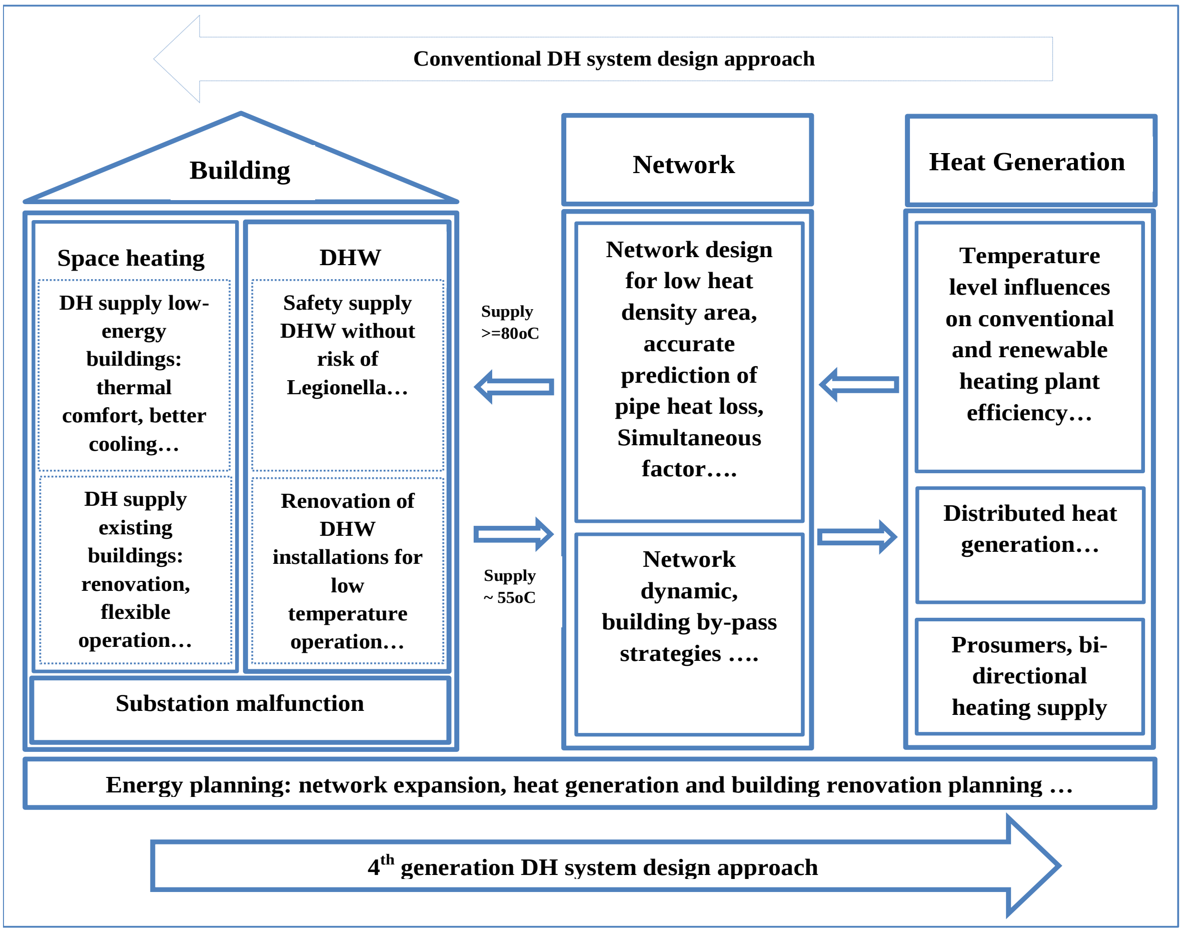

Figure 2 4th Generation district heating approach

these, water temperature is the most important factor. The national code for DHW normally regulates the hot water temperature in the range of 50-60°C according to the type and volume of DHW installations, location ofthe tapping point and the recirculation. The common solutions to treat DHW against Legionella bacteria, amoebae and other microorganisms include thermal treatments, chemical treatments, and physical treatments such as ultra-filtration or UV radiation.

A typical domestic hot water substation consists of heat exchange and heat storage units, a circulation pump, thermal and hydraulic controllers. In the report, two conventional DHW units are introduced with necessary modification to fit for low-temperature operation.

Instantaneous heat exchanger unit (IHEU) prepares the hot water with a plate heat exchanger (Figure 3). Comparing with storage tank units, IHEU are more compact, cost-saving, with low risk for Legionella contamination and better cooling of the DH water.

On the other hand, due to the stochastic nature of hot water tapping, large and rapid variation of draw-off flow rate, and large variation of flow parameters as district heating supply temperature and differential pressure, instantaneous heat exchanger unit requires a self-acting controller to fully response of such changes in DHW preparation. The capacity of the heat exchanger should be designed large enough to adapt large heating power during tapping. This subsequently requires large pipe diameter for the connected service pipe (pipe connects between building to street). Due to the reduced temperature difference between the primary side supply temperature and the secondary side tapping water temperature, heat exchangers with an increased unit heat transfer rate and more accurate fast-response thermal control is required for low-temperature operation.

Domestic hot water storage tank unit has the advantages to shave the peak heating load, allows a low charging flow rate of DH water and shorter waiting

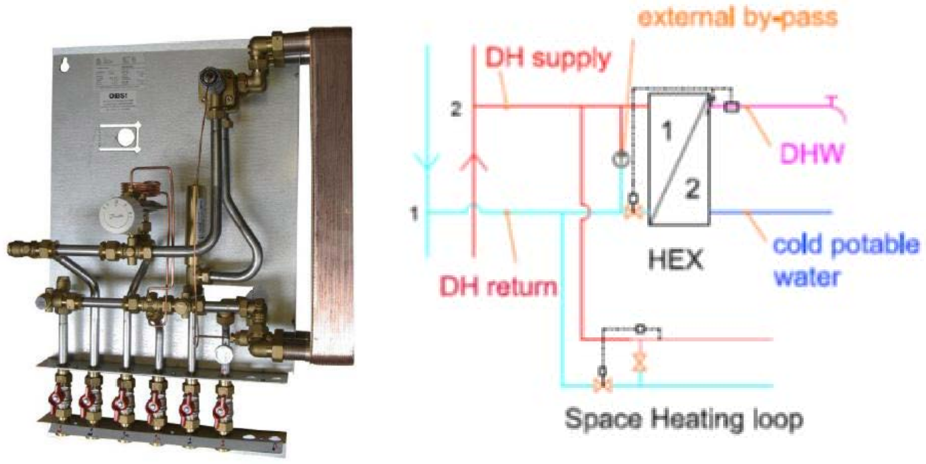

Figure 3 Picture and scheme of Instantaneous heat exchanger unit

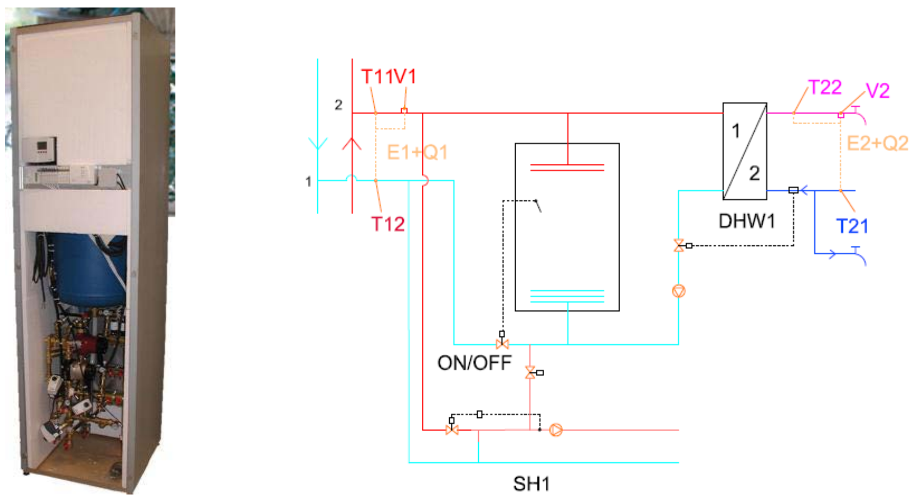

Figure 4 Picture and scheme of District heating storage tank unit

time. Therefore, the service pipe and its connected distribution pipes can be designed with smaller diameters, thus reducing network heat loss. In the low-temperature design, the storage tank is moved to the primary side and exchanges heat through the instantaneous heat exchanger on the secondary side to eliminate the risk of Legionella (Figure 4) [3].

The disadvantages of the storage tank unit are costly, occupying more spaces, requiring regular clean. Meanwhile, it is arguable that DHSU can reduce heat loss comparing with IHEU. On one side, storage tank has large heat loss from the tank (though part of the heat loss can be recovered for SH needs). On the other hand, the network dimensions depend greatly on the selection of simultaneity factors (SF). The measurements from the Lystrup project indicate that the SF selected for IHEU can be much lower comparing with the traditional design parameters [4]. After the first several consumers, the corresponding distribution network can therefore be dimensioned in the same way as the DHSU. This may make the DHSU less advantageous with regard to the total heat loss reduction due to its higher heat loss from the storage tank.

LOW-TEMPERATURE DISTRICT HEATING SUPPLY FOR SPACE HEATING

Low-energy building applies massive insulation and higher degree of air-tightness to minimize energy loss. Comparing with existing building, the heating load duration curve becomes more flat for low-energy buildings. The portion of DHW energy consumption becomes much higher in the total heating load. Meanwhile, solar radiation and internal heat gain has big influence on the building heating supply. There has not only concern to supply comfort indoor temperature during winter time, but also concern on over-heating during transitional period and summer time.

Three different heating systems include forced air heating (FAH), radiator and floor heating (FH) are reported in the project with comparison of consumer thermal comfort, peak load, and DH return temperature. The analysis shows that FAH has the best cooling followed by radiator and FH. Regarding the peak power, radiator has the smallest peak power. From thermal comfort point of view, FAH has the worst condition to control comfort temperature in each individual room.

The design of low-energy buildings has been the focus of current research and engineering practice, yet the majority of the buildings are existing buildings with high energy demand. To implement the LTDH into a large scale, it is essential to find technical feasible and economic sound solutions to convert the existing DH systems into low-temperature supply. The potential to supply LTDH to existing buildings has been investigated for typical Danish residential house built in 1970s. The feasibility to supply LTDH to existing buildings lies in the following factors:

- The radiators in the existing buildings may be over-dimensioned. This may due to larger radiator area was placed under the window to prevent the draught.
- The building had been gone through a certain degree renovation such as substituting highly energy-efficient windows, adding more insulation on external wall and roof, installing heat recovery in mechanical ventilation.
- The network can adopt flexible operation strategy. During cold winter season, the network should be operated in a flexible mode and supply higher temperatures than that as in usual.

The preliminary study indicates that with necessary refurbishment, a building heating system which was originally designed for the medium temperature DH system can run with LTDH when the ambient temperature is above a certain limit. Below this temperature limit, a flexible DH operation strategy is suggested to gradually increase the DH supply temperature. The duration for such operation is around 20% of the entire heating season in the studied case.

DISTRICT HEATING NETWORK ANALYSIS FOR LOW HEAT DENSITY AREA

One of the major barriers to supply DH to low heat density area is the excessive high relative heat loss. In order to reduce the network heat loss, different strategies can be applied in the LTDH design.

- Reduce temperature level
  By reducing network temperature from 80/40 ^{o}C to 55/25^{o}C, 30% of energy reduction is achieved.
- Reduce pipe dimension
  - Higher maximum network pressure level and allowable velocity limit
  - Lower differential pressure at the critical user
  - Dimension the pipeline according to more realistic simultaneous factor to avoid over-dimension.
  - Apply decentralized pump at street level to further reduce the pipe diameter.
- Apply advanced pre-insulated twin pipe
  - Apply pre-insulated twin pipe to replace the single pair pipe
  - Increase high insulation standard
  - Improve prediction of pipe heat loss
- Reduce thermal bypass losses
  - Triple pipe: minimum cooling of supply water
  - Comfort bathroom: maximum cooling of supply water
- Other strategies
  - Triple pipe
    - ✓ Use two supply pipes in winter time and one smaller diameter supply pipe during summer time. Typically used in service pipe with a booster pump.
    - ✓ Supply water at different temperature levels to meet ultra-low temperature SH demand and DHW demand.
  - Looped network
    Looped network maintains the differential pressure between supply and return pipe as constant value thus improve the network hydraulic. The network heat loss can be further reduced when it is coupled with the double pipe application.

CONCLUSION

LTDH brings advantages for both heat distribution and heat generation. It improves the CHP plant power to heat ratio, increase the solar thermal conversion efficiency and increase COP value for heat pump, enhance the utilization of geothermal thermal and thermal storage. LTDH is emerged with the need to address the challenge to expand and adapt DH for low-heat density built area in the future.

The aim of the 3-year IEA DHC Annex project is to widen the experience and lessons learnt to supply LTDH to low energy buildings and facilitate the market penetration through policy drive and regulation change, collate information from existing engineering practices to supply LTDH to existing buildings and identify optimal strategy to invest renewable heat generation capacity with coupling of building energy renovation.

Through the project, it is realized there still have space for further technique and system improvement. Meanwhile, the effectiveness of LTDH in real engineering application is not fully realized based on measurement of daily operation (for example, the network return temperature is higher than the designed value). This forms the basis to develop the next IEA DHC project ‘Transformation roadmap from high to low temperature district heating system’[5].

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HEAT EXCHANGER MEASUREMENTS IN A MASS FLOW CONTROLLED CONSUMER SUBSTATION CONNECTED TO A RING NETWORK

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ABSTRACT

The contribution of this paper is to demonstrate experimentally the feasibility of a novel district heating (DH) system that uses a new low-temperature technology based on ring network topology and a mass flow control system. The study is based on several previous works: a theoretical approach to the new concept, an optimization case study and a simulation of a heat exchanger in a consumer substation. The central part of the work is the analysis of a laboratory-scale system with the purpose of proving the usability of the new technology. Series of experimental measurements were conducted with the aid of a simulation model, getting a mean heat exchanger effectiveness of 0.88 as a result. Additionally, non-linear supply and return temperature curves were obtained, which implies higher temperature cooling and lower return temperatures. Furthermore, the new mass flow control enables equal flow rates on both sides of the heat exchanger, which improves the heat transfer and allows lower flow rates. These improvements led to the main findings of the research: substantial increase of the overall system efficiency and important savings in operational costs.

INTRODUCTION

This paper represents a continuation of several previous studies on the same subject: development of a new DH concept that enables the obtaining of new supply and return temperature curves and more significant temperature cooling. The following are the most relevant steps forming the background for this work.

The new DH model was introduced for the first time in 2013 by Kuosa et al. [1] in a static study in which a theoretical approach to the new concept was made under steady-state conditions. There were two key innovations in this concept: ring distribution network topology instead of traditional Y-topology, and mass flow control using variable speed pumps instead of valves in the primary and secondary sides. The features and benefits of the new model were demonstrated by mathematical modelling. Compared to traditional systems, improvements were obtained in the following aspects: lower DH water flow leading to lower pressure losses and pumping power demand, and lower return temperature and thus lower heat losses.

Then Laajalehto [2] and Laajalehto et al. [3][4] researched about the practical application of the new concept in a case study. “Grades Heating” calculation application [5] was used in a real loop-like DH network in Helsinki. All the theoretically expected benefits were confirmed, obtaining a more energy-efficient network. In this regard, optimal supply and return temperature curves were obtained in this particular case, allowing a drop in the total energy losses to minimum values. Specifically, average energy losses within the examined constraints (heat losses, pumping energy and surplus energy from the heat recovery system of the heat station) were reduced from 4.4% to 3.1%. Besides, improved network control was achieved due to the ring topology.

Finally, the operation of a plate heat exchanger (PHE) was simulated in a consumer substation corresponding to the new low-temperature model, finding high heat exchange efficiency as a result [6]. The PHE operation was studied by monitoring variations in flow rates, pressure losses and overall heat transfer coefficients for varying simulated outdoor temperature conditions. The use of mass flow control contributed to the optimization of the primary and secondary side flows, achieving almost equal flow rates on both sides of the heat exchanger, maximum temperature cooling and minimum pressure losses.

The aim of this study is to demonstrate experimentally the feasibility of the new DH concept, ensuring that the expected benefits are achieved. To this end, a laboratory-scale system was used to carry out a series of measurements simulating the operation of a consumer substation in a medium-sized apartment building, corresponding to different outdoor temperature conditions.

STATE OF THE ART

District heating plays a fundamental role in Northern Europe (with heat market shares above 50%) as well as in various other countries, such as the Czech Republic and Slovakia [7]. Furthermore, this technology has experienced a great development in the last decades, and there are new improvements coming out every year. Specifically, all kinds of DH systems are being optimized, obtaining higher efficiencies that imply lower fuel consumption and greenhouse gas emissions. In the same way, improvements are being made in other fields, which can have a strong effect on the development of DH systems. For instance, DH demand in Sweden is supposed to drop by up to 20% until 2025 [8], mainly due to the increase in energy efficiency in buildings.

In recent years, combined heat and power (CHP) has gained a notable importance in the share of DH owing to the new energy efficiency and greenhouse gas emission objectives, as it allows higher fuel utilization factors [9]. Another reason for this rapid growth is the aforementioned recent improvements in energy efficiency in buildings, which involves lower heat demand, leading to a higher share in the production mix [10]. The integration of CHP and DH is the best alternative for covering the heat supply needs in city areas. This combination is actually the most used system; for instance, it represents over 70% of DH production in Finland [11]. In fact, the European Union (EU) promotes the use of CHP in DH systems, although other heating alternatives are encouraged in the EU Commission's "Energy Roadmap 2050", which aims to reduce year 1990 greenhouse gas emissions by 80% by the year 2050 [12]. In this sense, the focus is on electrification of the sector by primarily using heat pumps and implementing large-scale electricity heat savings. Nonetheless, a study by Connolly et al. [12] showed that it is possible to achieve the same goals at a lower cost (approx. 15% reduction in heating and cooling costs) by using DH systems.

As for the latest developments in DH technology, interesting findings have emerged from studies in very different areas. Åberg and Widén [10] developed a fixed model structure based on linear programming that uses general parameters about the DH system and outdoor conditions to predict the heat demand, which is a useful tool for designing and optimizing DH networks. Grabemedhin [13] used a linear programming method in like manner to study the impact off biomass prices and emission allowances on the choice of fuels and production technologies for a certain case study in Sweden.

Other researchers, in turn, have focused on the integration of DH with other energy technologies. Jian et al. [14], for instance, optimized the operating parameters of an integrated system including DH water, wind, solar and natural gas, by using a group search optimizer (GSO) algorithm in order to minimize fossil fuel consumption. One of the main advantages of these integrated systems is the excellent response time for varying conditions, achieving savings up to 58.63 kgce (kilogram coal equivalent) per day.

Finally, it is relevant to mention a significant low-temperature DH study by Lauenburg and Wollerstrand [15], as it is related to one of the points (i.e. mass flow control) covered in this report. They focused on the secondary (consumer) side, developing a stable control system for variable speed pumps, which contributed to optimizing the circulation flow rate and getting lower return temperatures.

THEORETICAL CONSIDERATIONS

There are three key concepts that establish the basis for the improved energy efficiency of this new DH model: ring network distribution, mass flow control and non-linear supply and return temperature curves. The theoretical foundation of these principles is covered in this section, as well as the consequences of them.

Ring network

This topology is based on the idea of having equal pipe length for every consumer in the network. In traditional systems, the consumer closest to the plant has the shortest supply and return pipe lengths, whereas the furthest consumer has the longest lengths, as shown in green in Fig. 1. Taking into account that the supply pressure is unique for the whole network, proximate consumer valves have to be throttled while more distant ones are almost completely open. This leads to large and uneven local pressure differences and losses, which reduces the overall network efficiency and poses difficulties for the network control system.

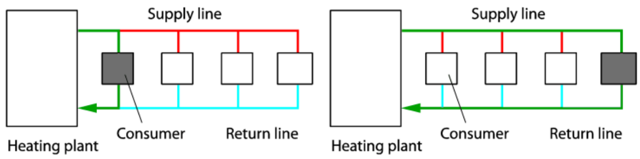

Fig. 1. Traditional network.

In ring networks, by contrast, the return line begins in the first consumer in such a way that water circulates towards the heat station in the same direction as in the supply line. This distribution equalizes the distances covered by the DH water flow of any of the consumers regardless their position, as shown in Fig. 2, which leads to the most important contribution of this topology: equalization of pressure difference between supply and return pipes. This fact simplifies the control system of the network to a great extent, as the previously mentioned uneven pressure and losses distribution is avoided.

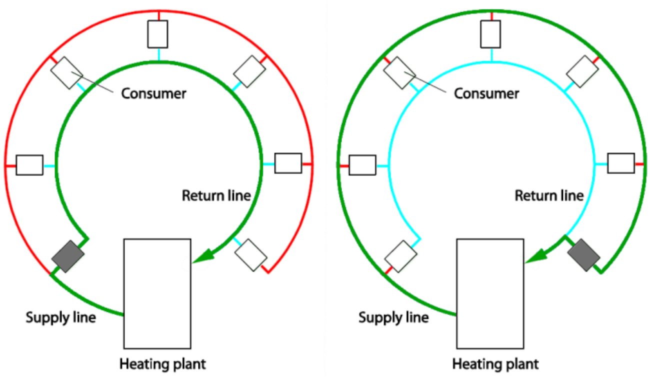

Fig. 2. Ring network.

So as to be able to apply this kind of distribution system, it is important that buildings are arranged in a certain way, as similar to a loop form as possible. Certainly, it is easier to implement it in areas where buildings have already been designed taking into account this topology but, either way, major changes in urban planning are not necessarily required in other cases.

Mass flow control

In the traditional DH model, primary and secondary side flows are controlled by valves and single-speed circulation pumps. There is only one central pumping station (usually in the heat station itself) for the whole primary side of the network, which results in lower supply pressure and temperatures for the furthest consumers, owing to energy losses in the pipes. Additionally, the motor valves controlling primary side flow to the heating and domestic hot water (DHW) heat exchangers represent extra pressure losses.

Besides, consumers' unequal heat demand is not taken into account with this unique primary side pressure, which means that the system is not optimal. The same thing happens to the secondary side: control valves open or close in order to adjust the flow required by the radiators to meet a certain heat demand ultimately determined by the outdoor temperature, while the single-speed circulating pump provides constant pressure.

On the contrary, the new model uses a radically different control system, replacing constant rotation speed pumps and control valves with variable speed local pumps, as shown in Fig. 3. Therefore, the flow of DH water is adjusted to meet each customer's particular heat demand, and valve-related pressure losses are eliminated. Water flow on the primary side is individually adjusted to assure a constant secondary side supply temperature. The secondary side pump rotation speed is adjusted in the same manner to achieve constant return temperatures from the radiators, depending on the heat demand determined by the outdoor temperature. These improvements enable higher temperature cooling and thus increased supply and reduced return temperatures, which in turn involve lower heat losses. Moreover, pressure loss reduction results in lower pumping power needs and allows smaller pipe dimensions, which have a positive effect on investment and operating costs. All these factors lead to an increase in the overall energy efficiency of the whole DH system.

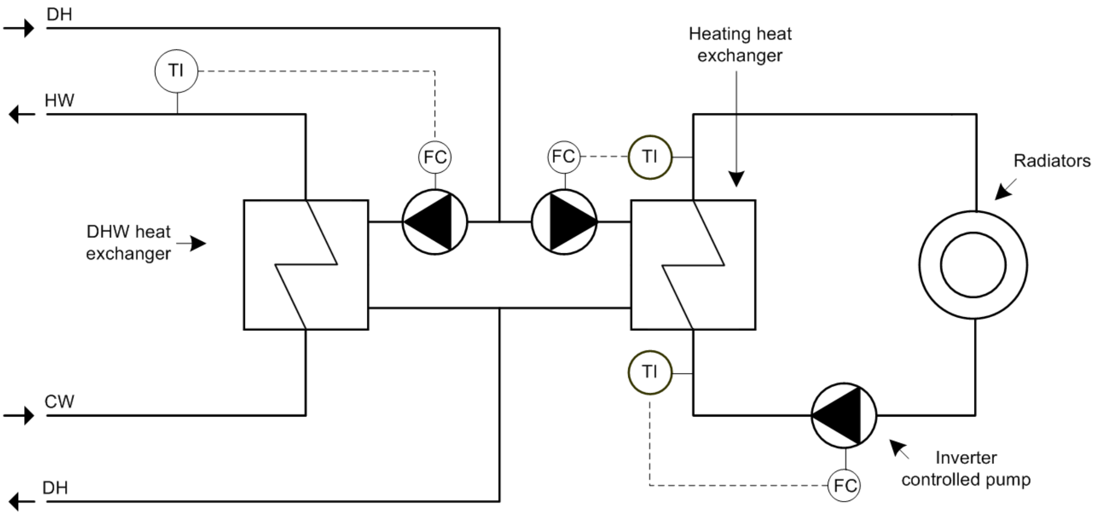

Fig. 3. Mass flow control applied to a generic consumer substation. [2]

Non-linear temperature curves

Distribution system heat losses are directly proportional to the average temperature of supply and return DH water. For that reason, it is very important to keep mean temperatures as low as possible, since that is the way to achieve the highest reduction in heat losses and pumping costs at the same time. However, it is difficult to reach this goal with traditional DH systems in low-temperature conditions, since supply and return temperatures have a linear relationship with the outdoor temperature, and thus the obtained temperature cooling is insufficient to satisfy the heat demand for most common outdoor temperatures. When the new mass flow control method is applied, in contrast, that dependence is not linear, which results in a greater temperature cooling (ΔT) for any outdoor temperature condition, as shown in Fig. 4. Higher temperature cooling values allow lower flow rates; in other words, they allow working in part-load conditions, which, in combination with variable speed control, improves pumping energy efficiency, as pressure losses are in direct square proportion to flow rate [1]. Other benefits are, for example, reduction of network heat losses in DH pipes (which is one of the main advantages of low-temperature DH systems), increase in heat accumulator capacity (due to lower flow velocity and reduced heat losses in those units) and higher power-to-heat ratio in the case of heat produced in

CHP plants. For all these reasons, non-linear temperatures are the most desirable condition, and the aim pursued in this series of experiments.

Fig. 4 illustrates the stated difference between these temperature curves. Note that subscripts “1” and “2” stand for primary and secondary side, respectively, whereas “in” and “out” refer to Fig. 5. It should be noted that operating supply temperatures correspond to low-temperature DH systems (50-80 ºC, in contrast to traditional systems, where primary side supply temperature varies usually between 70 and 120 ºC). In fact, the traditional model curves were placed in the same range of temperatures only for comparability reasons.

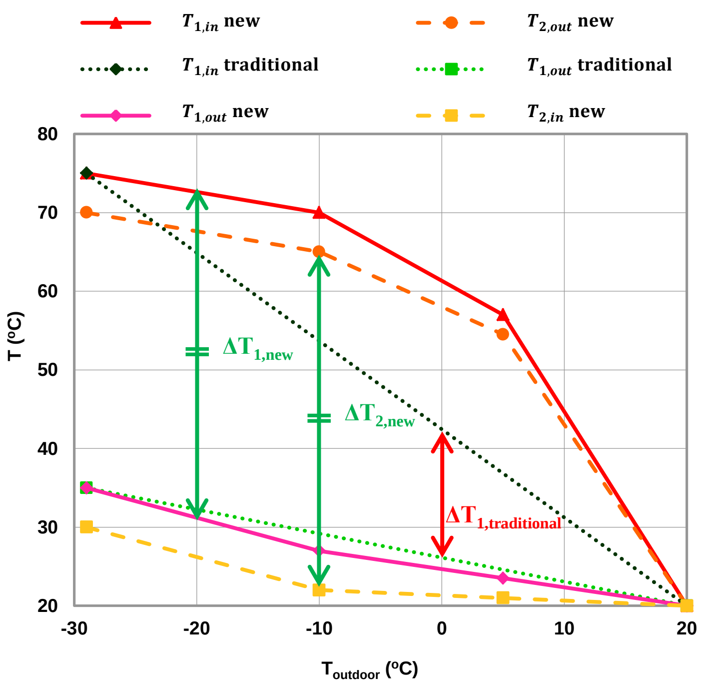

Fig. 4. Comparison of traditional (linear) and new (non-linear) theoretical low-temperature supply and return curves.

LABORATORY-SCALE INSTALLATION

An already existing laboratory-scale installation was used for the purpose of simulating a real application of the new DH system concept. The original installation was first built in 2000 by Hämäläinen [16] and used to conduct a series of experiments concerning the application of a mass flow control system to the secondary side of the traditional high-temperature DH model. Therefore, several modifications were made to the installation so as to adjust it to the conditions of the new DH concept.

The main change was the replacement of the existing heating heat exchanger (which worked properly in traditional high-temperature conditions, but provided a heat flow rate of only ≈ 1.8 kW in low-temperature DH conditions) with a bigger one (52 kW) able to deal with lower flow rates and higher temperature cooling values, according to the new low-temperature conditions. By the same token, both of the pumps were replaced by smaller ones able to handle lower flow rates. Additionally, some minor changes were made concerning piping and less important parts, in order to adapt the system to the new operating conditions.

Fig. 5 shows a simplified scheme of the used laboratory-scale installation, consisting of three separate water circuits that represent the main parts of a conventional DH heating system: primary and secondary sides and a cooling circuit simulating radiator cooling. The heat exchange between primary and secondary sides took place in the aforementioned PHE (I), which represents the heating heat exchanger of a consumer substation. Similarly, the secondary side was connected to the cooling circuit through a smaller PHE (II) that simulates the heat consumption in household radiators. Here, it is noteworthy that this study is limited to low-temperature space heating and no hot tap water generation is considered.

Supply water was heated in the steam generator and stored temporarily in a hot water storage tank (1 in Fig. 5 and Table 1). Then it was pumped by the primary side variable speed pump (2), whose speed was controlled by an inverter (11) in which frequency was manually tuned. Water in the secondary side absorbed heat in the heating heat exchanger (PHE I, 9) and released it via the smaller PHE (II) (10) representing the radiators. Thus, domestic heating consumption was simulated by the cooling circuit. The water in this last circuit came from an external closed loop and its flow was manually regulated by throttling a valve. This manual control allowed the determination of the appropriate flow rate to obtain realistic cooling values for the rest of the temperatures in the system. Hence, no replacement was needed for this small cooling circuit heat exchanger, as the cooling flow rates were notably higher than the secondary side ones (see Table 2), making a greater heat exchange surface unnecessary.

With regard to the measuring instruments, there were two main kinds of sensors: one ultrasonic flow meter (14, in Table 1) and six temperature-measuring devices (“TE”, 3-8), each one of which placed permanently in one of the pipes corresponding to a certain water stream. Three of those temperature sensors were thermistors (3, 4, 7), while the other three were thermocouples (5, 6, 8). Both types were connected to a data logger and had previously been properly calibrated by setting them to all show the same readings. Specifically, the thermocouples were immersed in water at 0 ºC and 100 ºC, so as to get proper signal processing and correct temperature readings. Those readings were updated every 5 seconds, providing a continuous monitoring of all the relevant temperatures in the system. As for the ultrasonic flow meter, it measured the velocity of the water flowing through a pipe when attached to it.

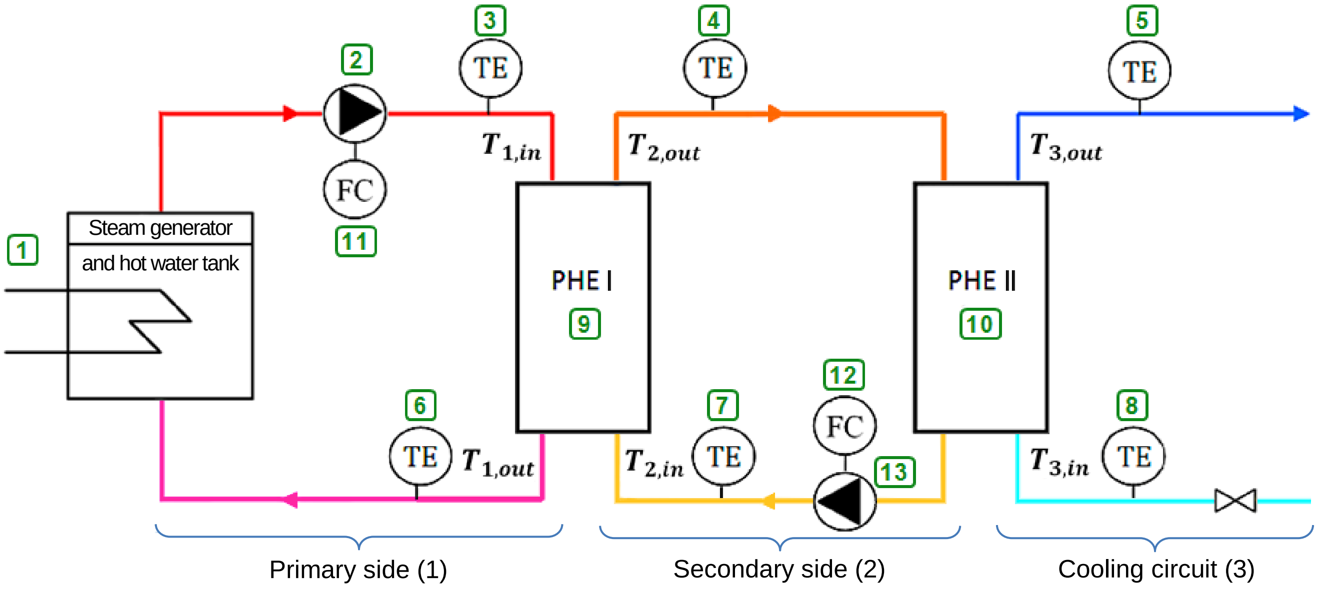

Fig. 5. Simplified scheme of the laboratory-scale installation.

Table 1. Laboratory equipment description.

No.	Type	Model information
1	Steam generator and hot water tank	Clayton Steam Generator, natural gas powered
2	Centrifugal pump	Lowara pumps 8V414F30, 3 kW, 2.4-8 m^3/h
3,4,7	Thermocouples	K-type
5,6,8	Thermistors	TAC EGWS 120
9(*)	Plate heat exchanger (I)	Funke Plate & Frame Heat Exchanger, FP 22-23-1-NH, 52 kW
10	Plate heat exchanger (II)	Modified Cetetherm PHE (heat transfer area ≈ 1 m^2)
11,12	Variable-Frequency Drives (Inverters)	Vacon IP21/NEMA1
13	Centrifugal pump	Kolmeks, Type P-20/4, 0.08 kW
14*	Mass Flow Meter	Micronics Portaflow300 Ultrasonic Flowmeter
-	Data Logger	HP BenchLink Datalogger 1.1

***** *Shown in Fig. 6.*

METHODOLOGY

The measurement process was divided into several test sessions, in each of which the operating conditions for a single outdoor temperature were simulated. Prior to the laboratory work, expected theoretical part-load temperature and mass flow values were calculated for all streams based on outdoor temperatures and an apartment building's static heat loads and then used as set points for this particular series of experiments. Those heat loads were calculated by adapting and scaling results from a model originally developed for the transient simulation of a similar DH system [6]. During the experiments, two magnitudes were measured –flows and temperatures– and the methodology used in all of them was always the same.

First of all, the cooling water inlet and outlet manual valves were opened, letting it circulate through the cooling circuit. Then the steam generator was started up and set to the calculated DH water supply temperature corresponding to the simulated outdoor conditions. It took about 30 minutes to reach the set temperature.

Meanwhile, the primary and secondary side pumps were started and its rotating speed adjusted via an inverter frequency tune so as to meet the previously calculated mass flow values. To this aim, the ultrasonic mass flow meter was utilized, which actually provided velocity measurements. Therefore, that information had to be combined with the knowledge of each circuit's pipe dimensions to get actual mass flow values. In order to simplify the whole process, mass flow set points were converted to velocity values so that it was the only magnitude used during the flow measurements. In principle, mass flows on both sides of the heating heat exchanger should be equal in such a way that heat exchange is optimum, which was the case of the previously calculated initial values used as set points. Once mass flows were adjusted to their expected steady-state values, periodic measurements were carried out along the whole measurement process to confirm that they remained constant, so that any corrections could be made if necessary. To that end, the sensor of the flow meter had to be moved and attached to one representative measurement pipe of the desired circuit each time, as shown in Fig. 6.

Water temperatures were measured continuously by the installed thermistors and thermocouples and then logged by the data logger and displayed on-screen as temperature curves in real time by a computer program. Hence, it was possible to monitor the evolution of all the temperatures in the system and thus notice when they reached steady state.

Once temperatures had stabilized, the obtained results were expected to be correct. However, the data logger showed different temperature cooling readings on both sides of the heating heat exchanger. Specifically, cooling on the secondary side was systematically lower. Taking into account that mass flows were supposed to be equal on both of the sides, such a fact was impossible. Hence, the existence of a flow measurement error was evident. Considering that all temperature sensors were fine-tuned and that in the case of mass flow measuring, by contrast, pipe dimensions and materials were unequal, it was concluded that the error came from the latter. With respect to materials, the pipe corresponding to the cooling circuit was made of copper, while the others were made of steel. As for the differences in pipe dimensions, which are believed to be the main reason that could have led to this inaccuracy, the fact is that the cross sectional area of the pipe where primary flow was measured was three times bigger than the one in the secondary side. Since the operating flows were relatively low, higher part-load conditions could have taken place in the biggest pipes, causing inaccurate flow measurements.

For the purpose of correcting that inaccuracy, the rotation speed of the primary side was progressively increased by adjusting higher frequencies in the inverter until cooling rates equalized on both sides and target values were reached.

When all parameters had reached steady-state, the obtained values were noted down, as those are the final results of the session. In fact, those values represent specific points corresponding to certain outdoor temperatures in the new supply and return temperature curves. Therefore, after all the measurement sessions regarding various outdoor temperatures, those curves could be constructed from all collected points (see Table 2 and Fig. 7).

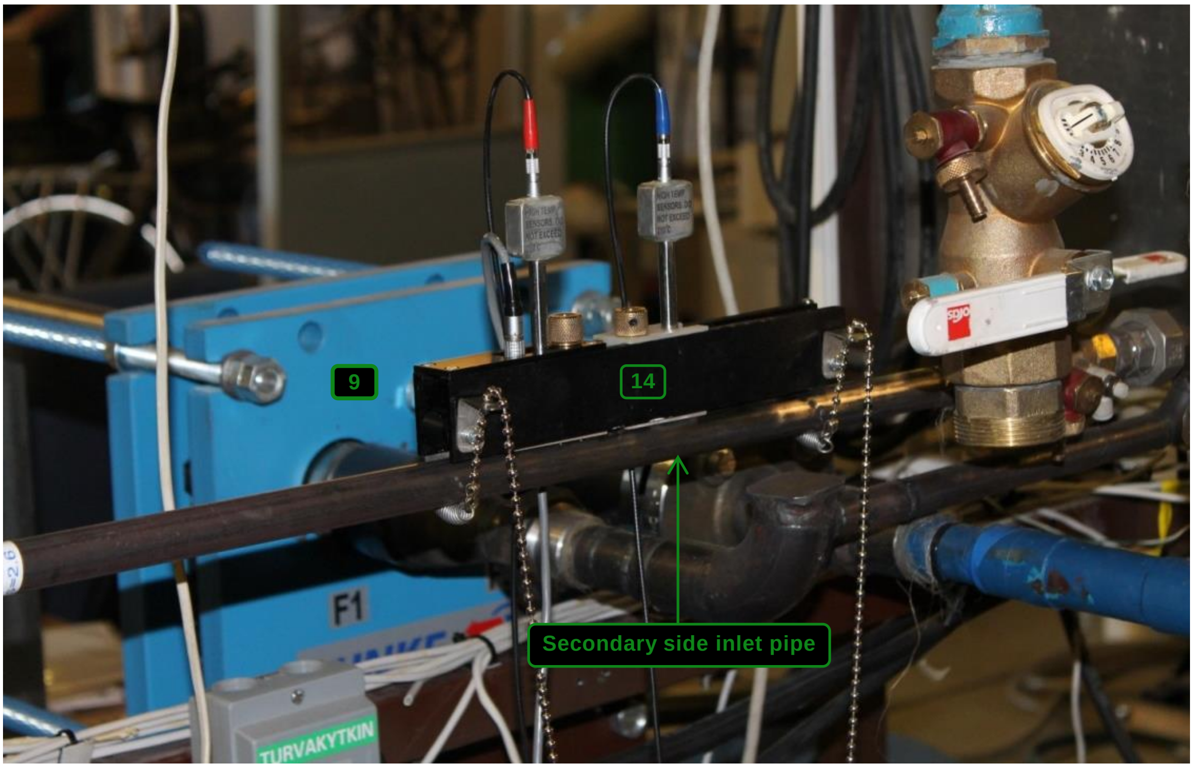

Fig. 6. Mass flow measuring procedure. Ultrasonic flow meter sensor connected to the measurement pipe belonging to the secondary side inlet of the heating heat exchanger. (Numbers identified in Table 1.)

RESULTS AND DISCUSSION

Table 2. Measured values. Primary, secondary and cooling circuit temperature and mass flow rates, and primary and secondary side temperature cooling (ΔT_1 and ΔT_2).

	Temperatures (ºC)								Mass flow rates (kg/s)		
$T_{outdoor}$	Primary			Secondary			Cooling		Primary	Secondary	Cooling
	$T_{1,in}$	$T_{1,out}$	ΔT_1	$T_{2,in}$	$T_{2,out}$	ΔT_2	$T_{3,in}$	$T_{3,out}$	$\dot{m}_1$	$\dot{m}_2$	$\dot{m}_3$
-29	76	35.7	40.3	30.5	68.7	38.2	21.8	35	0.404	0.314	0.825
-10	69.9	30.9	39	22.2	64.2	42	19.8	33.1	0.262	0.177	0.497
-5	65.7	28.7	37	23.3	59.9	36.6	18	33	0.227	0.173	0.328
0	61.9	27.7	34.2	22	55.5	33.5	19	30.9	0.185	0.201	0.407
5	56.3	27	29.3	21.7	52.4	30.7	17.7	31.9	0.173	0.138	0.237
Average			36.0			36.2			0.250	0.201	0.459

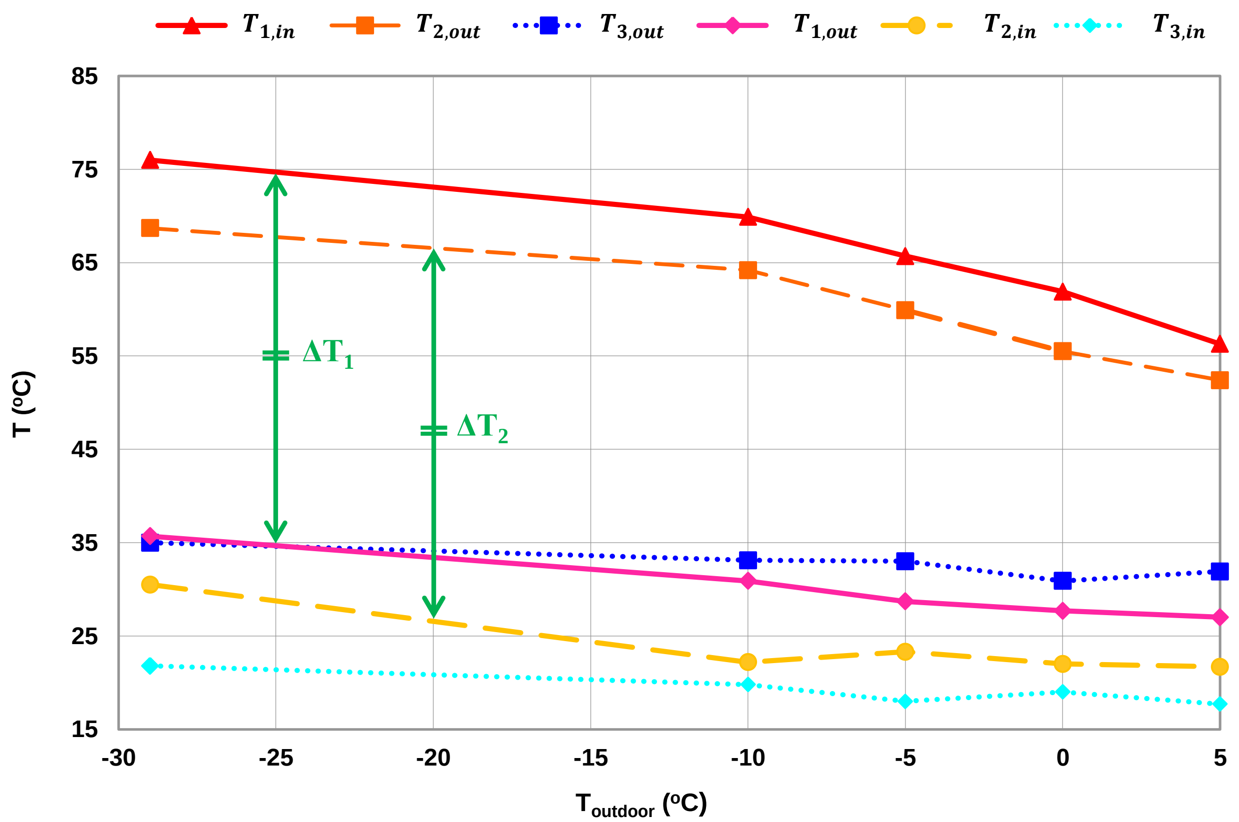

Fig. 7. Experimentally obtained primary, secondary and cooling circuits supply and return temperature curves.

The previous charts contain all data obtained from the measurement sessions. The exact values can be found in Table 2, whereas temperature curves are represented graphically in Fig. 7.

Thermal effectiveness of the heating heat exchanger (PHE I) can be calculated from these results by using the following equation (1) [17][18]:

$$\varepsilon = \frac{Q}{Q_{max}} = \frac{C \cdot \Delta T}{C_{min} \cdot \Delta T_{max}} = \frac{\Delta T}{(T_{1,in} - T_{2,in})} \qquad (1)$$

where C and C_{min} are reduced since mass flows and specific heat values are equal on both sides of the heat exchanger. Hence, the resulting expression depends only on temperatures, which are the most accurate measurements in this study, and thus the obtained results are reliable. The calculated mean effectiveness is 0.88, which involves a notably good thermal performance, even for this kind of plate heat exchanger.

In the same way, heat loads can also be calculated from the measured values, obtaining the results shown in Table 3. Here it should be noted that the displayed $Q_{obtained}$ numbers are the mean value of the results obtained for both sides of the heat exchanger, so that the mass flow measurement related error is corrected. As can be observed, the maximum expected heat load coincides with the nominal heat duty of the PHE I (see Table 1) and, in general, the obtained values are fairly close to the expected ones, which reinforces the validity of the experiments.

Table 3. Comparison of theoretically expected and experimentally obtained heat loads.

$T_{outdoor}$ (ºC)	$Q_{expected}$ (kW)	$Q_{obtained}$ (kW)
-29	52.00	56.80
-10	36.30	35.47
-5	31.88	29.59
0	27.40	26.25
5	22.98	18.72

Regarding direct measurement, as stated above, two different magnitudes were measured: temperatures and mass flow rates. Therefore, conclusions must be drawn from those results by applying previous knowledge when comparing the obtained values with the expected ones.

On the one hand, as already mentioned, one of the main goals of this series of experiments was to demonstrate the feasibility of obtaining non-linear temperature curves in a real application of the new proposed DH concept. For that purpose, all temperature measurements corresponding to different simulated outdoor temperature conditions (and thus heat loads) compiled in Table 2 were graphically represented in Fig. 7. As can be seen in that figure, the expected non-linear curves (Fig. 4) were obtained and thus the feasibility of practical applications of the new DH concept was proven. As a consequence of that non-linearity, combined with the fact that the obtained return temperatures are lower than the usual ones in traditional DH systems, temperature cooling turned out to be maximized for any outdoor temperature situation with respect to the one in current systems (see Fig. 4), which allows lower mass flow rates and thus pumping power demand. Moreover, network heat losses are reduced thanks to the lower return temperature (and thus average network temperature). Hence, the overall efficiency of the new system is higher, which makes it more desirable in any case.

On the other hand, mass flow was the second measured magnitude, as it can also be noted in Table 2. Here it is important to mention that, although primary and secondary side mass flows ($\dot{m}_1$ and $\dot{m}_2$) are expected to be the same, after the measurements the one corresponding to the primary side turned out to be higher. That is due to the measurement error explained in the previous section. In spite of the obtained mass flow measurements, temperature cooling (ΔT) values on both sides of the heat exchanger were always practically equal, as shown in Table 2 and Fig. 7. This implies that, in reality, mass flows were in fact equal in the same manner.

In addition, it can be noted in Table 2 that cooling circuit mass flow ($\dot{m}_3$) was significantly higher than both of the others, which is due to the fact that a higher flow was needed to simulate real conditions because of the small dimensions of the used heat exchanger.

Finally, the rotation frequency controlled by the inverters ranged from 7 to 16 Hz for the primary side pump and from 25 to 58 Hz for the secondary side one. These results are consistent with the size difference between both pumps.

OUTLOOK

Owing to its multiple benefits in comparison with traditional systems, the proposed DH concept could represent a turning point in the development of DH technology. Its application would be especially advantageous in new constructions, as the cost of installation would be lower than the one related to the currently used system because of smaller pipe diameters and the fact that valves would be removed, while operating costs would be even lower because of the improved efficiency. These improvements would clearly offset the only additional costs of the proposed system: the need for a larger number of pumps and a more complex automation system.

In the case of already built areas, the profitability of replacing the current DH system with a new one should be determined through a feasibility study. In order to assess if the system replacement costs would be offset by the savings in operating costs, several parameters should be analyzed, such as current system efficiency, building arrangement and installed equipment usability. In this sense, one of the most determinant factors is the topology of the area in question, since the upgrade to the new system is much more viable if the buildings are already distributed in a loop-like form.

CONCLUSIONS

The results obtained in this study demonstrate that it is possible to implement a mass flow control system in a consumer substation belonging to a ring network, getting increased temperature cooling as a result. The studied heating heat exchanger operated as expected as far as design point and part-loads are concerned, obtaining 0.88 effectiveness.

To summarize, the proposed DH technology is more efficient than the currently used systems, which has been proven through several previous studies and the series of experiments described in this paper. The increase in the overall efficiency is based on a number of factors, such as case-specific optimal supply and return temperature curves allowing higher temperature cooling and lower return temperatures, as well as lower flow rates and pressure and heat losses. All these points ultimately lead to more balanced and cost-effective DH systems.

Regarding the scope of applicability, the new system is not only suitable for new constructions, but also applicable to some already built areas that have an appropriate topology.

In general, the proposed system represents a big step forward in the development of low-temperature DH technology.

ACKNOWLEDGEMENT

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NOMENCLATURE

C	heat capacity rate (W/K)
kgce	kilogram coal equivalent
$\dot{m}$	mass flow rate (kg/s)
Q	heat load (kW)
ΔT	temperature cooling (ºC)
T	temperature (ºC)

Greek symbols

ε	heat exchanger thermal efficiency

Subscripts

1	primary side
2	secondary side
3	cooling circuit
expected	theoretically calculated value
*in**	heat exchanger inlet
max	maximum
min	minimum
obtained	obtained value from results
*out**	heat exchanger outlet

**In case of the secondary side, subscripts refer to the main heating heat exchanger (PHE I).*

Abbreviations

CHP	combined heat and power
DH	district heating
DHW	domestic hot water
EU	European Union
GSO	group search optimizer
HEX	heat exchanger
PHE	plate heat exchanger
TRV	thermostatic radiator valves
VFC	variable-frequency drive

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A NEW DISTRICT HEATING SYSTEM IN THE CITY OF BOLZANO: DEVELOPING SMART SOLUTIONS WITHIN "SINFONIA" PROJECT

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ABSTRACT

In the context of the EU project "Sinfonia", that aims to reduce Bolzano's primary energy consumption up to 40%, SEL AG, an Italian energy company is planning to extend the existing district heating and cooling (DHC) network and explore strategies to improve efficiency, environmental, and economic performance. This research aims to assess the potential energy saving of temperature and peak heating load reduction in the Bolzano's DHC network. Historical performance data from district heating (DH) users were collected and residential building were classified based on construction year and energy performance. The thermal properties of the identified representative buildings were used to develop an indoor climate and energy simulation model by means of IDA-ICE software. The simulation model was validated through real on-site temperature measurements. The potential reduction of temperature supply and peak heat load was evaluated by creating different temperature night setback scenarios. Results indicate that the temperature supply level could be decreased on the consumers' side up to 60 °C, without significantly affecting people comfort. Moreover night setback strategies produced a reasonable reduction of the peak up to 35% from the initial condition, increasing the energy consumption by 4 %.

INTRODUCTION

District heating (DH) represents a cost-effective and sustainable way to provide space heating and domestic hot water to consumers [1]. The DH network within the Bolzano province, with 788 km and 15000 users connections, provides more than 3000 TJ yearly, of which 2700 are produced from renewable sources as biomass and biogas [2]. Within this context, SEL AG manages the DH system of the city of Bolzano. Given the planned development of the network and the involvement in a European project called "Sinfonia", SEL AG is looking into solutions to improve the efficiency of the network and thereby contribute to the overall objective of reducing the energy consumption of the city by 40 % in the coming years.

Previous researches show the influence of reducing the supply temperature [3] [4], and of demand management methods [5]. However, within the Italian context, findings from previous studies are mainly based on simulation models that are not based on real cases. Thus, this study aims to evaluate the effects of supply and demand strategies on a real case, specifically the Bolzano DH network.

This research investigates how the creation of a smart DHC network in Bolzano can be developed to improve energy, environmental, and economic performance. The specific objectives of this project are to:

- Create a building classification to identify the representative building to analyse;
- Develop and validate a building simulation model based on real measurements;
- Evaluate the potential DH temperature supply reduction taking into account people comfort;
- Assess methods to reduce the peak heat load demand by means of temperature night setback.

On one hand, reduced temperature supply could result in a decreased comfort for those inhabitants of buildings presenting poor thermal properties. On the other hand, peak load reduction strategies could contribute to overcome this problem, obtaining economic and environmental benefits.

The development of the mentioned points provides an overview on the correlation between existing buildings and DH network testing solutions to improve the overall efficiency of the system.

THE BOLZANO DH SYSTEM

In Italy the development of DH systems began in the 70's. According to statistics provided by the EU association Euroheat & Power [6], in 2011 only 5 % of the Italian population was served by district heating including a total transmission network of nearly 3.000 km.

The existing Bolzano's DH system (Figure 1) is composed by two generation units:

- Bolzano Sud thermal plant (BZ Sud) which includes 2 combustion engines (natural gas) working in cogeneration mode and 4 boilers (natural gas and diesel). The maximum thermal capacity is 35.7 MWt and the electric 3.5 MWe.
- Waste to Energy plant (WtE) with its maximum capacity of 30 MWt and 10 MWe. The plant has just replaced the old incinerator and the large capacity is justified by the planned expansion project for the DH network.

Today the network provides heat to 170 users distributed over three areas: Ipes, Casanova, and the

Industrial zone while in the next future a larger share of the city will be involved.

The current Bolzano's DH network operates, as the majority of the Italian systems, at a temperature level ranging from 80 to 95 °C depending on the seasons, and does not apply any strategy to reduce the peak loads.

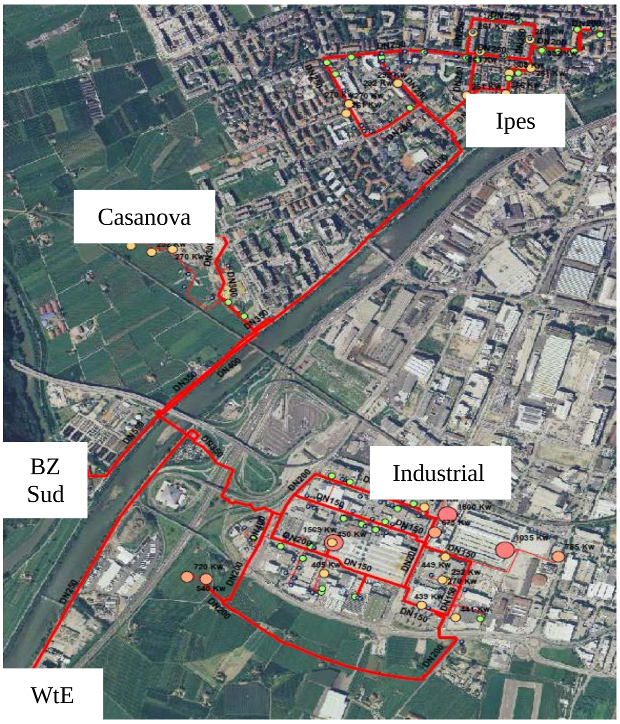

Figure 1: Bolzano DH network

METHODS

The method described below follows the specific objectives previously introduced and is hereby described according to the following structure:

1. Building classification;
2. Construction and validation of the building model;
3. Temperature supply reduction analysis;
4. Peak heat load reduction analysis.

General information about DH connected buildings was collected to perform the building classification. The outcome was the definition of the most representative building to further study. A second data collection phase was then required including specific thermal properties of the classification result, but also on site measurements. A further step consisted of the construction of a simulation model that was later validated reflecting real conditions. Finally the model was tested under different temperature supply and operation strategies scenarios.

The briefly presented adopted method is hereby described with more details.

Building classification

Building classification was carried out to identify, among the DH connected buildings, the most representative for the current research. In particular such building should be characterized by poor thermal properties and at the same time presents great potential in terms of peak load reduction. In addition the classification allows a simplification of the analysis and at the same time makes it replicable.

The method adopted followed the guidelines proposed by J. Portella including parameters as climate zone, energy consumption, construction year, and type of dwelling [7]. In addition to the mentioned features, type of heating systems, its operation and, area's dislocation were taken into consideration.

Construction year and type of dwelling information was collected by studying available documentations at the city municipality. Specifically dwellings were classified as residential and non-residential, while construction years categorized within specific time span ranging from earlier 1960 to date.

Climate zone could also be taken into account, but considering the city of Bolzano this information become less significant.

The missing documentation in terms of energy consumption for a large part of the buildings, led to follow a method that associates construction year with energy consumption for buildings located in a middle climate zone [8]. In this way buildings constructed within defined time periods were related to specific average energy consumption.

Based on these information the classification was conducted for the zones named as Ipes and Casanova, while the industrial area was excluded due to lack of information.

Construction and validation of the building model

Energy and comfort simulations were required to evaluate the potential results obtained from the proposed temperature and peak load reduction scenarios. With this purpose IDA ICE, a simulation tool for accurate study of indoor climate and energy consumption, was selected to assess the behaviour of the building model under different operation conditions.

The adopted simulation model referred to a single apartment belonging to the chosen building block.

The analysis in terms of temperature and peak load reduction was based on a typical working winter week from 21/01 to 27/01.

In order to study the effect of the suggested solutions there was the need to develop an earlier stage of the analysis which included the initial setting of the simulation model, and its validation based on real on site measurements.

The first simulation model construction required the acquisition of information related to the composition of the selected building. From available construction projects geometric features, and thermal properties of building's envelope were collected.

In the second part, the model was validated comparing simulations results with real on site measurements. Two simulation periods were identified for validating the model: the first corresponding to 72 hours in March and, the second to the initially established winter week (21/01 to 27/01).

To this end, information was collected on both consumer and network side. Particularly on the building side personal indoor air temperature on-site measurements by means of a temperature data logger (Testo 174T), were recorded for 72 h in March 2014 with a time step of 15 minutes. The lack of real measurements for the January period was overcome with personal interviews which revealed the temperature development throughout a normal winter day.

On the DH side data collection was conducted through the SCADA (supervisory control and data acquisition) system that is used to control the network. The gathered information refers to the substation installed at the building block studied including:

- Nominal substation capacity [kW]
- Instant Power [kW]
- Temperature supply and return [°C]
- Mass flow [l/h]

Values were collected for two time periods: March, and the working winter week with a time step of 15 minutes.

Weather data was also included in the data collection for both periods to perform reliable simulations.

The flow chart in Figure 2 shows the adopted procedure to go from the first setting initial simulation to the validated final model, of which results in terms of heat load and temperature profiles were comparable to the real measured data. The most important parameters to include when performing a IDA ICE building simulation were location, weather file, orientation, geometry, thermal properties of surfaces, thermal bridges, infiltration and room temperature set point. In addition the heating system needed to be proper dimensioned to reflect original working conditions. Such information was applied to the initial simulation model which is represented by block 1 in the flow chart.

Daily average space heating load (block 2) and temperature (block 3) profiles were extrapolated from simulation's results and used for comparison with real measured values. Specifically block 4 compares simulated and real space heating demand, the latter was estimated subtracting the domestic hot water demand during no heating period from the total measured load in the simulated period. The total space heating demand was divided by the number of apartments obtaining the single apartment space heating load. This operation is made under the assumption that hot water profile does not significantly change its profile from summer to winter and the use of space heating for different apartments normally occurs simultaneously.

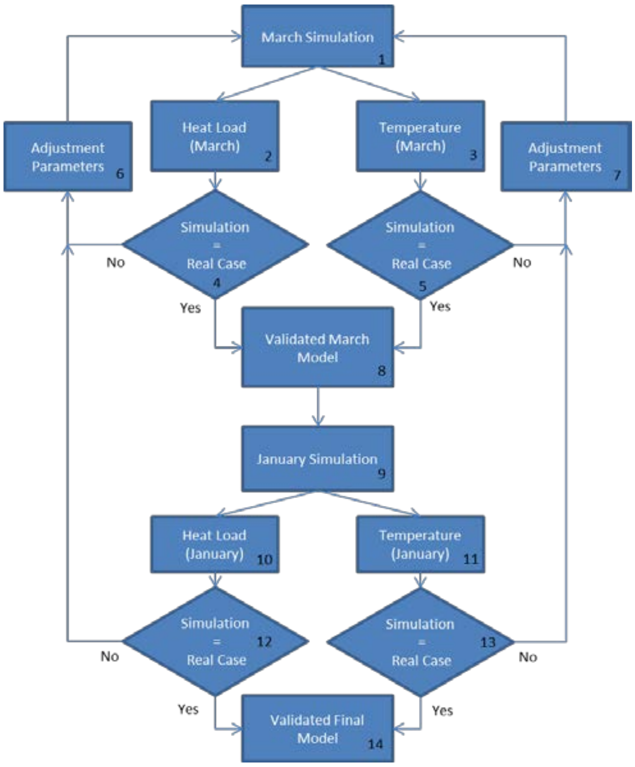

Figure 2: Flow chart, Validation Building Model

Temperature on site measurements collected during the March period were used to evaluate the temperature drop that was occurring in the house when the heating system was stopped. Simple calculation of thermal time constant τ [h] was conducted and compared for real and simulated indoor air temperatures according to relation 1:

$$\frac{T_{final} - T_{out}}{T_{initial} - T_{out}} = e^{-\frac{t}{\tau}} \qquad (1)$$

Where:

- Tfinal [°C] is the indoor temperature at the end of the period t
- Tinitial [°C] is the indoor temperature at the beginning of the period t
- Tout [°C] is the outdoor average temperature during the period t
- t [h] is the time period
- τ [h] is the thermal time constant

In order to positively verify blocks 4 and 5, few parameters' adjustments were required (blocks 6 & 7), especially in terms of building thermal properties, infiltration rate and temperature set points. Only when blocks 5 and 6 were verified the model was considered validated for the March period simulation.

The same procedure was adopted to additionally validate the model in correspondence of the winter January week. In this case heat load profiles were compared as done for the March period while temperature analysis was performed based on personal interviews conducted at the inhabitants. Of interest for this research was the demonstration that temperature drop during night hours occurring in the real case was comparable with simulations' results. The final validated model (block 14) satisfied both stages of validation and was adopted to further assess temperature and peak load reduction strategies.

Temperature supply reduction analysis

The temperature reduction analysis involved the creation of different scenarios of the same building simulation model. The developed simulations differed only on the temperature supply variable.

Table 1 describes the adopted temperature levels. The initial case was representative for the actual applied conditions to the building studied. The temperature of 70 °C is the one provided to the building from the secondary side of the heat exchanger.

The variation of this parameter within the developed IDA ICE simulation was conducted under boundary conditions at the boiler unit. Within the simulation the boiler replaced the secondary side of the DH heat exchanger.

Table 1: Tested Scenarios, Temperature Reduction

Initial Case	**T supply 1**	**T supply 2**	**T supply 3**
70 °C	65 °C	60 °C	55 °C

Simulations testing the mentioned temperature levels were conducted for the January winter week. Results are presented as averages on a daily basis. Specifically heat load demand and temperature profiles were analyzed.

Peak heat load reduction analysis

Several scenarios were also developed to analyse the effects obtained applying peak load reduction strategies.

The analysis was conducted maintaining building thermal properties unchanged while testing different peak load reduction strategies based on the night setback concept at different temperature supply levels as presented in Table 2.

Table 2: Tested Scenarios, Peak Load Reduction

Case A	The temperature supply was the same as in reality (70 °C). No peak load strategies were applied, so as the heating system was working according to the real program. It was used as base for comparison for all the other solutions.
Case B	The temperature supply was reduced according to the value reported for the specific case. No peak load strategies were applied, so as the heating system was working according to the real program.
Case C	The temperature supply was reduced according to the value reported for the specific case. The peak load reduction strategy implied a linear increment of indoor air temperature set point from 4 AM at 18 °C to 5.30 AM at 21 °C.
Case D	The temperature supply was reduced according to the value reported for the specific case. The peak load reduction strategy implied a linear increment of indoor air temperature set point from 3 AM at 18 °C to 5.30 AM at 21 °C.
Case E	The temperature supply was reduced according to the value reported for the specific case. The peak load reduction strategy implied a linear increment of indoor air temperature set point from 2 AM at 18 °C to 5.30 AM at 21 °C.
Case F	The temperature supply was reduced according to the value reported for the specific case. The peak load reduction strategy implied a linear increment of indoor air temperature set point from 12 AM at 18 °C to 5.30 AM at 21 °C.
Case G	The temperature supply was reduced according to the value reported for the specific case. The peak load reduction strategy implied a continuous heating operation during the night with indoor air temperature set point equal to 20 °C.
Case H	The temperature supply was reduced according to the value reported for the specific case. The peak load reduction strategy implied a continuous heating operation during night and day with indoor air temperature set point constant at 21 °C.

Results of this part of the research include a presentation of the new peak loads when applying specific strategies, energy consumption related to different operation conditions, indoor temperature profiles and a simple estimation of the potential percentage of consumers that could be theoretically added under studied circumstances. The latter was calculated by dividing the total peak load reduction with the space heating dimensioning peak for the single apartment which was assumed equal to 10 kW for this case.

RESULTS

Results obtained from the current research are presented in three main sections, the first describing the building classification that guided the choice of the user to further analyse. The second presenting results obtained through the validation procedure of the building considered. Results extracted from the analysis of reduced temperature supply and peak load reduction strategies are presented in the last part.

Buildings classification

The Bolzano's district heating network feeds two residential zones named as Ipes and Casanova and, the Industrial zone.

The Ipes zone includes 48 residential building blocks located at the farthest place from the generation units, approximately 3 km far from Bolzano Sud thermal plant. The Ipes zone is characteristic for Bolzano since is mainly constituted by social housing. The totality of the users in this area adopted the same technology to interface the DH network based on instantaneous heat exchange. With regards to the heating system, the apartments adopt steel water radiators with the peculiarity that the control allows the operation only from 5.30 AM to 10 PM. Most of the buildings were constructed within 80's and 90's, therefore an energy consumption ranging from 70 to 120 kWh/m^{2}year was assumed [8].

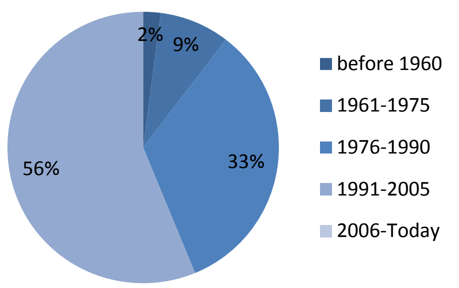

Figure 3: Ipes, Construction Year

Casanova represents a newly constructed district in the suburb of Bolzano. As Ipes, it is composed by residential users, specifically 9 building blocks and 2 single family houses. This area can be considered geographically the closest to the generation units since it is located less than 1 km far from Bolzano Sud thermal plant. Differently to the Ipes zone, the use of DH was coupled with the energy produced by renewable sources consequently DH substations were provided with storage tanks. In terms of heating system, the use of low temperature radiant heating was preferred to the conventional water radiators without setting any specific control's constraints. Casanova buildings, being constructed from 2006 to 2012 with a special focus on energy consumption, present an average energy demand approximately equal to 35 kWh/m^{2}year.

The chosen solution was a building block located in the Ipes zone which includes 75 apartments constructed in 1983. The selection was supported by the following consideration:

- On one hand the adoption of low temperature floor heating as in the Casanova district should avoid comfort problems in case of lower DH temperature operation. In addition, DH substations provided with storage tanks limit considerably the formation of high peak loads.
- On the other hand the large share of residential buildings constructed within 80's and 90's as in the Ipes zone and the use of water radiators dimensioned to work at certain temperature levels could lower people comfort if DH temperature operation would be reduced. In addition the present Ipes heating control strategy showed its direct influence on the creation of high peak loads.

The simulation was then conducted for a 90 m^2 apartment belonging to the chosen building block. Table 3 presents the most important thermal properties used for building the simulation model while Figure 4 the apartment's layout.

Table 3: Thermal Properties, Ipes

Surface	Thickness [m]	U-value [W/m^{2}K]
External Wall	0.32	0.462
Internal Wall	0.12	1.7
Internal Floor	0.175	2.38
Roof	0.36	0.7
Glazing	/	1.8
Infiltration rate 0.4 ACH		

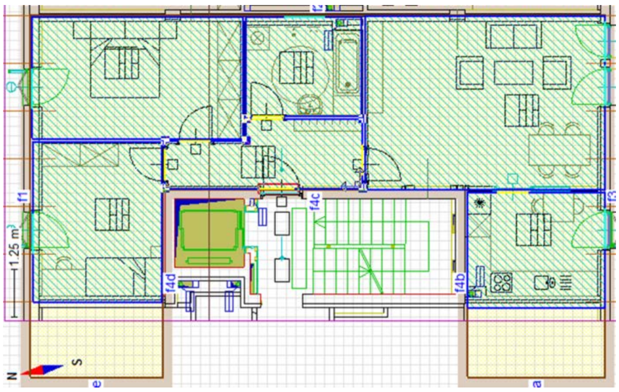

Figure 4: Layout and Orientation, Ipes

The DH substation connecting the building to the network included a 500 kW and 300 kW heat exchangers for covering space heating and domestic hot water demand respectively.

Construction and validation of the building model

As presented in the method section, the validation of the described building model was carried out for two specific time periods. Results obtained from the March validation procedure are reported in Figure 5 comparing the real estimated space heating profile with simulations' results. It is also presented in Figure 5 the indoor air temperature profile according to simulation.

The validation procedure performed for the March period showed that similar results were reached in terms of real and simulated heat load profile. Both profiles showed a significant peak at morning hours corresponding to starting heating system operation. The curves then decreased up to evening hours, at which another peak, of a smaller size, occurred.

In addition to the validation in terms of heat load profile, Table 4 presents thermal time constant of the building calculated based on temperature measurements and simulation results. The temperature used for such estimation resulted in two time constant that could be considered representative of the same building.

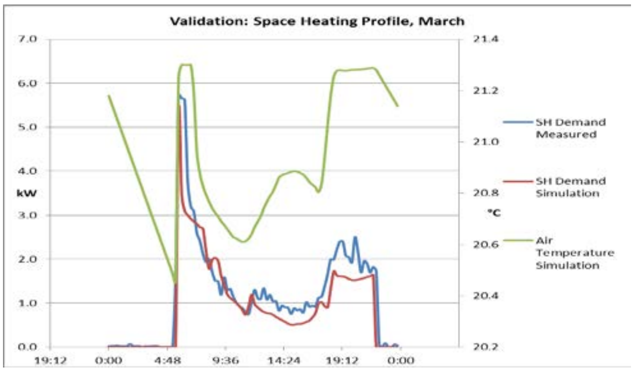

Figure 5: Validation Space Heating Profile, March

Table 4: Time Constant, March Validation

Time constant (simulation) [h]	Time constant (real) [h]
80	90.7

As mentioned in the methodology, the space heating profile for the single apartment was not available and consequently was extracted from the available total measured data of the building. Specifically Figure 6 presents the total and DHW profiles for the whole building block, from which the SH profile for the single apartment, which constitute the simulations' base, was obtained.

Figure 6 showed also that the deviation between space heating and domestic hot water profiles for the building studied was considerable. The total peak demand reached almost 600 kW, of which only 100 kW comes from domestic hot water use.

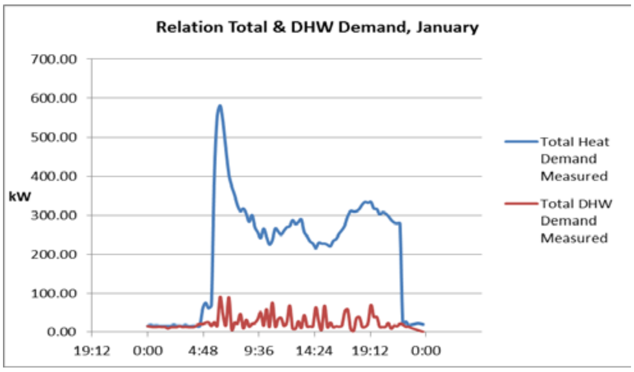

Figure 6: Total relation SH & DHW, January

Figure 7 compares the SH demand profile for the single apartment obtained from Figure 6 with the simulations results.

Also in this case, the heat load profile found from the simulation matched the estimated space heating profile for the single apartment studied. The morning peaks for both profiles were around 7 kW while the evening demands around 4 kW.

The lack of real on-site temperature measurements for the specific winter week did not allow the calculation of the time constant. Anyway, the night temperature drop was validated conducting personal interviews to the inhabitants who confirmed temperature levels around 18 °C at morning hours for an average winter day.

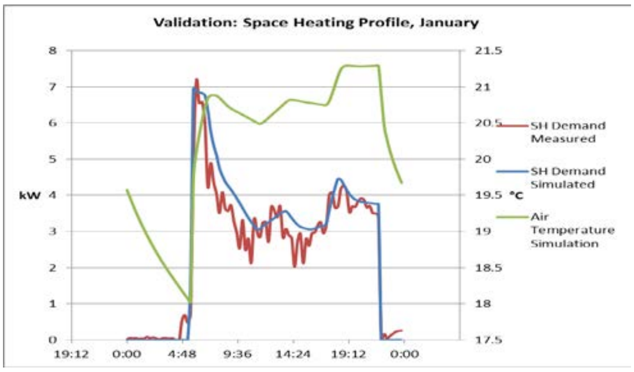

Figure 7: Validation Space Heating Profile, January

The simulation model was consider representative for the actual building and consequently was used for further temperature and peak load reduction analysis.

Temperature supply reduction analysis

The current chapter presents the obtained effects when applying a reduction of the temperature supply. Figure 8 shows that the heat load profile is reduced consequently to the reduced temperature. Especially lower the temperature mainly influences the peak hours while does not significantly affect the rest of the day. The largest decrement is registered at 55 °C, which lower the peak from 7 (initial case) to 4.6 kW.

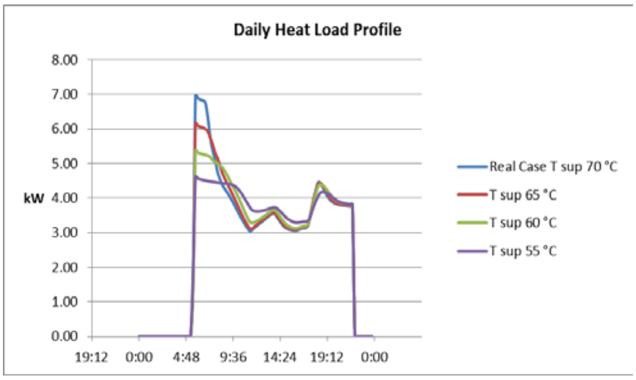

Figure 8: Heat Load Profiles, Temperature Reduction

The investigated issue related with operation temperature reduction is the effect that could result on the consumer's side. Figure 9 revealed on that aspect that little deviations could be obtained when implementing temperature levels equal to 65 °C or 60 °C. Differently it shows that 55 °C as supply temperature for the heating system is likely to result in reduced comfort for the inhabitants since the indoor temperature deviation is larger than 1 °C at morning hours.

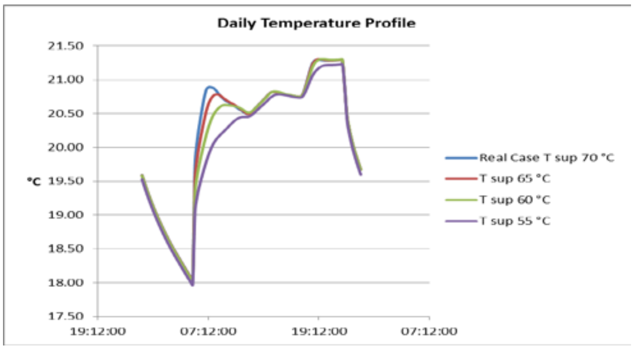

Figure 9: Temperature Profiles, Temperature Reduction

Peak heat load reduction analysis

Obtained results from simulations conducted applying peak load reduction strategies are presented. The simulated cases described in Table 2 were tested at all temperature levels considered in the previous results section. In order to provide an overview about the changes obtained in terms of heat load profile, Figure 10 shows the curves for the cases studied at the actual temperature level (70 °C).

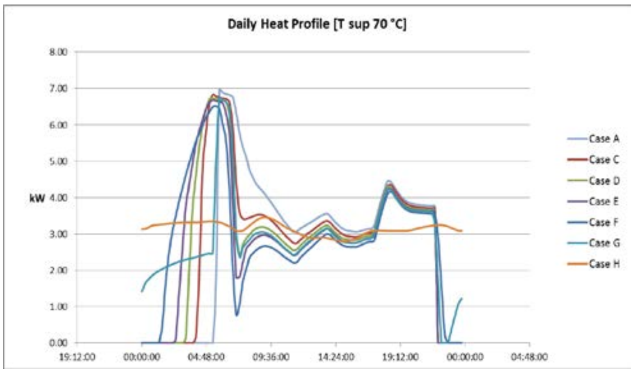

Figure 10: Heat Load Profiles, Peak Load Reduction

The anticipation of heating system operation lowered the peak which is occurring at morning hours in the real case. More specific analysis in relation to the peak reduction could be obtained from Figure 11 which presents the percentage reduction for the cases studied at all temperature levels. Few things are worth mentioning observing Figure 11:

- Lower temperature operation as proved by Figure 8 leads to lower peaks;
- Largest reduction is obtained for the extreme case in which the heating system operates continuously throughout the day, this solution is not influenced by different temperature levels;
- Except for Case H, the strategy proposed in Case F leads to largest reduction. For instance, considering temperature supply equal to 70 °C, the peak is reduced by 5 %.

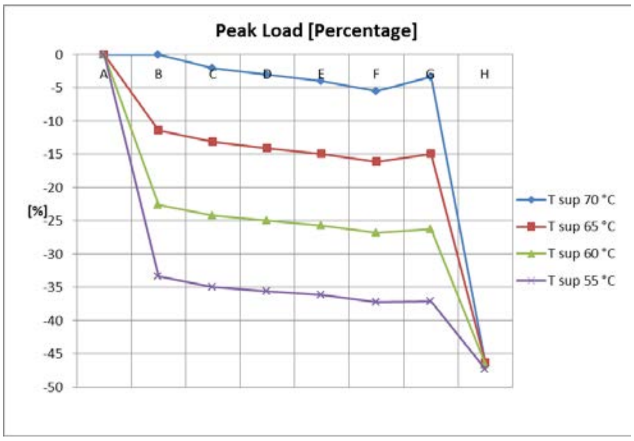

Figure 11: Peak Load Reduction, Percentage

Table 5, according to the calculation presented in the method section, presents what could be one of the direct effects obtained from the reduced peak load, that is the increment of potential consumers. The study shows that strategies adopted could increase by 10 to 30 % the number of consumers, reaching its maximum in case H with 40 %. Anyway additional consideration must be specified in terms of energy consumption as introduced by Figure 12.

Table 5: Potential Consumers Increment

Consumers Increment [%]	Case B	Case C	Case D	Case E	Case F	Case G	Case H
T sup 70 °C	/	1.9	2.75	3.5	4.9	3	40
T sup 65 °C	10	11.5	12.3	13	14	9.8	40.6
T sup 60 °C	19.8	21.2	21.8	22.5	23.4	22.9	40.7
T sup 55 °C	29.2	30.6	31.1	31.6	32.5	32.5	41.5

As mentioned another important factor to consider when implementing night set back strategies was the energy consumption that derives from them. Indeed some of the controls tested showed a negative response in terms of energy consumption resulting in a too large increment of it.

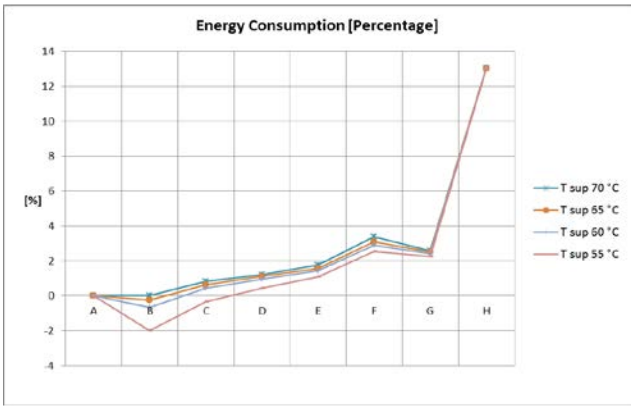

Figure 12: Energy Consumption, Percentage

Figure 12 presents the deviation from real conditions in terms of energy consumption obtained from the simulations conducted. A fundamental outcome of this part of the research was that all the strategies applied out of Case H resulted in an increment of the energy consumed lower than 4 %. Differently, simulation under Case H conditions showed energy consumption increased by 13 %.

In addition to the presented results, daily temperature profile were evaluated for all the tested temperature levels. It is worth presenting the outcome of the simulations conducted at 55 °C. Figure 9 proved that this temperature level coupled with the actual operation strategy could result in lower comfort for the inhabitants. Figure 13, instead provides an overview of how people comfort could be influenced by operation strategies. The result showed that the adoption of the lowest tested temperature level could be taken into consideration if coupled with proper operation strategies.

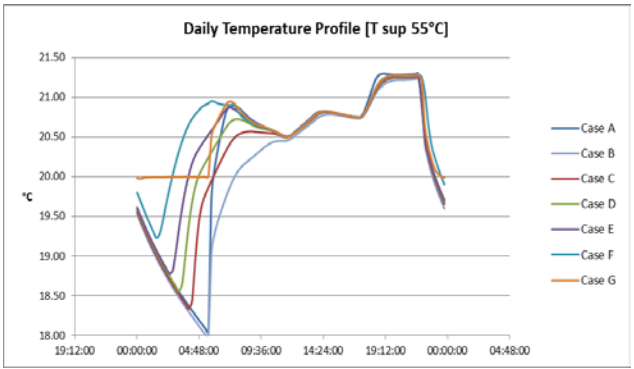

Figure 13: Indoor Daily Temperature, T sup 55 °C

DISCUSSION

The conducted research opens different discussion points which are hereby described.

1. The temperature reduction analysis shows that some limits should be preserved when adopting lower operation temperatures. 55°C for instance, seems to be too low in the case studied to provide enough comfort to the occupants even though it was proved that this temperature level could be taken into consideration applying appropriate operation strategies based on night set back. For instance simulations shows that low temperature operation mainly influenced the morning peak, and consequently applying an operation strategy which start the heating system during the night and linearly increases its set point up to the morning hours, significantly reduced comfort problems.

2. The extreme tested case H was performed to define the lower limit that could be theoretically reached when the goal is reducing the peak. Anyway the analysis in terms of energy consumption shows for this solution the largest energy requirement categorizing this case as inefficient for the research's purpose.

3. The reduced peak demand could lead to another significant advantage for the Bolzano's case, inasmuch the actual situation sees the waste to energy plant covering the base load while Bolzano Sud takes care of peaks. Looking at the planned development of the network the studied strategies could be adopted to maximize the use of the heat coming from the waste to energy plant and at the same time minimize gas boiler's use. This will provide great economic and environmental benefits being the Bolzano Sud plant more expensive in terms of operational costs and presenting a larger rate of emissions than the waste to energy plant.

4. Peak load reduction strategies could lead to another significant benefit. From a theoretical point of view the reduced capacity required could be employed by DH utilities to connect more consumers. In this way the DH market share would be enhanced obtaining also advantages from a societal point of view (larger substitution of single boilers presenting higher emissions rate).

5. With consideration to the studied Ipes zone, further improvement in relation to the energy consumption could be obtained by varying night set back strategies adopted. Larger energy consumption is expected applying the same strategy (e.g. Case F) to all buildings rather than diversify the strategies over the whole zone. This choice, in order to be efficient, has to be coupled with a deep analysis of every single building and its thermal properties to define the proper control.

6. Methodological considerations must also be provided:

Strength of the research is the application of real measurements to validate the simulation model. In this way a more representative outcome was obtained. Anyway some deviations could have influenced the results with consideration to on site measurements and estimation of the single space heating profile for the apartment studied.

OUTLOOK

At first the Industrial zone of the city should be included in further analysis since it constitutes a great part of the existing network in which different technologies than the residential areas are applied.

Furthermore in the next future the research will focus on how the concepts studied and presented in this paper can influence DH systems at all levels from design to operation. It will be studied how such changes can be applied to the existing Bolzano DH network in terms of dimensioning criteria, heat losses and pumps' use.

Once the system will be optimized under these terms the next is the development of a smart network improving its performance through intelligent control and communication integrated with system operational optimization.

CONCLUSIONS

Given the considerations and uncertainties stated in this paper some conclusions could be drawn.

- As mentioned in the outlook the final goal for Bolzano is the achievement of the development of a smart DH network. Anyway, several aspects at a lower level were highlighted to show their contribution to improve system's efficiency.
- The analysis shows that a possible temperature reduction can be taken into consideration from the consumers' side. However further researches are required to study the effect of this choice on the network side.
- With consideration to the peak load reduction studies, it was proved that by simply setting differently the set point, peaks could be reduced. Such strategy appears easy to apply, especially for those areas in which the heating system is controlled by a single institution (social housing). The company also might incentive the application of night set back control through economic benefits for the consumers.

ACKNOWLEDGEMENT

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ANALYSIS AND RESEARCH ON PROMISING SOLUTIONS OF LOW TEMPERATURE DISTRICT HEATING WITHOUT RISK OF LEGIONELLA

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ABSTRACT

Most regulations of domestic hot water supply temperature is around 55-60 °C, which potentially requires higher district heating temperature. However, high supply temperature of district heating causes many problems, such as the high heating loss, and obstacles for applying renewable energy resources. The most crucial restriction for applying low temperature district heating is the worry about the breakout of legionella, which exists preferably in low temperature hot water systems. Several novel techniques such as electric tracing and flat station were investigated for such dilemma. The pros and cons were compared in this paper. Both the energy and economy saving ratios were analysed comparing with high temperature supply scenario. Furthermore, the viability of the applications in different types of buildings for low temperature district heating (LTDH) was also discussed by using dynamic models.

1. INTRODUCTION

Energy consumption for heating accounts for large share in the overall building energy consumption, especially for cold region countries, like Scandinavia. One proper way to supply heat to areas with high heat density is district heating [1]. Currently, district heating covers almost 60% of the heat demand of the whole Denmark [2], and is planned to reach 70% to cover some low heat density areas by 2035[3]. Therefore, to make DH more competitive and energy-efficient, novel concept should be encouraged to carry out a new generation of DH (the 4th generation of DH).

To face such great challenge, corresponding changes should be taken place in district heating field. Nowadays, a great interest of applying low temperature district heating is drawing more and more attention. Low temperature district heating has many benefits, like it gives access to low density heat sources, and also can reduce the heat loss for the network and etc.

However, one big obstacles of applying low temperature district heating is the hygiene problem. Not all residential buildings are able to use the low temperature optimally. The existing systems in the residential buildings might be using a hot water tank, which is needed to be kept at 60°C due to legionella risks in still water, and this poses some problems when changing to low temperature district heating as the supply temperature normally is, at most, 55 °C and with heat losses in the pipes and the tank, the average temperature in the hot water tank will be lower than what is safe.

The temperature of the hot water plays very important role on legionella disinfection. However, it is not necessary to reach 60 °C to suppress the bacteria. A lot of laboratory research shows possible log-reduction of legionella concentration when the DHW temperature is around 42 °C to 50°C [4-7]. Furthermore, the temperature of 60 °C is neither comfortable temperature for human use, since the hottest tolerable temperature for human in a shower is about 43°C. Therefore, suitable solutions for safe supply of domestic hot water at comfort temperature should be found.

Most of the previous sterilization methods were based on biological point of view. Either some of the working conditions were very difficult to achieve, or abundant manpower and materials were required. Therefore, it could be very prospective to find an optimal solution with only necessary equipment, but can achieve low temperature and safe supply at the same time.

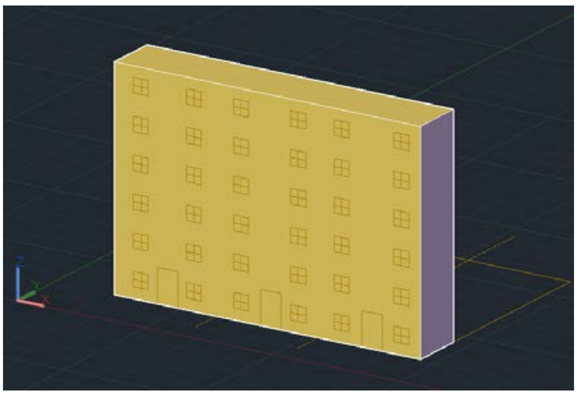
2. STATE OF THE ART

The research of DH-relevant aspects has been always carrying on, from the source to the end equipment. Since the technology is developing all the time, more and more new techniques have been proved their viability for district heating. B. Nordell and G. Hellstrom analysed the feasibility of supplying 30°C-45°C hot water by seasonal borehole for small scale district heating with combination of ground-coupled heat pump. The annual cost reduction was tested to be 20% [8]. A.N. Ajah and et al used Aspen Plus simulation tools comparing the performances of chemical heat pump and mechanical heat pump under different heat source temperatures. The results shown that chemical heat pump were more suitable for low temperature heat source, while mechanical heat pump was preferred by medium-high temperature heat source [9]. A.Hasan and et al proved the application of low temperature space (45°C/35°C) by equipping radiators in the room and floor heating in the bathroom in well-insulated buildings [10]. D. Rosa and et al made analysis for the pipe properties for low energy district heating, An optimal designed double pipe can save 6-12% heat loss by traditional twin pipe, and a triple pipe was developed for low temperature domestic hot water preparation with instantaneous HEX [11]. J.E. Thorsen compared the energy and economic performance of heat storage tank and heat exchange for domestic hot water preparation. The two methods had similar purchase price, but HEX worked better on reducing the risk of legionella [12]. He also made analysis on flat station- a new decentralised way of preparing domestic hot water. The energy saving ranged 2-4 kWh/m^2 yearly, and the risk of legionella can also be much reduced by it [13]. However, in terms of the realization of low temperature district heating, it is still on the cutting edge, because of the obstacle of legionella.

3. METHODOLOGY

Three main concepts for domestic hot water preparation were analysed in this study. They are in-line recirculation system, HWAT (electric tracing) system, and flat station system. To make the comparison more clear and concrete, an artificial case building was made up.

It was a 6-storey building with 3 blocks (staircase), located in Copenhagen region. Each floor has two apartments with the same internal structure and area. Therefore, there are 12 apartments per each staircase, and 36 apartments in total. The building blocks have substation in the basement, where the supply heat from the district heating network is transferred. The ambient temperature was assumed as 10 ^oC in the basement and 20 ^oC for the rest of the building, due to the climate zone it located.



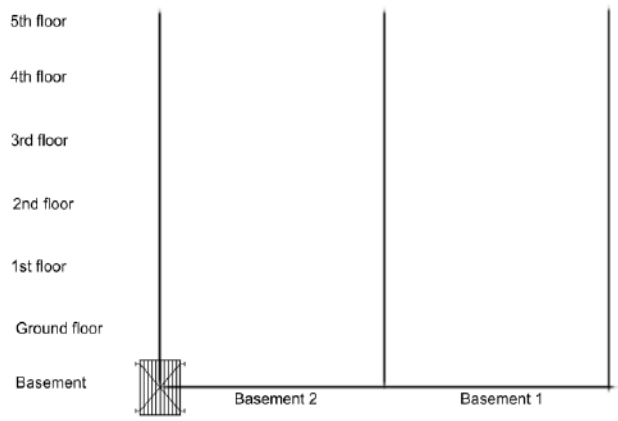


Fig. 1 Model building and DHW pipe network structure

A sketch of the pipe system inside the building is shown in Fig. 1. The height of each storey was assumed as 3 m, and the distance between staircases was 20m. Therefore, the overall length of the pipe network (including all the detours) was assumed as 94 m, all of which was bound by electric cables.

To assure safe supply without risk of legionella, the temperature range of this study was chosen carefully according to the latest version of DS439 for domestic hot water system design and DS 16355 for legionella prevention. The DHW temperature was designed as 55 ^oC at any point most of time, and no lower than 45 ^oC during peak load [14, 15]. Since the recirculation system is always connected with heat storage tank (the temperature of which should be kept no less than 60^oC according to standard), the average temperature of the in-line pipe is assumed to be 57^oC.

The in-line recirculation is one of the cutting edge of circulation concept. The idea is to make the circulation pipe inside the supply pipe. Therefore, the circulating water goes inside the supply pipe with counter flow. Through this way, the heat loss of the circulation pipe can be reduced as much as possible. In this study, the material for the outside supply pipe was PEX and inside pipe was stainless steel according to the guidebook. The pipe material for HWAT and flat station systems were both PEX. Insulation was considered according to DS 452. The thermal conductivity is 0.57 W/mK for PEX, 1.62 W/mK for stainless steel, and 0.037 W/mK for the insulation according to references.

The principle of three concepts for preparing domestic hot water of this case study is shown in the following charts.

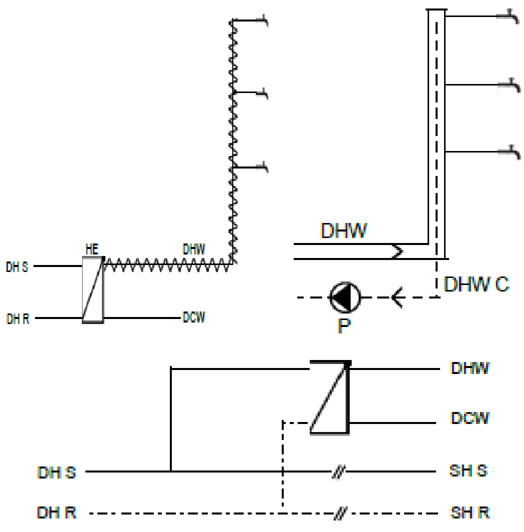


Fig. 2 Principle diagram for 3 different concepts

4. RESULTS

4.1 System dimension

The pipe dimension for all the systems was based on the number of apartments supplied.

Table 1 Pipe dimension for in-line recirculation system

Segment [mm]	Basement 1	Basement 2	Ground floor	1st floor	2nd floor	3rd floor	4th floor	5th floor
Exterior pipe dim	42 x 1.5	54 x 2.0	42 x 1.5	42 x 1.5	42 x 1.5	42 x 1.5	42 x 1.5	35 x 1.5
Internal pipe dim	14 x 2	14 x 2	14 x 2	14 x 2	14 x 2	14 x 2	14 x 2	14 x 2
Insulation thickness	30	40	30	30	30	30	30	30

Table 2 Pipe dimension for HWAT/ flat station systems

Segment [mm]	Basement 1	Basement 2	Ground floor	1st floor	2nd floor	3rd floor	4th floor	5th floor
Pipe Dimension	32 x 4.4	40 x 5.5	32 x 4.4	32 x 4.4	28 x 4.0	28 x 4.0	28 x 4.0	22 x 3.0
Insulation DS 452	30	30	30	30	30	30	30	20

Comparing Table 1and Table 2, the pipe dimension was much minimized by removing the circulation pipe. Through this way, not only the investment of the circulation pipe can be saved, but also the cost for supply pipe and insulation. Moreover, according to a lot of previous study, heat loss of DHW system accounts for very huge part of the total heating demand, sometimes even larger than the energy used for heating up the hot water. Therefore, the energy efficiencies of HWAT and flat station system are higher compare with in-line recirculation system.

4.2 Energy performance of different systems

Table 3 Heat loss of in-line system

Segment	Basement1	Basement2	Ground floor	1st floor	2nd floor	3rd floor	4th floor	5th floor
U-value [W/(m · K)]	0.238	0.238	0.238	0.238	0.238	0.238	0.238	0.212
In-line recirculation [W/m]	11.2	11.2	8.8	8.8	8.8	8.8	8.8	7.9

The heat loss coefficients were calculated for all pipe segments in the building. The results were shown in Table 3. Therefore, the overall heat loss rate for the entire building was 0.91 kW. The energy used only for covering the heat loss for in-line recirculation system was 21.92 kWh per day.

Table 4 Heat loss of HWAT system at 55^{o}C

Segment	Basement1	Basement2	Ground floor	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
PEX DS452	8.87	10.14	6.9	6.9	6.38	6.38	6.38	6.73

The heat loss of HWAT system varied a lot by different control methods. However, since 55 ^{o}C was set to be the higher limit for domestic hot water, the maximum heat loss is happened under this temperature. The overall heat loss rate for the entire building was 0.74 kW. For extreme situation, when the HWAT system was operated at 55^{o}C all the time, the energy used for covering the heat loss was17.69 kWh per day. It means that, even for the maximal heat loss rate, HWAT system still consumed approximately 20% less energy than in-line recirculation system.

In terms of the flat station system, as long as the system was designed properly, domestic hot water can be produced with short time by the instantaneous heat exchanger. Therefore, it is not necessary to have circulation or supplementary heat to keep the supply pipe warm. Thus, the heat loss for the pipe network for flat station is almost negligible.

However, since it is required to implement one heating apparatus for each flat, the amount of heat exchangers increases a lot, especially for large multi-storey building. Thus, the heat loss of heat exchanger will increase as well. Taking previous study[13] as reference, the case building with 36 units (apartments) could waste 5724 kWh/y, which was 15.68 kWh per day. This value is still 28.5% less than the heat loss of recirculation system and 11.4% less than the maximal heat loss of HWAT system.

4.3 Economic performance of different systems

By making use of the test data from Viborg Fjernvarme and catalogue from Danfoss, the economic performance for the case study building was carried out.

The comparison is based on simple calculations of prices for investment, operational and maintenance costs, so the price of valves and other small things are not taken into account. Also the price of getting the solutions installed is not taken into account as it is not known how long it will take to install the different solutions. Assume the energy price for district heat is 0.375 dkk/ kWh, for electricity is 1.13 dkk/ kWh.

Table 5 Specific cost for different concepts

	Invest. Cost [dkk]	**Operational cost** [dkk/y]**		**Main. Cost [dkk/y]**
		DH	**El**	
In-line	8858	3671	134	-*
HWAT	40962	0	3968	0
Flat station	329579	2147	0	6318

* information unavailable

** The operational cost from DH only included the part covering the heat loss

The cost of in-line recirculation system was the least among all three types of heating systems. However, besides the heat consumption, it also required electricity for the circulation pump. The operational cost for HWAT system included two parts- to heat up the water from 45°C to 55°C, and to cover the heat loss. And it also had the simplest system structure. Therefore, it can be equipped easily and has few maintenance fee. The cost for flat station seems to be the most. That was because each apartment needed to equip a heating unit. However, it has the least operational cost since its heat loss was the least. Moreover, this economic analysis did not take life time into consideration. If the life time for the heat unit is long enough, the investment cost per year could be reduced enormously. Meantime, both HWAT and flat station can give access to low temperature district heating without risk of legionella, even though the theories behind are different. For HWAT system, the idea is to use the electrical cable as supplementary heater, which can heat up the hot water to safe temperature. While talking to flat station, the concept is to minimize the total volume of each flat to less than 3 litres, thereby reducing the risk of legionella. Anyway, by taking such methods, the temperature of the DH network is possible to reduce from current level by 10-15 °C both for supply and return. And the energy saving for the whole network accordingly can be more than 30%, which gives a very promising prospect to low temperature district heating in the future.

5. DISCUSSION

5.1 Annual energy consumption of in-line recirculation systems

Table 6 Specific energy consumption for in-line recirculation system

	DH [kWh/y]	**El [kWh/y]**
Pipe work	8001	
Heat storage tank	1790	
Pump		119
Total	9791	
Per apartment	272	3

The total energy use per year can then be found as the district heating energy used to cover the heat loss from the circulation system and hot water tank and the electricity use for the circulation pump. The result can be seen on Table 6. The energy use for domestic hot water is not taken into account as it is assumed to be the same regardless of the installed solution.

From Table 6, it can be seen that, the owner of each apartment has to pay for 272 kWh heat and 3 kWh electricity for heat loss besides their real heat demand annually.

5.2 Control methods for HWAT system

In terms of the annual energy consumption for HWAT system, it depends strongly on the control methods.

Always max power

The simplest way of controlling the trace heating cables, is to have no control but just have the cables perform at maximum power at all times. The system can be further simplified by just installing the same power cables everywhere, so the cables will be over dimensioned in a large part of the system as the cables must be able to cover the heat loss of the largest pipes as well as heating the water to legionella safe temperatures. This, of course, is also the most expensive method. The principle of the control method can be seen on Fig. 3, where 1 on the y-axis is full power, and 0 is turned off. To eliminate some energy use, the cables could be adjusted for each pipe section according to its heat loss, but still always be at maximum power.

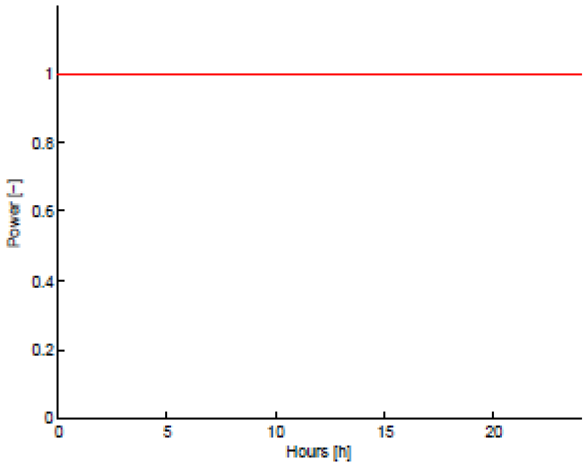


Fig. 3 Principle of full power operation

Always on with temperature set-point

A more realistic method is to have a temperature set-point in the control unit so the cables are always on until the water reaches a certain temperature. The energy use of this method depends a lot on the consumer profile as the temperature of the water is decreased when there is a tapping. So if there are frequent tapping this method uses more energy than if the tapping is concentrated in certain periods of the day as the cables need less energy to cover the heat loss than to heat the water to the set-point. The principle of this control method can be seen on Fig. 4where it is assumed the power is on maximum 50 percent of the time, and then covers the heat loss the remaining 50 percent. A set-point is assumed to be used on all the following methods to save energy and avoid unnecessary overheating of the water.

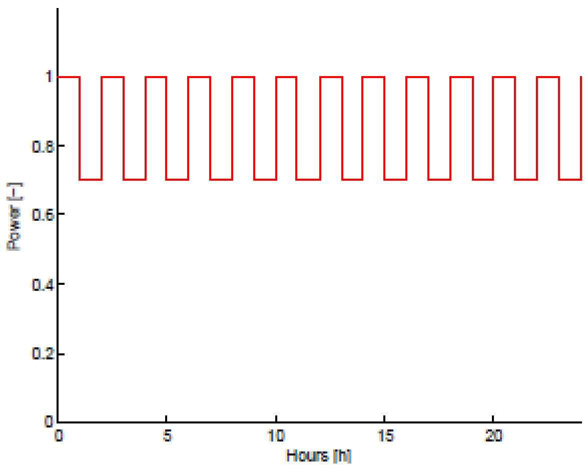


Fig. 4 Set point control method

Everybody has a day job

If it is assumed that everybody works the same time of day then there is a need to keep the water at the set-point temperature during the day as there are no tapping. This case is probably the worst realistic case as the available time to turn off the cable is very short. During the night it is assumed that tapping is very infrequent and therefore the water can be heated to the set-point at kept there to eliminate legionella. The principle of the control method can be seen on Fig. 5, where it is assumed there are 6 hours peak load, 3 hours in the morning and 3 hours in the afternoon, where the cables can be turned off. The rest of the night is assumed to have some tapping where the temperature drops and the water needs to be reheated.

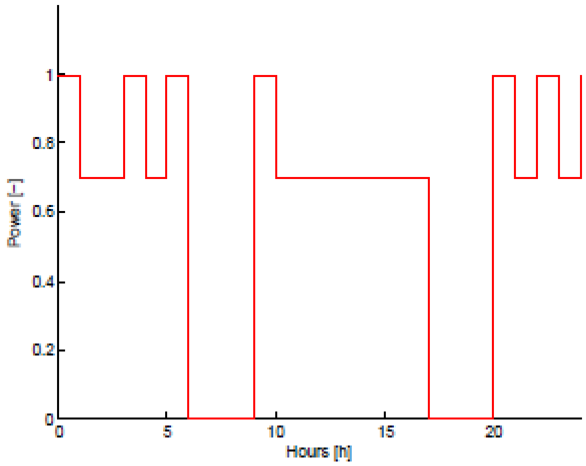


Fig. 5 Control method for daily work residence

Frequent tapping during day

In most apartment buildings there are frequent tapping during the day, which can make it possible to turn off the cable during most of the day. During the night it is assumed that tapping is very infrequent and therefore the water can be heated to the set-point at kept there to eliminate legionella. The principle of the control method can be seen on Fig. 6, where it is assumed that frequent tapping happened most of the day time. However, there were still some period in the day time that, the tapping cannot be considered as frequent, therefore the water still needs to be heated at some point. Such situation could happened during vacation time.

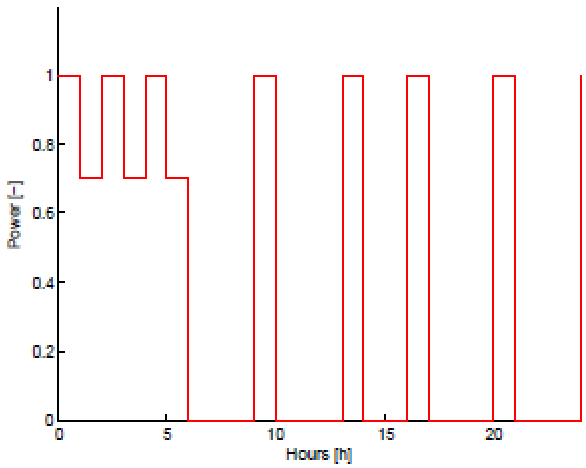


Fig. 6 Control method for frequent tapping during the day

Based on different control method, the overall energy consumption of electric cable can be varied a lot. It is obvious that, control methods shown in Fig. 5 and Fig. 6 consume much less power than in Fig. 3 and Fig. 4. And the user pattern plays a very important role on the method making process.

OUTLOOK

Supplying heating and cooling by districts is a good way of reducing distribution heat loss as well as lowering down the individual energy consumption. Especially in high heat density area, district heating has its superior benefit than other heat providing methods. To make district heating more competitive, as well as adapt to the strategy of fossil free in the near future, to shift current district heating to low temperature district heating is of great importance. As a result, the heat loss in the network can be much decreased, and more low / medium temperature heat sources can be utilized. To apply low temperature DH more properly, a lot of solutions are developed to assure the hygiene and comfort at the same time. Besides the methods compared in this study, there are also some other solutions worthy to be analysed.

Circulation with a Heat Pump

When having a circulation system with a heat pump, the evaporator of the heat pump is placed on the primary side of the district heating return pipe to extract energy, which will be re-entered into the system on the secondary side of the heat exchanger, via the condenser of the heat pump, to heat the domestic hot water further to cover heat losses in the circulation system. The principle of this system can be seen on Fig. 7.

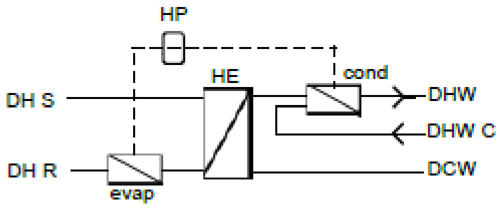


Fig. 7 Principle of heat pump solution

Through such heat pump solution, not only the DHW can be reheated to safe level, but the temperature of DH return line can also be reduced. Thus, it gives benefits to both the primary side and secondary side. The energy efficiency of the whole network is improved.

Electric Heating Element

The electric heating element is very simple. It is installed in the bottom of the hot water tank to heat the water further than what is possible with district heating alone. The principle of this system can be seen on Figure 4.8.

Fig. 8 Solution of Electric Heating Element

The idea of this solution is also based on temperature control. The heating element is used as supplementary heater for DHW. the benefits of this type could be the shave of the huge peak load for really big building, as well as the steady supply (both temperature and flow rate) of domestic hot water.

Therefore, if renovation of the substation can be carried out, these new solutions can be positive alternatives for existing ways of supplying heating to the consumers. The following matrix shows the possible match of new solutions and existing ways.

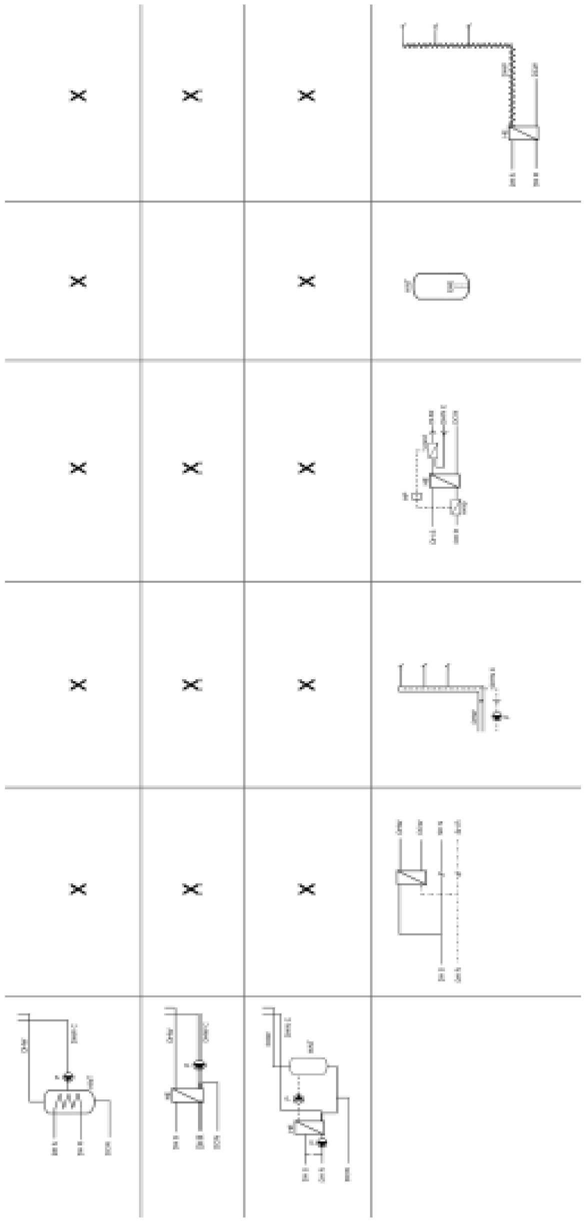


Fig. 9 The different existing situations and the compatible new solutions

The horizontal charts are hot water tank and circulation, heat exchanger and circulation, and circulation with both heat storage tank and heat exchanger.

CONCLUSIONS

This study compared three new solutions –in-line recirculation, HWAT, and flat station, which could become alternatives applied for low temperature district heating. A simulation building was made up to make the study more approach the real life. According to the results, even though the in-line recirculation system is one of the most advanced circulation type, it still waste much more heat during distribution and circulation than the other two solutions. By in-line recirculation, almost 10000 kWh heat and 119 kWh electricity were wasted just because of the heat loss every year. However, it still had the advantage of lower economic cost, high thermal comfort by short waiting time, steady supply temperature.

By utilizing the HWAT (electric tracing), the simulating building could save 20% energy annually only from heat loss, comparing with the recirculation system. Moreover, through optimized control method, the energy saving can be even more. However, the suitable control method strongly depends on the user pattern for DHW consumption. The structure and installation of HWAT system is also the simplest, which leads to very little maintenance cost afterwards.

The flat station waste least energy on distribution since it can provide heat on site by the simultaneous heat unit. The heat loss saving by flat station can reach 28.5% comparing with recirculation system. Although the investment expense of flat station seemed much larger than other two systems, flat station had the least operational cost. If the life time of flat station is longer, the comprehensive cost of flat station can be largely decreased.

To adapt to low temperature district heating in the future, the potential alternative solution should be analysed and prepared to replace the existing traditional substations.

ACKNOWLEDGEMENT

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SESSION 2

Urban Energy Systems, planning and development

The 14th International Symposium on District Heating and Cooling, September 7th to September 9th, 2014, Stockholm, Sweden

AN APPROACH TO ILLUSTRATE STRATEGIES FOR IMPROVED ENERGY EFFICIENCY AT THE MUNICIPAL LEVEL

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ABSTRACT

This work focuses on how implementation of well-known refurbishment strategies, applied on multifamily buildings in a post-war housing complex in Sweden can affect the generation of district heating. Both the energy use and the power load were considered.

The study was performed in Borlänge municipality, Sweden, where the municipality owns both the energy and the housing companies. The strategies for energy efficiency were simulated with IDA-ICE for the Tjärna Ängar area, a housing complex built between 1969-1971, with access to documented information about the buildings and energy audit. The results of the building simulation were implemented in a simplified model of the local district heating system.

The results indicate how different renovation strategies affect the demand of energy and power load within the district heating system and can be used to provide indicators for different scenarios. The larger goal of the research is how to maximize the economic and environmental efficiency of improvement strategies on a municipal level as well as how to find appropriate energy optimization methods that can be proposed by building contractors. The initial study presented here was conducted within the research program Reesbe.

INTRODUCTION/PURPOSE

According to the European Commission [1], all sectors need to invest in energy efficiency in order to reduce Greenhouse Gas (GHG) emissions. Buildings account for 40 % of the total energy use [2]. To address this problem the European Union (EU) member states have agreed on reducing energy consumption in buildings by 20 % by 2020 [2]. Also, according to Copenhagen Economics [3], "energy savings through the renovation of the existing stock is one of the most attractive and low cost options to reduce the emissions of CO_2", due to the large share of fossil fuels in the energy supply systems of the EU members [4].

During the years 1965-74 one quarter of Sweden's housing stock was constructed in a period known as "The Million Program" [5], where dwellings for 1 Million inhabitants were built, both as apartments and single-family houses. Functional planning and rationalization of the construction methods were the norm. Experimentation and political interests were challenged during these years [6]. Many of these buildings are after roughly 40 years in need of renovation and with the EU directives of energy efficiency in combination with low interest rates, advocates for renovation argues that this is a unique opportunity [3].

According to Gram-Hanssen [7], energy renovation is performed in connection with wear and tear renovations e.g. roof and windows. Energy efficient renovation is performed at a low rate that cannot match the EU goals.

The scope of this work is to investigate how energy efficient renovation of a million program area in Borlänge would affect the generation of district heating. Different energy saving renovation measures were studied to investigate their impact.

STATE OF THE ART

The public housing company in Borlänge municipality, Stora Tunabyggen AB, has started a renovation project in the Tjärna Ängar area. It is of the largest million program dwellings within the municipality. Given this situation a study showing the impact of different energy saving measures for the buildings are highly interesting. As in many Swedish municipalities the public housing company as well as the local energy company are owned by the municipality itself. Based on a perspective that includes both the generation and the use of energy, sub-optimization can be avoided. Therefore this study will also show the impact of the measures on the district heating system.

The Tjärna Ängar area is a neighbourhood built in 1969-1971 as part of the Million Program. The area consists of 42 similar three story apartment buildings and the total living area is about 115,000 m^2 [8]. One pilot building was chosen to be simulated and this object consists of a three story building built in 1971, with 2,822 m^2 heated area. This building is representative for the area [8] and has not been subject to any major renovation since built.

Borlänge Energi AB is the local energy company in Borlänge, producing approximate 390 GWh [9] of district heating every year. The production mostly consists of heat produced by a combined heat and power plant incinerating waste and excess heat from large industries in the municipality. During the coldest season and in case of emergency, oil fired heat only plants are used. The distribution of different energy sources is showed in Fig. 1.

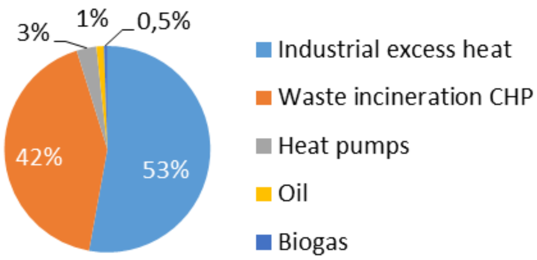

Fig. 1. Allocation between energy sources within the district heating system of Borlänge [10].

There are different types of customers, where multifamily buildings as the largest category. The distribution of different customers in district heating is showed in Fig. 2.

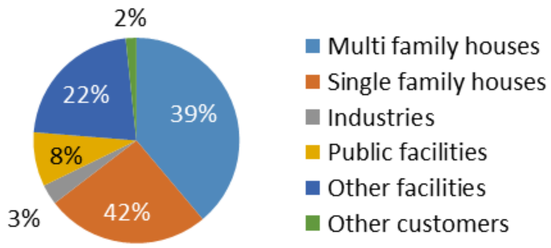

Fig. 2 Allocation of district heating between different customer categories [10].

The largest customer in the district heating system is the municipal housing company Stora Tunabyggen AB, using about 20 % of the annual energy from district heating in Borlänge [10]. In Fig. 3 the allocation to Tunabyggen is shown, where the district heating use of the area Tjärna Ängar is separately shown [10].

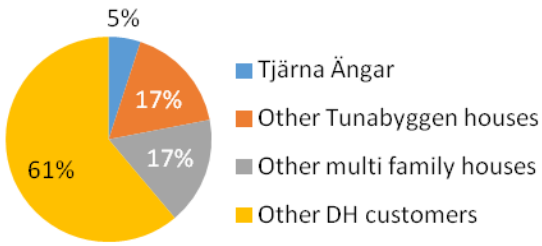

Fig. 3 District heating allocation between Tunabyggen facilities and others, the area Tjärna Ängar is shown separately [10].

METHODOLOGY

To illustrate the impact of energy conservation within the Tjärna Ängar area two different simulation tools were used. The numbers are referring to the flow chart in Fig. 4. First, a simulation of the pilot building in IDA-ICE was performed (1.), showing the impact of renovation only for the buildings energy use. Then, the results from the simulation were scaled up (2.) to show the changes in energy use of the entire area. Finally these results were used to simulate the impact on the district heating system (3.), using a linear optimizing model, developed in MATLAB [11]. The results from both the building simulations and the district heating system simulations were analyzed in (4. and 5).

Building simulation

According to EQUA AB [12], IDA-ICE is a building simulation software for study of the indoor climate and energy consumption of buildings and the interaction with their surroundings.

There are different levels of user interaction within the software which requires different information. In principle it is possible to simulate any particular installations configuration, such as solar heaters and heat exchangers, within the program environment. The program needs information about the building physical

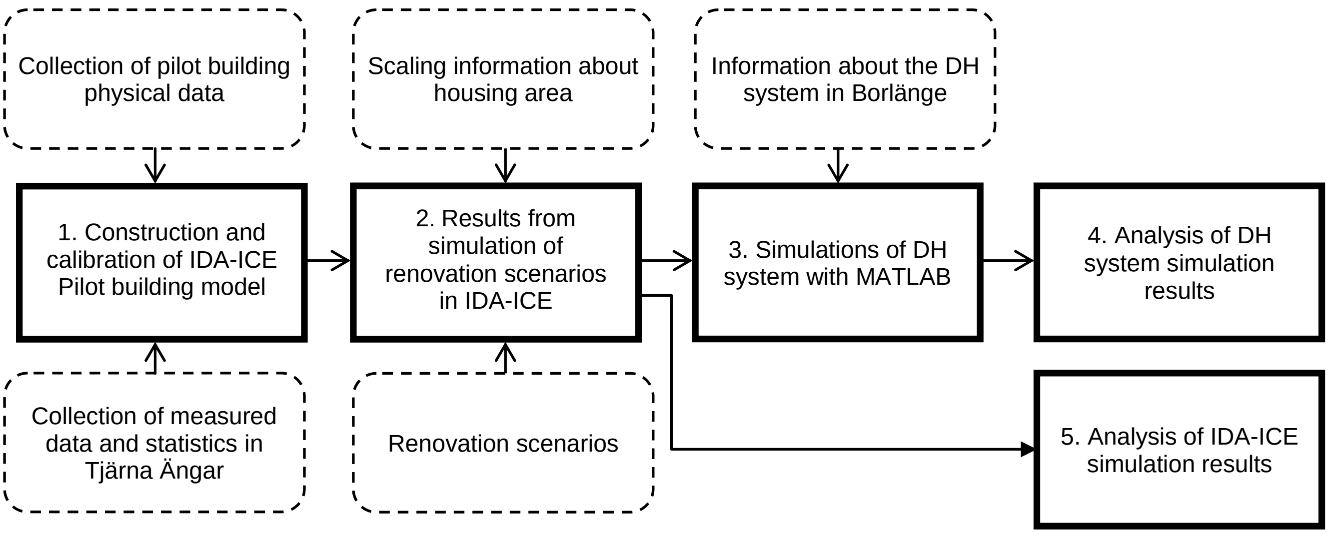

Fig. 4 The working procedure for the project, the boxes are showing different actions and the doted-line boxes are showing exogenous data . DH=District Heating

characteristics (e.g. wall constructions and windows, performance of installations and energy systems). Weather data is needed for any specific place; in this case the weather data file was obtained using the Meteonorm software [13].

Fig. 5 Building model in IDA-ICE.

At first, the current building was simulated, according to Fig. 5, using the details given by the housing company (see Table 1).

In order to calibrate the simulation, a temperature data logger was installed in the heating supply and return pipes on the secondary side of the heat exchanger. With this data it is possible to estimate the heat power used within the building for space heating purposes. The simulation data was compared with the measured data using the energy signature method [14], to validate the simulated conditions.

Table 1. Construction data of the buildning, used as input data in IDA-ICE. The table shows both the as built scenario and a passive house scenario.

Variable	Current building	Passive house
External Walls insulation	120 mm mineral wool	480 mm mineral wool
Cold Attic	150 mm mineral wool	300 mm mineral wool, roofing felt with 100 mm mineral wool
Ground	300 mm loose Leca	300 mm loose Leca
Ground floor	250 mm concrete floor	250 mm concrete floor, 60 mm mineral wool
Ventilation	Forced	Heat Recovery
Widows	2 pane glazing, clear	3 pane glazing, low emissivity
Individual metering of domestic hot water	No	Yes
Indoor temperature	21°C	20°C

In the second simulation a passive building package was proposed, based on the experience of the Brogården Project, in Allingsås, Sweden [15]. Also, individual measures were simulated; e.g. adding attic insulation, external wall insulation, heat recovery ventilation (HRV), change of windows and a decrease of indoor temperature.

District heating system simulation

The district heating modelling tool used in this study was developed by M. Åberg [11]. The scope was to cost-optimize the operation of district heating systems, with a minimum amount of input data. The tool is a fixed model structure (FMS) based on linear programming and is developed in MATLAB. The input data and the results from the simulations were imported from and exported to MS Excel. On the production side of the district heating system the model structure requires information about the fuel costs, the plant capacities, fuel efficiency and the power-to-heat ratio of the production units. It is also possible to specify a month of non-operation (for e.g. a maintenance month) for each production unit and also the capacity of excess heat re-cooling. On the distribution and demand side, the model needs information about the annual heat demand, the system capacity factor and the system minimum temperature. The distribution losses also need to be specified.

The model consists of different nodes, representing fuels, conversion from fuel to district heating and electricity, distribution, demand and the electricity market. In Fig. 6 Structure of the model with boxes showing start-, conversion- and demand nodes and lines representing energy flows are shown. The nodes are shown with lines in between, representing the energy flows between the different nodes. The calculations for optimizing the production are made for each 12-hour period during one year [11].

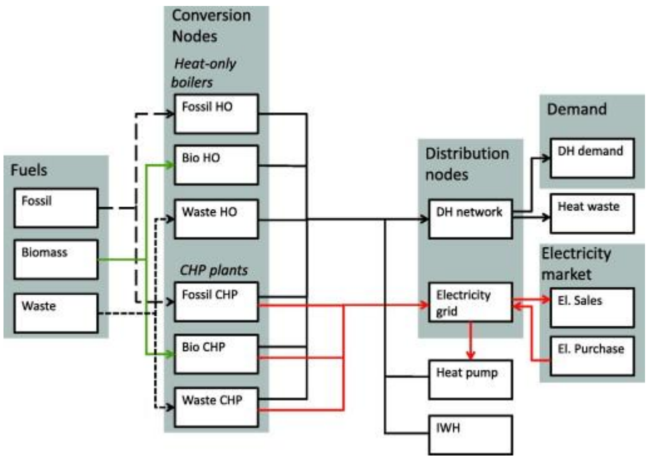

Fig. 6 Structure of the model with boxes showing start-, conversion- and demand nodes and lines representing energy flows [11].

The situation in Borlänge is quite complex, e.g., the incineration plant is shut down during summer for maintenance and the industrial excess heat covers the needs for district heating. When it comes to electricity consumption, it might in some cases be cheaper for the energy company to start an oil fired boiler than to use the heat pumps. Due to this, fuel costs have not been included in the model to simplify the simulation. The capacity of the different conversion nodes, including heat pumps and industrial excess heat, were included. Most important the annual heat demand of Borlänge was included, the statistics used in the first case, without any energy conservation made, were from 2013. Depending on the results of the building simulations, the annual heat demand was reduced corresponding to the size of the energy savings. This means that the total district heating use of Tjärna Ängar was reduced with a percentage according to Table 2. The statistics for the district heating consumption during 2013 was used also for these simulations.

RESULTS

Building simulation

The as-built scenario shows that the building have a specific energy use of 157 kWh/m^2 per year, where 120 kWh/m^2 corresponds to active heating, 35 kWh/m^2 to assumed Domestic Hot Water (DHW) consumption and 2 kWh/m^2 to equipment operation (lighting was not taken into consideration in the simulations). The results for the passive house scenario were 78 kWh/m^2 total energy use where 5 kWh/m^2 corresponds to equipment operation, and an estimation of 16 kWh/m^2 DHW based on the Brogården experience in Allingsås, Sweden [15]. Both scenarios are shown in Fig. 7

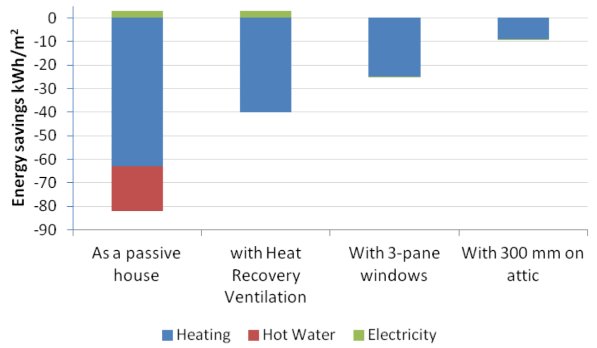

Fig. 7 Energy saving results of selected simulation scenarios.

Except for HRV all single measures have an electricity consumption of 2 kWh/m^2. All scenarios (except Passive House) have a DHW use of 35 kWh/m^2 based on Sveby standards [16].

Table 2. The end use district heating savings for the different renovation scenarios.

	End use DH Savings
Passive House	53 %
Heat Recovery Ventilation	26 %
Three-Pane Windows	16 %
300 mm Mineral wool insulation on walls	8 %
300 mm Mineral wool insulation on attic + 100 mm Mineral wool insulation on roof	6 %
1°C Temperature Decrease	9 %

District heating system simulation

The simulation of the district heating system without any measures is shown as a heat load curve in Fig. 8. The curve shows the need of power in each time step during the year with the most energy consuming periods to the left. The x-axis shows the time and the y-axis the average power needed during each 12 hour period. The entire area shown is equal to the district heating demand during the year. The curve is based on statistics on district heating usage from 2013.

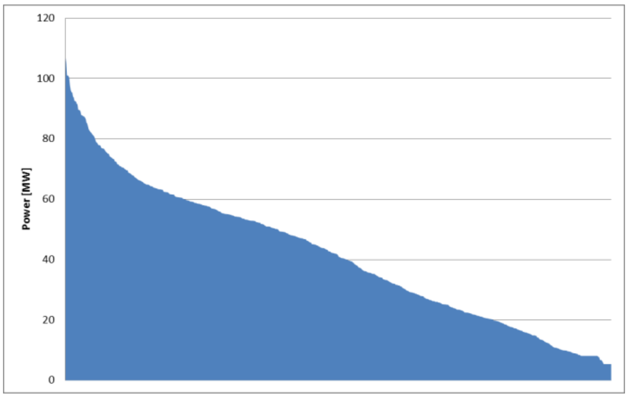

Fig. 8. Heat load curve for Borlänge district heating system based on 2013 statistics.

Simulating the different renovation scenarios gives an annual reduction of the heat load curve. The percentage is a yearly average reduction of the power demand presented in Table 3.

Table 3. The reduction of produced district heating for the different renovation scenarios.

	Reduction of produced DH
Passive House standard	2,6 %
Heat Recovery Ventilation	1,3 %
Three pane windows	0,8 %
300 mm insulation in walls	0,4 %
300 mm insulation in attic	0,3 %
Reduced indoor temperature with 1 °C	0,5 %

DISCUSSION

In order to clarify the potential of energy efficiency within a district heating area a concept which combines both building and energy system simulation were developed. These results can show the impact of energy saving measures within an entire district heated area. To combine two different modelling tools means that the system border has been relocated and includes the building with its technical installations as well as the central unit for energy generation and the distribution system in between. With this method measures in the district heating system can be compared with measures in buildings, to investigate whether they are interacting or countering each other.

At this stage only rough results of what will happen with the district heating generation when implementing energy efficient measures is simulated. Since this study focuses on the potential of the proposed method, simplifications were made within the building simulation.

The FMS model gives, as it is constructed to be able to optimize with small amounts of input data, standardized results of how the district heating system will react when energy efficiency measures are implemented. However, specific results of the lowered heat demand is not available, since the tool is constructed to cost optimize district heating production. Still, the full capacity of the FMS model is not used in this study, since fuel prices has not been included. It would have been possible to show an optimization of the heat generation, based on the different price levels if included. The complexity of the running parameters makes it hard to optimize the district heating production in Borlänge only with respect to the fuel costs. Due to the complexity of accounting different production units this study has been limited to the district heating demand.

When it comes to energy efficiency in buildings there could be different views between the housing and energy companies, sometimes leading to stagnation. Since the municipality is bound to follow requirements from higher authorities concerning energy efficiency as well as environmental impacts and economical aspects, the same situation applies to the companies of the municipality. To get the maximum output of the process regarding energy efficiency, cooperation is needed on a concern level and reliable information about both present and future situations in the energy system is needed. To optimize the energy situation, both buildings with energy efficient measures and the generating and distribution systems of energy have to be considered to avoid sub-optimization.

In summary it is found that the proposed approach with the two tools has been found applicable for the scope of the investigations in early stages and indicates promising features for further development to obtain more refined and detailed results.

CONCLUSIONS

An advantage with the proposed method is that even with a very limited amount of data can be used to visualize the direction of the impacts on the district heating system.

This method can be used by decision makers when energy efficient measures would be performed on a large scale. The results can be used to illustrate the impacts of these measures in the production and distribution of district heating.

To clearly show the impacts of energy efficient measures within Borlänge a more robust model of the district heating system is needed. A proposed improvement could be to link the IDA-ICE model with the district heating model in an hourly basis in order to illustrate the power impact in the different energy sources. This could also be linked to the real specific use of each unit within the system.

This method is generic in the way that it can be applied to any dwelling area that is subject to energy efficiency measures within a district heating system.

ACKNOWLEDGEMENT

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REALISING THE SOCIAL BENEFITS OF DISTRICT HEATING THROUGH STRATEGIC PLANNING

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ABSTRACT

Affordability, low carbon and security are hailed as the three critical characteristics of our future energy system. In this respect, district heating offers towns and cities many attractive characteristics. In particular, under the right governance models, it can offer social benefits by lowering energy costs and alleviating fuel poverty.

This research uses the case study of the UK, a country where less than 2% of heat is delivered by district heating, but where levels of fuel poverty are a significant challenge. UK local authorities play an active role in the early planning stages of district heating and many are aiming to alleviate fuel poverty with these projects.

The results show that the full variety of actor motivations are not reflected within their decision criteria; although local authorities aspire to take a strategic planning role, this is not reflected in the mapping tools that they use in feasibility work. We propose a more flexible approach to mapping for strategic planning and consider its role in bringing forward DH schemes that reduce fuel poverty.

INTRODUCTION

To date there has been limited implementation of district heating in the UK; only 2% of heat is supplied in this way [1]. However, the UK needs to radically transform its heating systems in the face of the energy trilemma: generating and supplying affordable, low-carbon, and secure heat.

In this paper we pay particular attention to the need to provide affordable heat in the domestic sector, and the issue of fuel poverty.

We consider the development of district heating (DH) in the UK, with particular focus on schemes that are led by local authorities. We examine the motivations of local authorities in developing DH schemes and the decision criteria they use in the pre-feasibility stage of the planning process (used to develop the business cases for a scheme and ensure political and stakeholder buy-in before detailed technical and economic assessment is carried out). We then consider whether the mapping and planning tools used by local authorities are fit for the purpose of meeting their stated objectives.

Policy context of DH in the UK

District heating became a focus of UK energy policy when it formed a critical role within the UK Heat Strategy 2012 for heating in cities [1]. One of the steps outlined in this strategy was increased support for local authorities to overcome the capacity and capability barriers and challenges to developing heat network projects. In the UK this signifies a step change in the way heat is delivered, moving from a centralised gas network model of provision to locally coordinated schemes. Local authorities, which have traditionally played little or no role within the energy system, are now being asked to offer a trustworthy source of advice, coordination of local stakeholders and, most critically, strategic energy planning [2]. This is interesting because local authorities have different motivations to traditional energy bodies and, therefore, the decision-making process (usually based on techno-economic) needs to emphasize alternative criteria. As a result, central government has put in place support mechanisms to enable local authorities to take on the role of a local strategic energy body using heat-mapping tools and training support.

The Heat Network Development Unit (HNDU) was formed by the Department of Energy and Climate Change in 2013 [3] to improve the capacity of local stakeholders to deliver DH, share best practice between projects, and fund feasibility and planning maps for towns and cities. The majority of available funding is for planning and feasibility studies with the aim of creating a business case to attract investors. Capital funding for projects is less plentiful and is restricted to EU funding or Energy Company Obligation (ECO) funding, which is imposed on energy companies in the UK to improve energy efficiency in low income, fuel-poor and hard-to-treat residential properties. ECO funding has most notably been used successfully to fund schemes connecting blocks of social housing flats, improving the comfort levels for residents within the flats and reducing fuel costs. However, due to the remit of HNDU and the lack of government capital funding for schemes, the majority of local authority activity has focused on mapping and feasibility studies with the idea of attracting external investors.

Affordable warmth

Providing affordable warmth to residents is a key challenge for local authorities in the UK and features explicitly in many local authority strategies and plans [4]. Fuel poverty (sometimes referred to as energy poverty) occurs when a householder cannot afford basic comfort levels of heating (other energy use is also included but in this paper we refer to heating levels). In the UK, it was estimated that 10.9% of all households were living in fuel poverty in 2011 [5]. Its causes are recognised as the combination of three main factors: low income, poor energy efficiency and high fuel prices [6], the latter being the dominant driver [7].

The issue of affordable warmth also features prominently on the UK national political stage. The Warm Homes and Energy Conservation Act of 2000 set a legally binding target for the UK government to eradicate fuel poverty by 2016 [8]. However, in recent years the issue of fuel poverty has not remained consistently under focus within the national political debate. The government recognised within the 2013 Energy Bill that its 2016 target was not achievable in the time frame. A new target is due to be set this year [9].

Fuel poverty is not just an issue in the UK and Ireland, but exists across Europe.

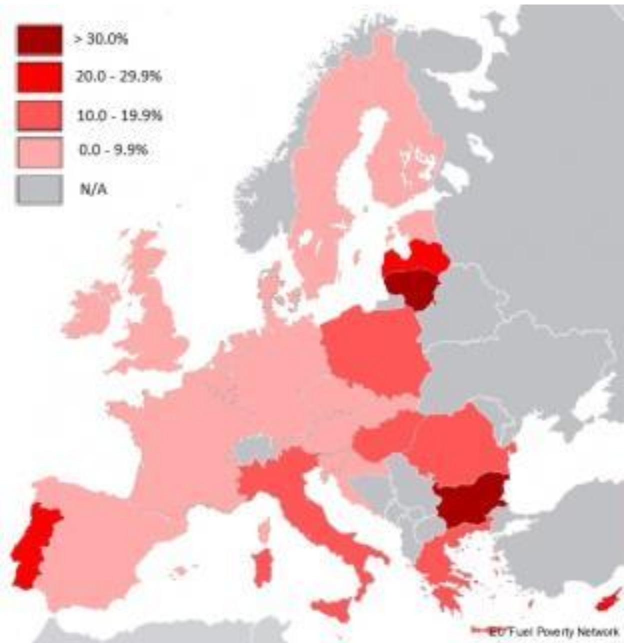

Fig. 1: % of households unable to afford to keep their home adequately warm (data source: EU SILC 2011) [10].

However, energy-efficiency measures alone will not be sufficient to eliminate fuel poverty [4]. Efficient and low-cost provision of heat through DH could therefore make a significant contribution to fuel poverty reduction in the domestic sector.

Current modelling tools

As discussed previously, use of mapping tools is commonplace for district heating planning and development. This research considers the appropriateness of tools and techniques for capturing opportunities for achieving multiple aims with district heating, such as fuel poverty reduction alongside carbon reduction, and financial return on investment.

Current methods are predicated on modelled or real heat-density data based upon today's heat loads. For example, the National Heat Map [11], developed by the Department for Energy and Climate Change in the UK, displays modelled heat demand at a postcode resolution to offer an initial view of whether district heating might be technically and economically feasible within an area. Funding awarded through the HNDU for feasibility studies in England and Wales has enabled local authorities to commission consultants to take a similar approach at a more detailed level, adding in information about secondary heat sources, public buildings, and potential piping routes with the aim of developing business plans “which can be used to attract commercial investment” [12]. In Scotland, the Scottish Government opted to create a more detailed planning map for the whole of the country rather than commissioning consultants for each individual region. The energy-efficiency levels of much of the UK’s building stock are not taken into account within heat maps, despite the fact that generally the housing stock is poorly insulated. Other considerations such as fuel poverty levels can be added in to these maps at the discretion of the local authority, but in general the primary objective of undertaking these exercises is to identify the site locations with the maximum potential for financial payback.

The effectiveness of modelling tools for stimulating new district heating projects is still contested. For example, at a meeting of 39 local authorities and housing associations as part of the Vanguards network, members of the meeting felt that modelling tools did not help to overcome the significant and complex barriers preventing individual projects being installed on the ground. They felt that the experience and knowledge of individuals within local authorities was what was needed [13] . However, other members felt that further development of tools was required.

Current modelling tools using heat demand mapping as their basis don’t allow local authorities to look at aspects (other than revenue generation) that might motivate their involvement in the development of district heating.

STATE OF THE ART

This work investigates the incorporation of social considerations within the development process for district heating. We assess the appropriateness of existing tools for incorporating these considerations within the decision-making process and propose recommendations for better strategic planning.

We pose the following research questions:

- What are the main motivations for local authority involvement in district heating in the UK?
- What decision criteria are used to identify potential schemes, and are these aligned with original motivations?
- What decision-support tools are used by local authorities in the pre-feasibility stage?
- Do these tools support developments that meet the main motivating objectives of local authorities?

METHODS

In order to understand the motivations, decision criteria and use of modelling tools in local authority-led district heating schemes, we conducted 11 semi-structured interviews with key actors in 6 local authorities in England and Scotland, as well as 3 private sector companies and 2 other public sector stakeholders. These interviews were transcribed, and thematic analysis was conducted.

In addition, we reviewed a range of policy documents; the policy context in the UK is moving rapidly and some significant policy changes were implemented during the timescale of this project.

Relevant quantitative data was collated to develop a simple spatial mapping tool that addresses issues arising from the results of the interview work. This tool and a brief analysis of its benefits are described in the discussion section.

RESULTS

Motivations and decision criteria

Many local authorities see district heating as bringing benefits for tackling fuel poverty and this is often cited in press releases as a key motivation for developing schemes. For example, the Scottish Government [14] and Hull City Council [15] have both recently announced the development of heat networks to support fuel poverty reduction.

However, a key part of this research was to investigate whether social criteria, such as a reduction in fuel poverty, were incorporated into the down-select for project sites, given that our literature review highlighted that many of the support tools currently available focus on techno-economic considerations.

It became clear from analysis of the interviews with the six local authorities that the motivations for developing district heating vary widely between authorities. There is no consensus on the benefits that organisations are looking for from district heating.

Social criteria were important, not just in terms of fuel poverty alleviation, but also for regeneration of council-owned housing stock. District heating was seen as a solution for improving the living conditions of residents in social housing as well as meeting regulatory requirements for social housing standards. Especially where capital funding was available, this was seen as a way to reduce the costs of heating and maintenance for residents and the local authority, respectively.

Carbon reduction was often mentioned as an important driver. There was also a financial consideration for carbon reduction, as public sector organisations not covered by the EU emissions trading scheme are required to buy allowances for the tonnes of carbon they emit under the Carbon Reduction Commitment (CRC) energy efficiency scheme [16]. Therefore the ability to deliver carbon savings through use of district heating can offer financial savings to public bodies.

Alongside social and environmental concerns, economic motivations were prominent. Local authorities focused on increasing the competitiveness of their local region, using district heating to attract industrial activity to the area and thus creating more local jobs.

Despite a clear articulation of the local authority's drivers for wanting to develop district heating, the decision criteria used for planning and construction of a business case for a scheme did not necessarily reflect these drivers. By analysing the interviews and noting the mention of motivations and decision criteria, the following broad areas and rankings of importance were revealed[1].

[1] Technical feasibility is, of course, important, irrespective of the underlying motivations.

Table 1 Observed rankings indicating the relative number of times motivations were stated by local authorities planning district heating schemes vs. the number of times different decision criteria were mentioned for use within planning to construct a business case for a scheme.

Motivation	**Decision Criteria**
1. Social Regeneration of housing stock Fuel poverty	1. Economic Where are opportunities to offer lower-risk, financial returns to: - Potential investors? - The local authority?
2. Environmental Carbon reduction	2. Social Where are opportunities to use ECO funding for a residential DH scheme? Are there opportunities to add on households to a planned commercially competitive scheme?
3. Economic Regional competitiveness e.g. attracting industries wanting low-carbon heat and electricity Local economic growth	3. Environmental Will the carbon savings offered by a scheme reduce costs on the CRC?

Whilst the rankings are obviously subject to interpretation in our coding and, given the small sample, are not necessarily statistically significant, the mismatch between motivations and decision criteria is striking, and clearly supported by the recorded narrative.

Current use of mapping tools

The next stage of this research goes on to explore in more detail how local authorities are currently using mapping tools within the DH development process.

As mentioned previously, the HNDU and the Scottish Government are encouraging use of heat mapping by local authorities to identify potential development sites and attract financial investment [17]. Mapping was perceived by all those interviewed to have an important role in the planning process and was often part of the pre-feasibility decision-making. Many of the organisations were in the process of developing a heat map, or had ambitions to develop one to assist in the selection of suitable heat network projects. There were no common tools used; many had created bespoke methods and had used consultants to undertake feasibility studies.

In England, the DECC heat map was mentioned as an initial base upon which to do early planning and "give a level of confidence that there is enough heat demand in the city" (Interviewee in one English local authority). The data from this map was seen as a useful basis upon which to develop a more detailed city-scale map which also included factors such as anchor loads, waste heat plants, and any sort of constraints. In England councils were also hoping to receive funding from HNDU to support the development of maps. The current application of these maps predominantly aims to identify sites that are most likely to offer a commercial opportunity and, therefore, the maps focus on characteristics, such as current heat demand, that indicate likely technical and economic feasibility of a potential scheme. Local authorities clearly possess a wealth of local knowledge about the locations of areas with social deprivation or regeneration requirements, and these were considered informally in many cases. However, the use of such tools to formally build in consideration of wider social objectives of the council had not generally been considered:

"At the moment we've really not looked at how we could deploy a heat mapping tool to community regeneration areas." (Scottish local authority)

The Scottish Heat Map, soon to be launched, is an exception to the use of heat mapping that focuses primarily on techno-economic criteria. The Scottish Government's activity in this area has concentrated on building a heat map for Scottish local authorities that enables consideration of both fuel poverty reduction potential and commercial model potential. This is the best example of a planning tool which enables the construction of a business case for more than just financial benefits. At this stage the map is not yet complete so the role of mapping and its effectiveness for stimulating strategic development approaches cannot yet be assessed, although this is certainly an area for further research.

Gap between use of mapping and motivations of stakeholders

In the context of budget cuts in local authorities and increasing demand on council services [18], district heating projects need a strong business case for them to be given the go-ahead over other competing priorities. Clearly articulated and consistent objectives agreed at a strategic level are essential to enable such a business case to be constructed. The tools offer an evidence base to convince decision makers that district heating is worth investing time or capital in over other projects.

"I think that gives you more evidence and evidence is useful if you're writing applications and trying to make a business case" (English local authority)

The interview analysis indicated that, particularly in England, there is an opportunity for local authorities to adjust their planning and development process to enable a better reflection of their authority's chosen objectives when constructing a business case for a project. The current approach of the HNDU encourages the use of decision criteria to focus on where financial income can be generated for the provider. However, this approach will not always deliver effectively for the alternative motivations, such as fuel poverty reduction.

From the interviews there was a clear mismatch between the motivations of local authorities and the decision criteria that they use to identify feasible sites for DH. The next section explores how current mapping techniques could be adapted to better incorporate these motivations in the decision-making process. It also explores the significance of including data to represent social criteria on district heating planning.

Issues of mapping heat demand

In all of the existing tools and assessment methods currently used the estimated heat demand of an area is the primary metric. There are, however, two issues arising from the use of estimated heat demand as the main criteria for assessing feasible DH sites:

1. It is particularly difficult to assess heat demand for households in fuel poverty, as they, by definition, are suppressing their energy use due to financial constraints. Fuel-poor households, particularly those with low incomes, have lower heat demand per m^2 floor space than non-fuel poor households [19]–[21]. This, therefore, makes them a less attractive area for profit-driven providers to invest in DH. However, if affordable warmth was provided via DH then the actual heat demand may be higher. It is particularly difficult to predict the heat consumption of fuel-poor households since they are more vulnerable to fuel price rises and other financial shocks [4]. This poses difficulties for sizing of systems and predicting their financial pay-back periods, and also the setting of heat tariffs to enable covering of basic maintenance and fuel costs.
2. Heat demand does not give an indication of the energy efficiency of a building. It may be that insulating the fabric of the property is a more beneficial route to reduced energy consumption than provision of district heating.

In addition, heat demand is used to support decisions on techno-economic criteria which, when used on its own, drives decisions toward priorities in these criteria over social factors. Taking these three aspects together means that factors related to fuel poverty are excluded from the decision which means that schemes with potential to address fuel poverty might be overlooked.

For local authorities seeking to develop a robust, commercially viable business case that also meets objectives of reducing fuel poverty we propose that a metric related to heat demand, e.g. housing density, be used instead. This gives an alternative metric of techno-economic feasibility, as it is directly related to demand, but also allows other factors to be represented. Combined with other data on fuel poverty and tenure status, this would provide evidence to build a business case and gain political and stakeholder support for schemes that meet social criteria whilst still including technical and economic feasibility criteria.

Developing a multi-criteria spatial mapping tool

How can mapping tools allow flexibility for local authorities to adapt them to explore a mix of objectives, not just for maximum financial return? To explore this question, a simple mapping exercise has been completed using publically available data sets, including social data, to compare the outputs of existing tools.

First, we explore whether housing density could be used as a proxy for indicating potential technical and economic viability for DH, instead of the current assessment using modelled heat demand. Second, we compare an existing map with one which includes social criteria as an initial indication of how this might change the prioritisation of potential schemes and the construction of business cases that bring multiple benefits.

The mapping has been conducted at a census output area level (approximately 150 households per area). Each area has been scored based on whether it exhibits characteristics to suggest there are technical, economic and social benefits of DH to be realised in that area[2]. Thematic maps are created based on a calculated score for each area. The scoring calculation is summarised in figure 2. Areas within the top 10 percentile for a considered characteristic receive an increased score. When multiple characteristics are considered they are weighted to represent their importance within the business case construction. In this example, where social criteria are added in, for figure 5 the housing density has been weighted as 60%, and social criteria of fuel poverty and index of

[2] Details on how the scoring has been calculated can be found at in the authors report to the funders [23]. The mapping work is available publically through an interactive online tool called the Leeds Heat Planning Tool http://sure-infrastructure.leeds.ac.uk/leedsheat/ .

multiple deprivation are weighted jointly as the remaining 40%.

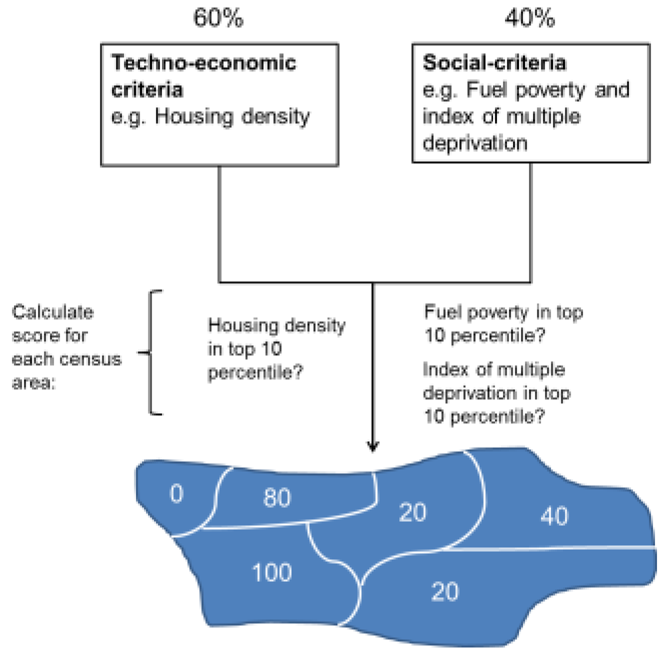

Fig. 2 Summary of how scoring was calculated to assess census output areas in Leeds based upon multiple criteria

DISCUSSION

Comparison of mapping

Three maps of a case study in Leeds, UK are displayed in appendix A for comparison. Figure 3 shows an excerpt from the National Heat Map [11], showing modelled residential heat demand in 2012. Figures 4 and 5 display the alternative maps produced to consider housing density levels and the addition of social criteria.

A comparison between figure 3 and figure 4 shows that housing density gives a proxy for the areas of highest heat demand. There is a correlation between the locations of the areas with the densest residential heat demand on the national heat map and the densest housing. The use of housing density instead of heat demand ensures that the analysis is not affected by issues such as under-heating due to fuel poverty. In addition, the use of freely available data provides a quick and easy means for local authorities to start assessments where more detailed heat demand data isn't available.

The addition of social characteristics into the analysis allows prioritisation of the technically suitable areas. In figure 5 there is a clear priority area that has the potential to achieve social benefits with district heating. This is indicated on the map. This area contains a high housing density combined with households in fuel poverty with high levels of multiple deprivation. When these considerations are not used it is not clear which area might achieve social goals. For a local authority wishing to use district heating for regeneration or fuel poverty reduction this mapping helps to prioritise areas by explicitly reflecting their strategic motivations within the early planning process.

Even with the simple use of open data in this example there is sufficient information to strengthen an early-stage business case. The use of multiple criteria can align the case with the strategic priorities of a local authority and make it more likely to persuade decision makers of the value of district heating for their region.

The role of planning tools in context

We have shown that simple spatial mapping of freely available data may support decision-making in local authorities where the aim is to achieve alternative social value outcomes to those that are solely economic. This represents a first step towards better decision-making to reflect the multiple goals of local authorities. However, we recognise that the development process is significantly more complex than communicating data effectively. It is important to remember that planning tools facilitate a particular mind-set and focus that can exclude others, e.g. in the UK the commercial and the social have been separated. However, it is not necessarily the case that the mere inclusion of socio-economic data within mapping tools would enable local authorities to overcome the overriding context of budget cuts and more urgent priorities for a local authority. It is well recognised within the literature that the surrounding regime and institutions in the wider energy system are just as critical to the successful uptake of a technology as the physical or economic case for a technology in isolation [22]. Planning tools are one way to support actors to negotiate through a resistant regime. We recognise that such tools do not provide the complete solution to such complex problems. However, we argue that they provide an important evidence base to persuade decision makers. The use of tools could in fact be more effective if they were better aligned to the strategic goals of the local authority.

OUTLOOK

We believe there is a need to further understand how such tools are treated and valued within the decision-making process. Our future work will seek to explore whether evidence of social benefits from successful DH projects could be brought into decision-making for future schemes with the broader aim of reducing fuel poverty across Europe. We also propose to broaden the data included within early planning tools to bring an understanding of the context of the wider energy system.

CONCLUSION

DH can offer a range of environmental, economic and social values to the area it serves. These values are perceived differently by different actors. For example, this research highlights the variation in ambitions and motivations for encouraging development of DH between local authorities in the UK. Social motivations such as fuel poverty alleviation featured highly in many authorities' strategic aims for projects, but, for others, DH was an opportunity to create revenue or attract industry and jobs to their area.

The complex process of DH development requires a number of factors to align simultaneously to allow a project to go ahead. Consideration and articulation of the motivations and drivers of the actors involved in developing a scheme is essential to the success of this process. Mapping tools have a clear supporting role to offer in the early planning stages and construction of an initial business case. However, the value of these tools is diminished if they are not aligned to the strategic aims of the decision makers in question.

The methods currently used focus primarily on identifying potential schemes that would generate the maximum financial profit and attracting financial investors to fund the schemes. Although this is an appropriate course of action for some local authorities, for others with more socially driven strategic aims the mapping tools used will not offer the right information to construct a suitable business case.

Tailored specifications for mapping exercises, created in line with explicit strategic objectives, would allow consideration of a much broader set of criteria and data which better reflect the aims of the local authority.

We conclude that, for a particular locality, the potential value of DH could be articulated better through the methods proposed here. The use of simple spatial planning tools, using open data and metrics that reflect heat density (rather than demand) and social criteria such as fuel poverty and deprivation, could be used to build the business case for schemes that would support social as well as economic objectives.

ACKNOWLEDGEMENT

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APPENDIX A

Fig. 1 Extract from the DECC National Heat Map showing modelled residential heat demand in Leeds, UK.

Fig. 2: Map showing census output areas with housing densities in the top ten percentile for Leeds, UK.

Fig. 3 Map showing census output areas scored for high housing density (60% weighting), and two social indicators (40% weighting) of fuel poverty levels and the index of multiple deprivation for Leeds, UK.

LARGE-SCALE UTILISATION OF EXCESS HEAT - ASSESSMENT THROUGH REGIONAL MODELLING

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ABSTRACT

The use of excess heat (EH) in district heating (DH) may contribute to increased sustainability through reduced use of primary energy. In Sweden biomass has become an important DH fuel during the last decades. Currently, there is a strong focus not only on use of biomass in heat and power generation but also for the transport sector. Competition for biomass, as a limited source, is thus likely to lead to higher demand and increasing prices of biomass. This study addresses the long-term system effects and connecting costs of three DH systems though a transmission pipeline that enables an increased use of EH from a large chemical cluster. The assessment is carried out with the optimising energy systems model MARKAL_WS, in which DH systems in the Västra Götaland region of Sweden are represented individually. Options for the production of transport biofuel as one potential competitor for biomass use are also included. The results show that the investment in the pipeline is cost-efficient when our energy system optimization takes both the DH systems and the transport sector into account, resulting in reduced total system cost.

1. INTRODUCTION

District heating (DH) systems represent a structural and organizational energy efficiency measure since they recover low temperature excess heat (EH) from thermal power plants, waste incineration, and industries [1]. The recovered heat is distributed through a heat network to supply residential and commercial buildings and industries with space heating and hot tap water. This heat recovery system could increase the utilization of EH in the European Union (EU27) member states by four times compared to current average levels (9%) [2]. The European Commission proposes strategies to cut 80-95% of annual greenhouse gas emissions by 2050 compared to 1990 levels in the Energy Roadmap 2050 report [3]. The utilization of EH in DH systems would also effectively decrease the cost of this substantial CO_2 emission reductions in the EU energy system [4].

In 2010, DH systems had a market share of nearly 60% (66.5 TWh) of the total heat supply to residential and service sectors in Sweden [5]. The supplied heat originates from different sources. While biomass (including forest residues and energy crops), municipal solid waste and peat combustion contribute to a large share (63% or 42 TWh), industrial EH has a relatively small share of less than 7% (4.5 TWh) of the heat supply. The high share of biomass is due to favorable policies, including energy and CO_2 emission tax on fossil fuels combined with a tradable certificate system for renewable electricity generation. As a result, biomass is used both in heat only boilers (HOB) and increasingly in combined heat and power (CHP) plants.

Biomass is a limited resource which can be utilized not only in DH systems for heat and electricity generation but also in bio refineries to produce transport biofuels. In Sweden, there is now a strong interest in transport biofuel production. This increasing interest in biomass use is likely to lead to competition and consequently higher biomass prices. Therefore, for future sustainable development of DH systems, biomass may be substituted with other heat sources or technologies where this is possible.

Various studies have shown environmental benefits of industrial EH utilization in DH systems [6],[7]. Recently, a total of 21 TWh/year unused industrial EH that could possibly be utilized in Swedish DH systems was identified, of which 2 TWh/year can be utilized directly [8]. Capturing the available potential depends on the willingness of industries and DH companies to collaborate. This collaboration concerns mainly costs and economic benefits, e.g. how to share costs of construction of heat exchangers and heat networks, and how to share the expected revenues.

Parameters that affect the collaboration have been analyzed in several studies. In one study, techno-economic parameters were analyzed and classified as obstacles or facilitators of the collaboration; yet, structure and length of contract and cultural distance rather than geographical distance were identified to be crucial in initiating the cooperation [9]. Parameters that could hinder the collaborations included unwillingness to take risks, imperfect information, asymmetric information, credibility and trust, opposition to change [10], high interest rate and short payback time for investments within industries [8], policy instruments, and international energy prices [1]. In contrast, involvement of universities through building optimization models of DH systems and industries was shown to facilitate the collaboration, resolving the imperfect information parameter [10].

A few studies have addressed economic aspects of industry-DH utility collaborations and assessed the potential economic benefits. For example, EH sources combined with large cities and taxes on fossil fuel use and CO_2 emissions motivates the high investment cost of heat distribution networks in DH systems, increasing the competiveness of DH systems compared to individual heat supply solutions [2]. Heat networks, shared between different stakeholders, including several DH systems and industries, have also been identified to be a promising solution for increased utilization of industrial EH. Ignoring the infrastructure cost, it was shown that under different scenario conditions, most of the stakeholders in a small region in Sweden, including three DH systems and three industries, would benefit from a shared heat network and the total system net benefit was also large [11].

The economic feasibility of potential industrial EH supply from a large chemical cluster in Västra Götaland (VG), a region in the south-western part of Sweden, to DH systems was analyzed and it was shown that the EH delivery could be profitable for a wide range of capacities from a few kW up to maximum of 235 MW, when 10% interest cash flow rate of return in 15 years for capacity investments within the cluster was assumed [12]. In this latter study, only the cost of heat exchangers within the cluster limits, where the EH was purchased by a DH company, was included in the economic analysis.

In this line of research, we expanded the system perspective to include both the DH systems and the chemical cluster in the VG region, accounting for all investment costs within the cluster limits and also between the cluster limits and the DH systems. Mid-term environmental and energy system impacts of a heat connection between the chemical cluster (located in Stenungsund) and one large (Gothenburg) and two small (Stenungsund and Kungälv) DH systems were assessed with a regional perspective [13].

Stenungsund is a small town with a population of about 25.000 people located about 50 km north of Gothenburg, which is the main city in the region with about 530.000 residents. The Mölndal DH system (a part of southern Gothenburg urban area) is connected to the Gothenburg DH system by a 1.1 km transmission pipeline with the capacity of 10 MW. Between Gothenburg and Stenungsund is also the small town of Kungälv with a DH system currently based on a biomass CHP. Kungälv was recently connected to the Gothenburg DH system through a transmission pipeline with a capacity of 19 MW. Currently, the chemical industries supply the Stenungsund DH system with heat; however, their EH capacity is considerably larger than the demand in Stenungsund (see [12]).

Providing a comprehensive view concerning the heat connection in the VG region, this study aims to assess the economic impacts of the heat connection. With a long-term focus, this paper answers to the following research questions with a regional perspective:

- How would the energy system be affected by DH pipelines between Stenungsund and Kungälv/Gothenburg?
- How would the total system cost for DH supply be affected by the construction of DH pipelines between Stenungsund and Kungälv/Gothenburg?

2. METHOD

The method applied is based on scenario analysis and energy system modelling. We design one main scenario and three sensitivity cases. For each of these, we assume two options: either that an investment in the Stenungsund – Kungälv (SK) and Stenungsund-Göteborg (SG) pipelines will not be made ("no connection"), or that the investment in and operation of the SK and SG pipelines will be possible from 2025 ("connection"). Then, we apply an energy system model to generate future developments of the DH sector for each scenario for the "no connection" and "connection" options respectively. Next, we assess the difference, in terms of heat supply and total system costs, between "connection" and "no connection" for each of the scenarios as:

$$\Delta X = X_{Scenario/case,\text{"connection"}} - X_{Scenario/case,\text{"no connection"}} \quad (1)$$

Thus, 'ΔX' presents impacts of the "connection" on the heat supply and total system costs.

Our assessment of the pipeline impact applies two different sectoral perspectives: (1) an inter-sectoral perspective, in which options for transport bio fuel production are included, with synthetic natural gas (SNG), (2) a single-sector perspective, with no bio fuel production option and thus no alternative regional biomass demand, No SNG. The first perspective represents a broader systems approach taking both the stationary energy sector and the transport sector into account where the two sectors are allowed to compete for the regionally available biomass resources. In this way, the assumption of a regional biomass market and the profitability of the investment in the new infrastructure become linked. The second approach is a narrower systems approach, which includes only the stationary energy sector represented by the DH systems in the region. Finally, we compare the two perspectives impacts and reflect on the importance of the choice of existence of a biomass competitor to the DH systems.

With the assumption that the DH sector seeks to minimize the total cost of heat production through the choice of cost-effective technologies and resources, a dynamic cost-optimizing energy system model can be used for estimating the system response to an intervention. To make a regional assessment possible, we need the model to represent the technical and economic aspects of each individual DH system in the VG region.

2.1 Model

We choose a computer-based model to represent the system comprehensively and in a structured manner. The modeling approach enables evaluation and comparison of economic, environmental and technical aspects of studied systems quantitatively under different conditions and scenarios. MARKAL [14], a well-established cost-optimizing bottom-up model generator, comprises the properties required for this assessment. In MARKAL, an objective function minimizes the total system cost within a large number of constraints, generally through linear programming (LP). In this study, we adapt and further develop the MARKAL_West_Sweden (MARKAL_WS) model application. This model, which represents the energy system of the Västra Götaland region, was developed and applied in three earlier studies [13, 15, 16].

The current version of MARKAL_WS has a time horizon reaching between 2010 and 2050 and is divided into nine model periods (i.e. the length of each time period is 5 years). It is comprised of 37 DH systems with different system characteristics, such as demand levels, installed capacities and energy technology options. Each DH system is described in great detail in regard to available technologies and investment options for DH generation. Other parts of the energy system, such as fuel extraction and end-use technologies, are described in a less detailed way. In addition to HOBs, the model representation also includes CHP technologies and bio-refineries with biofuels for transport as main output. Markets for electricity and transport biofuels are defined with exogenously assumed prices to which these products can be sold. The objective function of the model, which is minimised in the optimisation, thus represents the cost of DH generation of the region when credits for sold electricity and transport biofuels are taken into account.

In this version of the MARKAL_WS model, a better description of the EH capacity from the large industrial chemical cluster in Stenungsund is added. We also add investment options for Stenungsund – Kungälv (SK) and Stenungsund – Gothenburg (SG) DH pipelines. The EH is assumed to be available for DH without cost, i.e. any monetary transaction between industry and DH companies as payment for the EH is considered to be within the system boundaries. In the present study, the SK and SG pipelines are studied and the system cost is optimized, including perfect foresight, over 40 years.

In the model, the total cost of the energy system is optimized with regard to an individual demand for DH in each DH system. We assume that the DH demand is independent of price fluctuations. The duration curve of DH is defined by four seasons: summer (5 months), winter (2 months), cold winter (1 month) and spring/autumn (4 months).

We apply the “lumpy” investment option in MARKAL which change the linear LP model into a mixed-integer programming (MIP) model. With a linear model, technologies can be built at any capacity level (thus disregarding economies of scale), while with a MIP model selected technologies can only be built at discrete capacity levels. In this study, the bio-refineries and the SK and SG pipelines can only be built at discrete investment costs while other technologies are handled in a linear manner.

In this paper, a currency exchange rate of 9 SEK=1 EUR is used.

2.2 Model scenarios

In this study, we simulate a scenario with ambitious climate targets in line with a 2-degree maximum global warming and based on the 450 ppm scenario of the International Energy Agency´s World Energy Outlook [17], referred to as the 450 ppm scenario. Energy policies and prices are implemented accordingly.

A model discount rate of 5% is used for all kinds of investments; and the heat demand is assumed to be constant from 2010 to 2050 representing a future where possible expansions of the DH grids equal heat demand reductions due to building energy efficiency measures. Further, the major part of the old refineries in Gothenburg is assumed to be closed in 2025 strongly reducing the amount of locally available EH.

Three sensitivity cases are used to assess the robustness of the model outcomes with regards to parameter values for which future levels are uncertain and of particular relevance for the present study: the level of interest rate for the new investments in the heat exchangers and pipelines, local policies for fossil fuel use and future heat demand. In addition to these factors, the sensitivity cases apply the same conditions as the 450 ppm scenario.

The INTRATE sensitivity case produce a situation where a high interest rate, 11%, and a short payback time,15 years, are required for investments within the chemical cluster, while the interest rate is only 2.5% and the payback time as long as 30 years for investments in the SK and SG pipelines.

The No NG sensitivity case reflects a local political ambition, which asks for phasing out of the NG use in the region until 2030.

Finally, the Reduced Heat Demand (REHD) sensitivity case represents a decreasing DH demand, linearly decreasing by 25% from 2010 to 2050, in line with a recent study [18] showing that a high application of energy conservation measures and heat pumps in the buildings would lead to a 20% decrease in total DH demand from 2007 to 2025.

2.3 Energy markets

Fossil prices utilized are based on the 450 ppm scenario in International Energy Agency´s World Energy Outlook [17].

The energy prices used (from 2010→2050, for DH) are:

- Light fuel oil: 64.7→54.9 EUR/MWh
- Heavy fuel oil: 42 →34.6 EUR/MWh
- Natural gas (large plants): 28.3→18.5 EUR/MWh

Three types of biomass resources are represented in the model: residues from forestry (tops, branches and stumps), energy forest from cultivation on agricultural land, and bio-pellets. Markets for forest residues and energy forests are assumed to have a local/regional character while the bio-pellets market is assumed to be international. The availability of bio-pellets is assumed to be unrestricted due to import possibilities and the prices (from 2010→2050) are 35→87 EUR/MWh, in line with the ENPAC model [19].

Forest residue supply curves, defining the production cost and potential in VG, are included in the model [20, 21]. For simplicity, we model the supply curves as stepwise variations in the production (Figure 1). Energy forest (willow) yields are assumed to 28 ha/GWh [22] and, in the model, its price is based on production costs, 20 EUR/MWh [23]. In 2001, the land use for energy forest cultivation in VG was 900 ha [24]. In the model, this area can increase and in 2050 reach 36900 ha, which is equal to the lay-land available in VG [25].

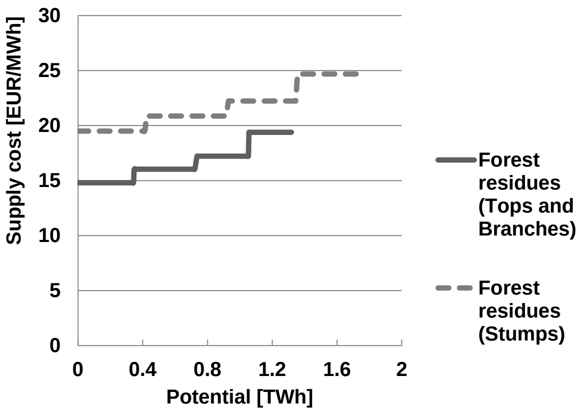

Figure 1- Assumptions of Wood chips/forest residues supply curves (2010-2020) [20, 21].

Since the electricity system is international rather than regional, electricity prices are treated exogenously. In our 450 ppm scenario, we use average electricity prices for each year based on outputs from the ENPAC model [19] . Then electricity prices for each season of a year are assumed to be a function of the average electricity price of the same year. The function is here equal to the difference between the real electricity prices for each season and the average electricity price in 2010 (in percent).

The electricity prices used (from 2010→2050) are:

- Winter cold: 70 →119 EUR/MWh
- Winter: 64 →109 EUR/MWh
- Spring and fall : 50→86 EUR/MWh
- Summer: 36 →61 EUR/MWh

It is assumed that the SNG can be sold as transport fuel at a price equal to 80% of the diesel price at filling station (i.e. including distribution costs for diesel) (from 2010→2050, SNG prices are 73→94 EUR/MWh). The lower price for SNG is in accordance with the historic difference between diesel and gas prices, and compensates for the higher cost of gas vehicles compared to diesel vehicles. Two levels of SNG distribution cost are included in the model representing distribution through the existing NG grid in VG (lower cost) and the construction of a new gas grid in the region (higher cost), see also [15].

2.4 Climate policies

In this regional study, a simplified energy policy situation is simulated: a cost for CO_2 emissions, a subsidy for renewable electricity generation and also a subsidy for transport biofuel. These policies, defined in the model in an exogenous way, are included in all model scenarios. The CO_2 tax is assumed to increase linearly during the studied period from 25.2 EUR/ton CO_2 in model year 2010 to 153 EUR/ton CO_2 [17] in the model year 2050, i.e. at the end of model time horizon. Subsidies for renewable electricity and biofuels are based on historic tradable green certificate (TGC) system costs (20 EUR/MWh) [26] and proposed tax exemptions on biofuels (52 EUR/MWh) [27], respectively.

2.5 Technology assumptions

Technology data of the current version of the MARKAL_WS model is to large extent based on earlier versions of the model [15, 16]. For cost and performance data for HOBs and CHPs, we refer to [15]. The model also includes investment options for potential new bio-refineries for production of SNG assumed to be used as transport fuel. For the assumptions of bio refinery SNG technologies we refer to [13]. For the purpose of this study, additional model development and updates were required with regards to the heat exchangers at the chemical cluster and also the SK and SG pipelines.

The investment cost of building heat exchangers at the cluster for different capacities was calculated for the supply and return temperatures of 80 and 50 degrees respectively [28]. For simplicity, in this model the investment cost of heat exchangers is defined as a linear function of capacity. For the capacities less than 150 MW [28]:

$$\text{Investment cost [MEUR]} = 0.13\text{[MEUR/MW]} * \text{capacity[MW]} \quad (2)$$

It is assumed that the investment in and operation of the SK and SG pipelines will be possible from 2025. In the model, the investment cost of the SK pipeline, 35 km length, is assumed to be 1100 EUR/m for capacities less than 50 MW. Further, the investment cost of the SG pipeline, 55 km length, is assumed to be 2600 EUR/m for capacities up to 150 MW [29].

The circulation pumps required to circulate the hot water in the pipeline produce heat energy by friction in the pipes. This friction heat can be considered as a form of added electric heating and, thus, no temperature drop occurs in the flow direction in the transmission pipelines. The total pumping power required to circulate the water in the transmission pipeline is 0.5% of the heat delivery [5]. The pipeline operation and maintenance cost is assumed to be 0.1 EUR/MWh [30]. In the model, the lifetime of the SK and SG pipelines is 30 years.

3. RESULTS

3.1 Inter-sectoral perspective, with SNG

Even without investments in the new heat exchangers and heat pipelines, the “no connection” option, heat production in the VG region varies drastically over time in the 450 ppm scenario, i.e. from heat production in biomass CHPs and HOBs to heat production in NG CHPs and heat pumps. While the major share of EH from the old refineries in Gothenburg is assumed to disappear from 2025, the biomass use in CHPs and HOBs is reduced (see below). Heat for EH and biomass is replaced by heat from NG CHPs (in particular around 2025-2040) and heat pumps (at the end of the modeling horizon) (Figure 2).

The substantial reductions of heat from biomass HOBs and CHPs occurring between 2015 and 2020 is due to investment in one stand-alone 200 MW bio-refinery SNG production plant in the region somewhere close to the NG grid. This new investment leads to a shift of biomass use from the DH systems to the transport sector due to higher profitability of biomass use in SNG production than in heat and electricity generation when the availability of low-cost regional biomass is limited.

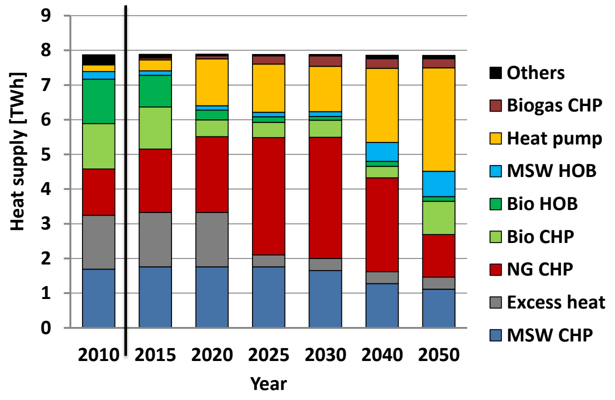

Figure 2- Model results of heat production in the VG region in the 450 ppm scenario, “no connection” (Abbreviations: MSW (municipal solid waste), NG (Natural gas), Bio (biomass), CHP (combined heat and power), HOB (heat only boiler)). Actual heat production in 2010 is shown as reference.

The closing down of the old refineries in Gothenburg in 2025 opens opportunities for investments in the cluster heat exchangers and in the SG pipeline. The models choose to invest in the full capacity available, 150 MW. Figure 5 illustrates that the new EH supply to the DH systems would replace NG CHPs earlier and substitute the heat pumps later in time in the region. These effects are consistent with the model results that, in the “no connection” option of the 450 ppm scenario, NG CHPs have a large share between 2025 and 2030 while the use of heat pumps increase towards the end of the studied time horizon (Figure 2). The new EH displaces biomass in the DH systems in time step 2025 only. The quantity displaced in that time step is too small to allow for an earlier investment in SNG production in the region compared to the “no connection” option. This means that the connection does not affect the SNG production at all according to the model results.

The decreased EH supply in 2030 is due to relatively high electricity prices in this time step which promotes electricity generation in NG CHPs. As a result, a large share of heat is supplied by running NG CHPs, utilizing EH in the DH systems decreases (Figure 5).

Since the heat demand in Kungälv is considerably smaller than in Gothenburg, the existing pipeline between Kungälv and Gothenburg is sufficient to cover the Kungälv EH demand. The model, thus, has no reason to take the extra cost of constructing a new SK pipeline. As a result, all available EH is supplied to the Gothenburg DH system.

Our sensitivity cases show that the EH utilization in the region in 2030 is sensitive to the possible phase-out of NG in the VG region (No NG in Figure 5). When NG use is not allowed, the competition between NG CHPs and the EH stops. Consequently, even at very high electricity prices the full utilization of EH is feasible.

The new heat infrastructure investments (150 MW heat exchangers within the cluster and the SG pipeline) would considerably increase the system cost (net of taxes) of DH supply in the region. The sum of taxes, however, decreases drastically (see Figure 3). This reduction in CO_2 taxes is due to less use of NG in the DH production. It should be noted that the presented aggregation of the CO_2 taxes indicates cost for the DH sector but revenues for the government. In other words, the results indicate that the pipeline is profitable for the companies involved in the cooperation but not for Sweden as a country. On the other hand, the society as a whole benefits from the reduced CO_2 emissions.

The sensitivity analyses on the 450 ppm scenario illustrate that the system cost (net of taxes) of DH supply is highly sensitive to the possible phase-out of NG. Without NG use in VG from 2030, the No NG, considerable cost savings occur as a consequence of the connection due to both reduced need for heat pump investments and consequently reduced electricity demand (Figure 3).

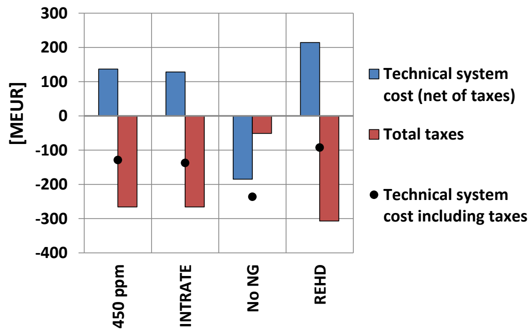

Figure 3- Differences in system cost (net of taxes), sum of taxes and system cost including taxes in the VG region due to the “connection”.

3.2 Single-sector perspective, no SNG

With the single-sector perspective, assuming no alternative biomass use outside of the DH sector (No SNG), biomass CHPs and HOBs supply a relatively large share of heat in the “no connection” option. The reduced EH supply due to the closing of the Gothenburg refineries in 2025 leads to an increased amount of heat from NG CHPs (in particular around 2025-2030) and heat pumps (at the end of the modeling horizon) (Figure 4).

With “connection” allowed, the model invests in a 150 MW capacity (heat exchanger and SG pipeline) but the investments are made in 2035, 10 years later than with the inter-sectoral perspective applied (Figure 5 and Figure 6).

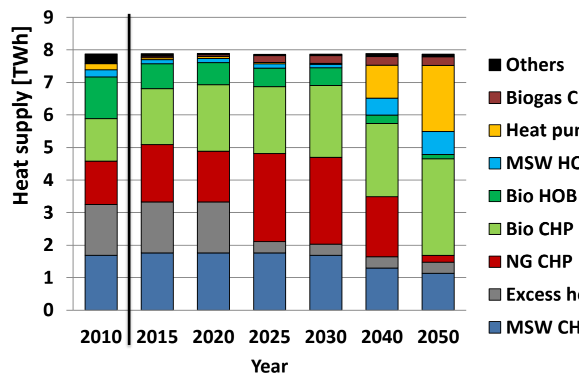

Figure 4- Heat production in the VG region in the 450 ppm scenario, the single-sector perspective and “no connection” (Abbreviations: MSW (municipal solid waste), NG (Natural gas), Bio (biomass), CHP (combined heat and power), HOB (heat only boiler)).

Figure 6 illustrates that the new EH supply would replace NG CHPs and heat pumps rather than the bio CHP production (compare with Figure 4).

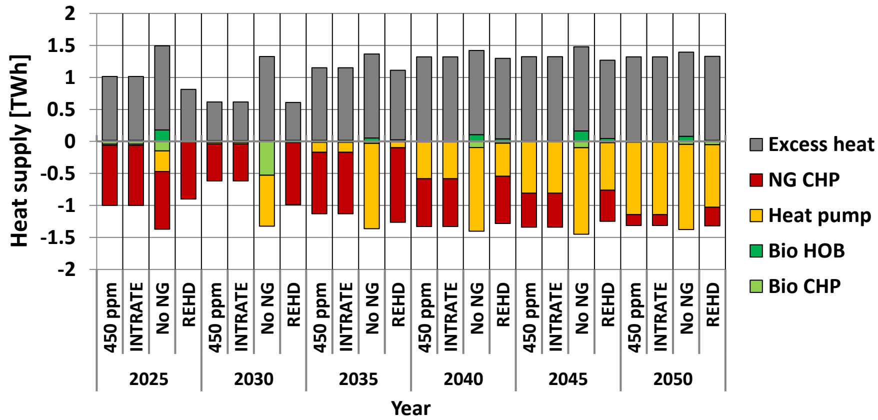

Figure 5- Differences in heat production in the VG region due to the “connection” (the positive and negative numbers show increase and decrease in heat supply from different technologies respectively).

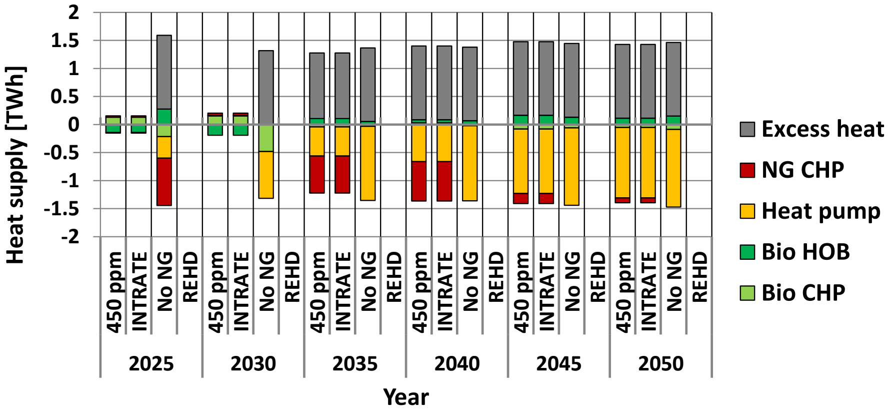

Figure 6- Differences in heat production in the VG region (with the single-sector perspective) due to the “connection” (the positive and negative numbers show increase and decrease in heat supply from different technologies respectively).

Our sensitivity analyses show that the utilization of the new EH in the region is sensitive not only to a phase-out of NG and but also to the heat demand levels (No NG and REHD in Figure 6). When NG is not permitted in the VG region, the EH utilization occurs 10 year earlier than in the other cases. In REHD, the model choose not to invest in the SG pipeline due to the reduced competition for biomass (in the absence of transport bio fuel/ SNG production) combined with the heat demand reduction in the region, making the pipeline investments infeasible.

The system cost (net of taxes) of the DH supply and sum of taxes would be affected similarly to the inter-sectoral perspective. However, the reduction in the total system cost including taxes is less compared to the inter-sectoral perspective (the black dots in Figure 3 and Figure 7).

The sensitivity analyses on the 450 ppm scenario illustrate that, similar to the inter-sectoral perspective, the system cost (net of taxes) is highly sensitive to the phase-out of NG (No NG in Figure 3 and Figure 7). In addition, the reduction in the total system cost including taxes with the single-sector and inter-sectoral perspectives are equal (the black dots the No NG in Figure 3 and Figure 7).

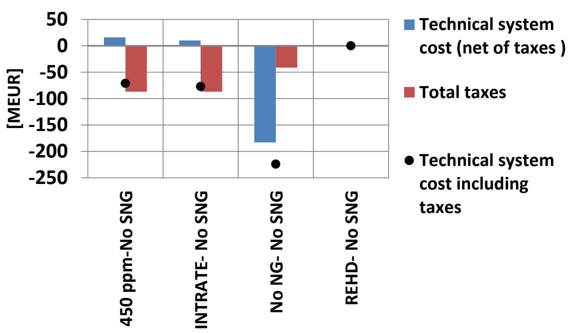

Figure 7- Differences in system cost (net of taxes), sum of taxes and system cost including taxes, in the VG region due to the “connection” (with the single-sector perspective).

4. DISCUSSION

The heat supply optimization in the entire VG region including investment options for the use of EH from the Stenungsund chemical cluster in DH systems leads to new investments (in heat exchangers within the industrial cluster and in the heat pipeline between Stenungsund and Gothenburg) in most but not all of the tested cases. These investments depend both on the scenario assumptions and on the energy system perspective applied. When investment options for transport biofuels are included in the regional heat supply optimization, the new investments are cost-effective. However, when regional heat supply optimization ignores the alternative regional biomass demand (represented as transport biofuel production), the heat infrastructure investments are infeasible in one of the sensitivity cases applied, when the heat demand declines.

In our model, in the absence of the EH from the Steungsund chemical cluster, the DH systems in the region would increase the use of biomass, NG, and electricity to meet the heat demand. Since the limited biomass in the region can be used in transport bio fuel production, the DH systems would be more dependent on imported NG and electricity. Both of these fuels are associated with an extra cost, as the CO_2 emissions tax, for the DH companies. The NG is utilized in CHP plants, producing the by-product electricity that would increase the income of DH companies with rising electricity prices. However, the dependency of the DH systems to the imported NG also jeopardizes supply continuity. In addition, local political decisions for phasing out fossil fuel use in DH systems might prevent investments in any new CHP plants and shut down the existing NG CHPs. These challenges with the use of NG and electricity in the DH systems also support the investment in the new heat pipeline in the region.

The result of our study shows that over 1 TWh/year of energy could be saved in the region. This energy saving also increases the competitiveness of the chemical cluster compared to similar industries not having access to the infrastructure to sell their EH. This extra revenue for the cluster is combined with reducing their cost of cooling down the EH, and avoided cost of CO_2 allowances since EH supply to DH system is qualified for free allocation of CO_2 allowances according to the EU-ETS post 2012 [31].

The chemical cluster currently uses fossil fuels as its energy source. It is argued that the utilization of the EH from fossil fuel sources in the DH systems is against very ambitious emission reduction efforts in other sectors; i.e. transport and power sectors. Our study results illustrate that the EH would replace large amount of NG use in the DH systems, decreasing local CO_2 emissions.

The profitability of EH supplying industries may change with time, and a decision to close down production facilities, or considerably lower production, would result in a loss of heat supply to the DH systems. In this way, EH collaborations imply increased supply uncertainty. This could be dealt with in two ways; either, when the industries are willing to take a large share of the common pipeline investments; or when industries make other large investment in their facilities for totally different purposes. Such actions be interpreted by a DH company as a kind of guarantee indicating less risk that the industry is going to shut down in a near future [9]. In our case, the Stenungsund chemical cluster has plans for investments aiming at sustainable chemistry by 2030 [32]. This would apparently decrease the risk of DH supply uncertainties.

Our model results highlight the importance of an inter-sectoral perspective in energy system analyses. The investments in the new infrastructure in the DH systems, which were cost-effective under various conditions with a regional and an inter-sectoral perspective, became uncertain with a regional but single-sector perspective.

The MARKAL model applied in this study becomes short-sighted at the end of the time horizon (i.e. 2040-2050) since beyond the model time horizon running costs are not taken into account. This resulted in the large investments in heat pumps in the last model years. Therefore, we acknowledge that the model results towards the end of the studied time horizon are rather uncertain.

The presented study is using a specific EH resource and the region of Västra Götaland as our case. The same method can be applied to other EH heat resources and regions but the outcomes of the study are obviously highly case dependent.

5. OUTLOOK

The results presented in this paper are still at preliminary stage. For the future work biomass prices will be scrutinized. Further, a second main scenario will be analysed, in which instead of ambitious climate targets, current existing or decided political climate targets would be in place until 2050. Other sensitivity analyses (e.g., on the investment costs, the interest rates, excess heat supply levels from the chemical cluster) will also be developed to address the future uncertainties of the large scale EH supply from the Stenungsund chemical cluster in the DH systems in the VG region.

6. CONCLUSION

The main conclusion of our study is that investments in the new infrastructure required to utilise the large scale EH from the Stenungsund chemical cluster in the DH network of Gothenburg are cost effective and lead to the reduction of total system cost in the DH systems of the VG region in the long term with an inter-sectoral approach applied. The profitability of the investments in the new heat exchangers within the cluster and the heat pipeline between the cluster and Gothenburg depend on the system perspective limits and the degree of other regional biomass competition.

Since regional low-cost biomass availability is constrained, excluding the transport bio fuel (SNG) production (an example of competitor to DH systems for biomass use) from our regional perspective somewhat decreases the profitability of the investments in the new infrastructure due to relative abundance of biomass use in the DH supply. A reduction of heat demand in the region reinforces the lower profitability of the new investments in the absence of the competitor, avoiding any investments within the cluster and in the SG pipeline.

The infrastructure investments would change the DH supply in the VG region both in the short and long term. In most cases analysed, the EH utilisation would replace NG CHPs and heat pumps.

ACKNOWLEDGEMENTS

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COMMON LOCAL RESOURCE MANAGEMENT AS A POSSIBILITY TO DEVELOP DISTRICT HEATING IN NEW AREAS

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ABSTRACT

Sweden started early to develop district heating (DH) in urban areas. DH is the main heat source for multi dwelling buildings (MDB) with an approximate connection rate of 85% in 2013. This level does not leave much space to connect more MDBs to DH as the low hanging fruits have already been picked.

Most of the remaining MDBs are smaller units and/or located in areas with a low building density that are dominated by single houses. Other countries such as Denmark have successfully connected areas with single houses to DH but in Sweden the connection rate of single houses is as low as 15%. Therefore this area provides a potential focus for improvement by implementing a new management system based on the well established model of private road management (enskilda vägföreningar) to improve financial resources in such areas.

The majority of DH systems in Sweden were developed by municipalities when more financial resources were available. Today, economic resources are much more limited in both municipal and private DH companies, and costly projects with long payback times are hard to implement. On top of that, the establishment of new DH systems involves a time consuming and costly decision making process. New investment models are necessary to facilitate the establishment of new DH systems.

The aim of this paper is to investigate how the private road management model can be transferred to establish and finance local DH grids or systems. This could be a stand-alone system or a subnet connected to an already existing network.

DH companies select their investments with respect to resource constraints and choose the most profitable option, while local housing associations, similar to local road associations, prioritize to manage necessities in a more efficient way.

When local property owners finance and manage the DH project by means of common local resource management, the financial burden can be split and carried by those who benefit from the investment. Housing owners who are not only connected to a DH system but also own (parts of) it are more interested in the local heat supply system. This increases the acceptance and has a positive effect on connection rates.

INTRODUCTION

Sweden started early to develop district heating (DH) in urban areas. In the beginning of the development the focus was on connecting together one MDB area's central furnace to the other in order to capture the biggest heat consumers within the central part of the city to a common DH grid, thereby bundling the total heat production at one central furnace facility.

As a big share of the initial MDB were municipality owned, one could also see this process as one of the first outsourcing processes to bundle the heat production in one place, with a central management often placed under the municipal grid company. Often even bigger housing complexes with many MDB were served by an internal heat supply piping system, which reduced complexity and investments for the DH companies.

At that time it was important to convince large building owners to subscribe rather than collecting subscribers on a building by building basis. (Municipal) housing company's decision structures were straight forward compared to cooperative housing associations which were time demanding.

DH companies were very flexible at that time on the conditions to connect large consumers on one hand, and DH and housing companies received government subsidies and loans which fostered the development [1].

Additionally, it was the time of oil boilers and the oil crisis was initiating the shift towards DH and renewable energy. Oil was still fired over a long time in DH facilities. Later in the 1990s, this procedure occurred again, this time to connect the remaining MDB furnaces when local DH companies where buying of the heat furnaces (often oil furnaces) of many housing companies in order to connect them to the local DH grid. Single houses and single house areas have been neglected over long periods even when the DH grid passed the housing area.

Some municipalities had high ambitions to connect single house areas and succeeded with that while others have failed. Even the availability of waste heat from local production was not always integrated within the local energy supply, as the example of Kiruna shows were the local mining company is dumping heat that could supply the whole city.

DH is the main heat source for MDB with an approximate connection rate of 85% in 2013 [2]. This level does not leave much space to connect more MDBs to DH as the low hanging fruits have already been picked.

Today most of the remaining housing stock is located in the localities around the core locality where the DH boiler is located and single house areas within the core locality. Expending DH to further municipal localities is expensive and does not have a high level of success. Many housing owners are positive towards DH but did not want to lose the alternative to switch fuels when connected to DH. Today, new subscribers are not keen on to dismantling and removing their previous boiler as they still want to have the choice to switch to the most economically heat supply available, similar to DH companies. Single houses have shifted their heating fuels a couple of times depending on the political mainstream, mainly from oil to electricity and then biomass, namely pellets, which mainly using the old boiler from the time the house was built.

STATE OF THE ART

Other countries such as Denmark have successfully connected areas with single houses to DH but in Sweden the connection rate of single houses is as low as 12% [3]. In the current situation the increase of heat pumps and biomass is squeezing out DH. To change this trend it is necessary to find new ways to improve the benefits of DH and to integrate the local population in this process.

Therefore this area provides a potential focus for improvement by implementing a new management system based on the well established model of private road management (enskilda vägföreningar) to improve financial resources in such areas.

Henning & Lorenz conclude, depending on their investigations, that approximately 10-50 percent of the single house owners in areas where the DH sees a potential are not interested in connecting them to DH [4]. There is a broad diversity of alternative heating systems for single houses so that a local dominance for one system is hard to reach. Additionally, all houses have an existing heating system with an unknown remaining service life. Compared to single house heating solution, this is the most disadvantage for DH as it become efficient when the majority in an area gets connected to the system. The above focused aspects have not yet considered the trend towards LEB, which reduces the heat demand in the area drastically so that the profitability of a DH network is dependent on the proper design for the area.

In spite of the gloomy outlook, there are lots of possibilities to establish DH in new areas. Most of the remaining MDBs are smaller units and/or located in areas with a low building density that are dominated by single houses. This provides a mix of different heat demand profiles – single houses and MDB and public buildings – where some large consumers with a need for a renewal of the heating system can be the initial starting points for local DH. These startups will be mainly established in existing and fully developed built up areas and they need to be optimized to meet the requirements of the area and to reduce losses to a minimum [5].

Reasons and consequences of the chosen path

The majority of DH systems in Sweden were developed by municipalities when more financial resources where available. The development of DH was a political decision which was supported from the government through grants and loans, and even subsidies for those who were shifting to DH.

The government divided the market in two segments: the dense urban areas where the municipalities were establishing DH, and the state owned power company, which was responsible for connecting the rest of the country with electric power, even for heating. This chosen structure was resource efficient and increased energy efficiency, which is an important aspect of sustainability for most governments [6] when creating energy policies for a more environmental conscious system, which is still valid today.

This worked for a number of decades until the power prices increased and the development of the heat pump changed the market. Today it is hard to leave that path; the political framework has approved that concept for a long time and changes are slow [7] as there is a more stringent split between single houses and MDB areas so that, compared to other countries, a formal segregation between those two types of dwelling exists. There are very few housing areas with a mixed housing structure and few small MDB houses in smaller localities. The connection rate of MDB shows that most of the MDB are located together, which in turn was also supported by the million housing program. On the other hand, this creates difficulties to connect the remainder, which the decrease of the line heat development shows.

The increasing establishing cost for DH and the decreasing heat demand in the housing stock makes it difficult to develop DH in new places even considering that technological developments have opened for connecting even sparsely populated areas as the fourth generation of DH shows. In comparison to technological developments that lead to technical transitions caused by different impacts [8], a structural change will lead to structural transitions how small grids can be managed.

Today, economic resources are much more limited in both municipal and private DH companies, and costly projects with long payback times are hard to implement. On top of that the establishment of new DH systems involves a time consuming and costly decision making process. New investment models are necessary to facilitate the establishment of new DH systems.

Transferring the private road system to DH

What are the effects of establishing a similar framework like the private road management model for DH grids?

Sweden has a long history in managing roads in joint property management (JMA) where the local community owns the road system and is responsible for maintaining it [9]. The legal framework is recognized by the Swedish system and is funded by the state because it is regarded as beneficial for maintaining the national road network. The management is assumed to be cost efficient and the layout allows identification of needs that can be supported from the government when it is assumed that it fulfils a social purpose the state cannot provide as cost efficient. The framework provides a lot of experience linked to common pool resource management and building up a framework implementing the Design principles for Common Pool Resource (CPR) institutions [10] would straighten the position.

LIMITATIONS OF THE PAPER

In this paper we limit ourselves to effect on the investment side of DH grids. The theory of the interaction of common pool resource transfer to DH grids has to be discussed in a broader context in a separate paper.

In a further step, it has to be investigated how the private road management model can be transferred to establish and finance local DH grids or systems. This could be a stand-alone system or a subnet connected to an already existing network.

The joint property management of private roads is resource efficient on one side and subsidized in general by the state. The resource efficiency derives from the need of a road infrastructure at cost price and with a lean management.

DH companies select their investments with respect to resource constraints and choose the most profitable option, while local housing associations similar to local road associations prioritize to manage necessities in a more efficient way.

THE CONCEPT METHOD

Knowledge is strongly established in a local context, but its transfer across national borders is limited. The same limitations exist regarding knowledge transfer between different disciplines or technologies – in this case, the transfer of experience from civic road management to the DH development.

The development of DH has reached a limit where traditional expansion mechanisms in areas with a low heat line density have become less and less profitable. Different strategies are necessary in order to establish new DH systems.

The goal of this paper is to provide insights into the experiences from other fields of competence and across national boundaries to develop an adapted framework for establishing new DG grids that can be implemented on a national and international level.

This paper examines new investment and ownership strategies for DH in neighbourhoods with single houses where the local distribution grids are financed and owned by the local community, alone or together with a DH company. Thus, the DH system is split into two parts: the heat generation plant and the main grid, being owned and operated by the DH company, and a local DH grid with community involvement.

The establishment of DH has been an ongoing process for several decades. Today the most feasible projects have been realized and further development is associated with high initial investments and a low return on investment (ROI) due to a low heat line density in the remaining areas, which contain a higher proportion of single houses. Establishment of new district heating grids in areas with single houses is difficult since DH companies have a limited investment budget which will be allocated to the investments with the highest ROI.

It is not necessarily unprofitable to establish DH in most areas with single houses, but there is a risk that the investment will not be profitable if traditional DH structures are used. The largest investment requirement for any new DH system is the construction of a new DH grid. Therefore, it is necessary to find alternative possibilities for outsourcing or co-financing this part of the system.

Traditionally DH grid and heat production is owned by the DH company. Consequently this results in the investment decision demanding the same ROI for both investment parts. Huge amount of limited resources are locked in a few number of investments which have to be compatible with all other investments in the firm but also as save and reliable as the other investments. The long term commitment to invest in a DH grid is binding up huge resources so that it might be beneficial to leave this investment to investors that demand a lower ROI than the DH firm. This creates a greater freedom to invest in more projects and in the part that has a high ROI, heat and power production. It also opens to establish more new DH networks with a better compatibility.

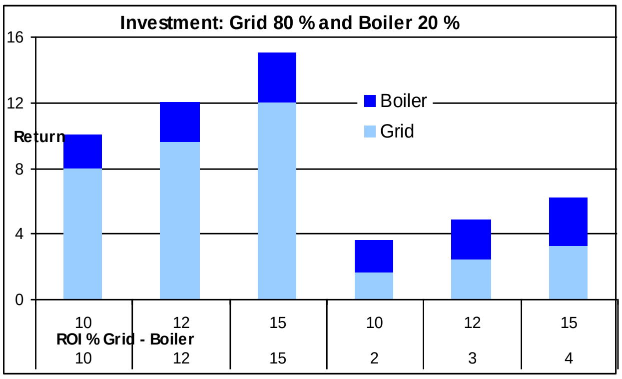

Fig. 1: Change of total ROI with different ROI for grid (80 %) and boiler (20 %)

In two examples, it was assumed for the first example that the grid establishment demands 80 percent of the total investment resources while the boiler only consumed 20 percent. In a second example we assumed that both demanded half of the investment costs. Furthermore, it was assumed that ROI demanded by the DH firm is 10, 12 or 15 percent while the local administration demands 2, 4 or 5 percent ROI. Alternatively it could also be argued that as the heat supply normally demands cost, no profit is expected at all from the local subscribers, who are also the grid owners.

In the 80/20 example (Figure 1) the three bars at the left show the return when the whole investment is done by a DH firm while the three bars at the right side show how much the total return has reduced by reducing the ROI for the grid. The fixed costs are reduced by approximately 60 percent compared to the traditional set up.

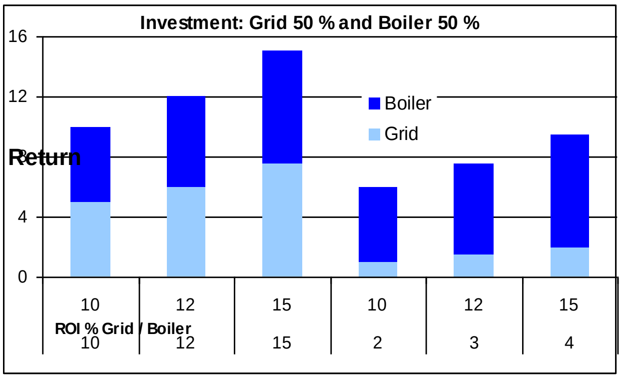

Fig. 2 Change of total ROI with different ROI for grid (50 %) and boiler (50 %)

In the 50/50 example (Figure 2) the three bars at the left show the return when the whole investment is done by a DH firm while the three bars at the right side show how much the total return has reduced by reducing the ROI for the grid. The fixed costs are reduced by up to 50 percent compared to the traditional set up.

Depending on the grid length, the share of the grid cost increase compared to the boiler house.

RESULTS

This paper shows that it is feasible to implement new DH grids, even in areas with a low heat line density. This will have a positive impact on the development of DH in areas which are mostly not connected to DH today, i.e. areas with a large share of single houses.

This topic is also significant for the development of fourth generation DH as it faces the same challenges with regard to the high initial investments required.

How the two parties divide the different ownership - financing, ownership, administration, and organization - is depended on individual goals of the local stakeholders.

The results also show that the cost for the investment can be drastically reduced. As the investment in the grid and boiler represent the fixed cost of the system this lead to drastically reduced heating cost that the customers and grid owners can participate while the DH company still is fulfilling its investment goals

DISCUSSION

In order to identify mechanisms and tools that can be used to manage DH grids with community involvement, the experience of civic road management in Sweden helps as the knowledge needed for creating such a framework is available.

The separation in grid and boiler is a possibility to become more competitive to alternative heating systems. It also provides a sense of belonging to the grid owners, which makes them more likely to participate.

This is a possibility for local DH development where competition with heat pumps and pellets burners is massive and the success is dependent on the number of properties connected to the new grid rather than the size of the network.

OUTLOOK

The possibilities to adapt a framework similar to the civic road association facilitates the establishment of similar structures for DH. Structures that are familiar and where the experience of one system can be transferred reduce the burden significantly. This reduces risk of failure and it makes the establishment much easier since the lessons learned from the civic road system can help to create a reliable system from the start.

More than half of the Swedish road network is managed by joint property management associations for civic roads (vägföreningar) who are supported by the Swedish state to carry out this task. This management of a common pool resource can also be regarded as local/urban governance. The joint property management (samfällighetsförvaltning) is administered by the Swedish mapping, cadastral and land registration authority.

State involvement in the development of new DH can with such a framework, be formulated to foster new DH in sparsely populated areas to increase new DH grids that are not easy to establish. Involving more participants in the establishment provides more possibilities to increase DH.

The design of a legal framework for split ownership and management of DH systems needs further research into which requirements are necessary to establish a similar organizational and legal framework equivalent to the one of civic road management and how this framework can be implemented in Sweden, as well what possibilities for implementation in other European countries could be.

CONCLUSIONS

When local property owners finance and manage the DH project by means of common local resource management, the financial burden can be split and carried by those who benefit from the investment. Both parties benefit from the establishment of the DH network: the property owners, by being able to install a reliable and cost efficient heat supply that fulfils their needs at low costs; and housing owners, who are not only connected to a DH system but also own (parts of) it and who are more interested in a local heat supply system. This increases the acceptance and has a positive effect on connection rates

For the participating DH Company the investment becomes smaller and less risky, but not less profitable.

The setup also leads to lower heat costs as the financing of the grid is done by the local heat subscribers and therefore, it is rather an investment necessary to fulfil the proper functioning of the dwelling than an investment that get a ROI. In general the grid owners would also be satisfied when the cost for the grid would be zero as they value it as a basic necessity for their property to function.

This research will open up new possibilities to implement DH and make DH more feasible in areas with low profitability. Split ownership and management will create new possibilities for DH. This concept takes in external investments and frees the DH company from the investment burden for less profitable grids.

Regarding possibilities to expand DH in areas where profitability is often marginal and investments are done due to political goodwill, this creates great opportunities to establish DH in new areas. For the DH company, this engagement in DH differs from the traditional one, as it has a stronger focus on the core business with a higher ROI, rather than owning small grids. Local communities benefit from this development since the housing owner gains access to a more economical and reliable heating solution.

With this new concept, the investments for each DH network involvement will be smaller, the risks lower, and the ROI higher than with comparable traditional ownership and management of DH grids. The range of responsibilities depends on the local agreement and involvement of the DH firm.

How much the DH sector can benefit from this research is dependent on the extent to which the experience from the road management can be transferred to DH. There is a good potential to facilitate local participation and investment of the housing owners who need to be connected to a DH grid.

This could be seen as a critical development by some established DH companies, but under the consideration of the core business of DH companies the ownership of non-profitable grids should not be included. The change in the layout makes the involvement of the DH company more profitable as a different group of owners (who see the grid as a necessity instead of a profit-driven investment) does not demand the same ROI, and because of this, the implementation as a whole becomes more profitable and feasible.

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MULTI-OBJECTIVE OPTIMIZATION OF THE DESIGN AND OPERATING STRATEGY OF A DISTRICT HEATING NETWORK - APPLICATION TO A CASE STUDY

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ABSTRACT

In this study, a methodology and computer tool were used to define a set of optimal solutions for the design and operating strategy of energy conversion technologies for district heating network. The method is multi-objective, as the optimum are found with regard to economic (heat cost) and environmental (CO_2 emissions) criteria, and multi-time, as the optimum are found for a whole year instead of a single operating point. The proposed method helps the decision maker to answer the following questions: which type and size of heat production technologies - and with which set of available primary energy - are best suited for the district for current and future demand? Which operating strategy is to be followed? The methodology has been applied to a test case on a district heating network in France, where the aim is to find the best solutions to respond to an increase in heat consumption and loss of one combined heat and power plant.

NOMENCLATURE

$C_{s,t}$	Linear cost of equipment *s* at time-step *t* [€/MWh]
$F_{min,s}$	Technical minimum of equipment *s* as a percentage of maximum power
$F_{s,t}$	Utilization of equipment *s* at time-step *t* [MW]
HP	Heat price [€/MWh]
$I_{s,t}$	Linear impact of equipment *s* at time-step *t* [tCO_2/MWh]
M_{CO2}	CO_2 content [gCO_2/kWh]
Q	Input or output stream multiplication factor
t_{CO2}	CO_2 taxes [€/tCO_2]
U_s^{min}	Minimum unit size [MW]
U_s^{max}	Maximum unit size [MW]
U_s	Continuous variable for sizing of equipment *s* [MW]
Y_s	Binary variable for selection of equipment *s*

INTRODUCTION/PURPOSE

District heating networks (DHN) contribute to reach the goal set by the European Commission of “3x20”: 20% less CO_2 emissions, 20% higher efficiency and 20% renewable energy by 2020. Indeed, due to its larger scale, DHN can help use renewable energy and waste heat recovery more easily and also improves the overall system efficiency.

However, there are many different technologies that can be implemented on a DHN, and the best solution is not trivial. Indeed, this depends on the objective sought (low cost, low investment, high efficiency, low CO_2 emissions etc.), on local resources (solar irradiation, biomass, geothermal sources, industries, gas distribution etc.) and economic context (fuel costs, technology costs, government incentives etc.), as well as on the type of clients (residential, commercial, office etc.) and construction density. Optimization can be an extremely useful tool to identify optimal solutions among a large set of possibilities, based on various criteria (economic, environmental).

A methodology based on multi-objective optimization and taking into account the supply, distribution and demand of DHN simultaneously was developed and applied to a case study.

STATE OF THE ART

As can be seen in Connolly et al. [1], there are many existing energy simulation and optimization tools covering a large variety of problems and contexts. Some of those tools can only be used to simulate or optimize the electric sector, especially at a national scale (Aeolius, EMCAS, EMPS, GTMax etc.), and do not include heat. Other tools cover the heating sector, but are used at a national or regional scale (EnergyPlan, MARKAL/TIMES, ENPEP-BALANCE, MESSAGE, IKARUS, PRIMES, etc.), and not at the district level. Also, some tools only provide a technical evaluation, but without a complete economic evaluation including both operating costs and investment cost (Aeolius, H2RES, SimREN). Moreover, many tools are used to simulate or optimize a certain type, or limited number, of technology, and not a district heating network with different type of production equipment (energyPro, COMPOSE, RETScreen, BCHP Screening Tool etc.).

Some optimization tools which can be used at the DHN level have been identified (Balmorel, Invert, LEAP). However, they are not multi-objective.

The review in Fazlollahi's thesis [2] showed that several gaps had to be addressed, such as:

- the simultaneous optimization of the supply side, distribution and demand side
- a multi-objective optimization model for designing the layout of the distribution network and transportation of resources, taking into account the temperature levels
- a solving strategy with acceptable resolution time for optimizing the size and operating strategy of a DHN
- a global sensitivity analysis to select robust and reliable solutions
- a flexible computational tool for implementing the methodology

METHODS/METHODOLOGY

An illustration of the developed methodology is shown in Fig. 1. It can be split up into three main phases:

- Structuring phase: The required data is collected and put into form - using the appropriate syntax - to be used in the following steps.
- Optimization phase: The configuration and operating strategy of the DHN model is optimized with respect to multiple objectives (cost, CO_2 emissions) by varying a set of decision variables. A set of solutions characterizing the Pareto frontier are obtained.
- Post-processing phase: The solutions obtained in the optimization phase are analysed using specific graphs, and sensitivity analyses can be carried out. This analysis will help decision makers choose the optimal solution.

Structuring phase

As can be seen in Fig. 1, the data required to solve the optimization problem are:

- A list of the existing production and distribution equipment on the DHN, with their main characteristics (energy sources, maximum and minimum power, thermal and electrical efficiency, coefficient of performance, electricity consumption, operating period, fixed and variable operating costs, investment costs). In the case of a new network, no data is required (all equipment will be new).
- A list of the (new) available equipment to be used in the optimization, with their characteristics. In addition, the maximum power range of the equipment has to be specified. Furthermore, the investment cost has a fixed part (dependant on the presence of the equipment) and a variable part (dependant on the maximum power).
- The network's heat demand profile. This profile consists of 8760 hourly values representing a standard year. To simplify the problem and reduce calculation time, the hourly profile is converted into a limited number of typical days, each with a limited number of segments. The typical days and segments have to be chosen in such a way that the yearly demand profile is well approximated (see Fig. 3 and Fig. 4). Typical days are also used to define operating periods of certain equipment, such as combined heat and power plants. A description of the methodology used to define typical days is given in [3].
- The available fuels / energy sources (maximum yearly availability and instantaneous available power) and their characteristics (cost, CO_2 emissions).
- Additional operating constraints, such as equipment priority or minimum annual usage.
- The general economic parameters (project lifetime, interest rate, subsidies and taxes).

Optimization phase

The optimization can be sub-divided into 4 main steps:

- Master optimization
- Thermo-economic simulation model
- Slave energy integration optimization
- Environomic evaluation

The master optimization consists in minimizing the two objectives (heat price and CO_2 content) by varying the decision variables associated with the power (U_s) and presence (Y_s) of each available equipment. The CO_2 tax (t_{CO2}) is an additional decision variable which allows to take into account the environmental impacts in the slave optimization. This is achieved by using an evolutionary, multi-objective algorithm. A more detailed explanation of the algorithm is available in [4].

For each iteration, the master optimization sets the decision variables (U_s, Y_s, t_{CO2}), which fixes the configuration of the system (type and size of each equipment), and passes it down to the thermo-economic simulation model. The latter determines the thermo-economic state of the system at each time segment t (i.e. the multiplication factor of input and output streams Q for each unit (see Fig. 2), the linear terms for the operating costs $C_{s,t}$ and CO_2 impacts $I_{s,t}$ of each equipment and the operating boundaries of each equipment) using the decision variables, the technical, economic and impact characteristics of each equipment, and the values of variables for each time step such as the heat demand.

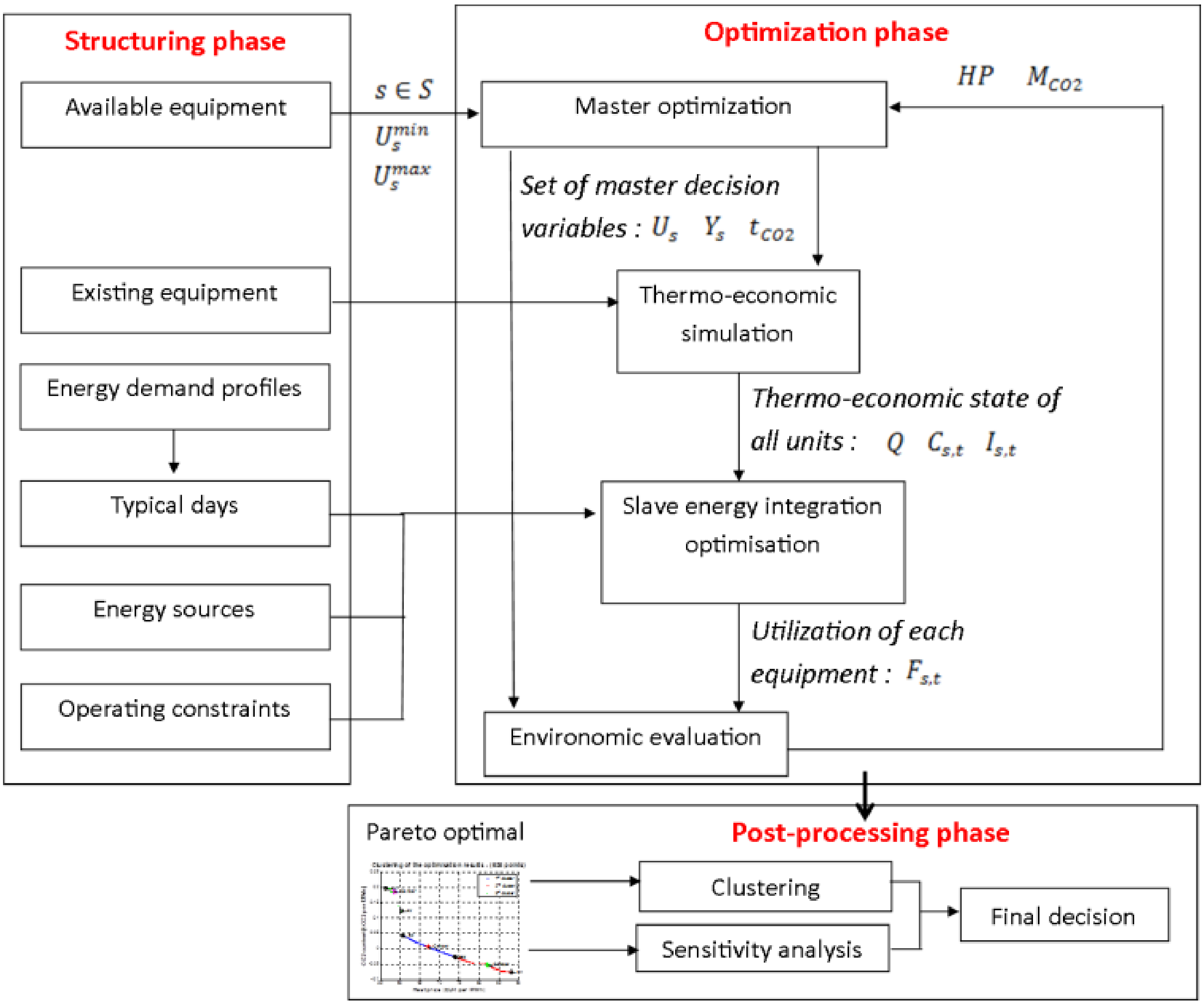

Fig. 1 - Illustration of the developed methodology

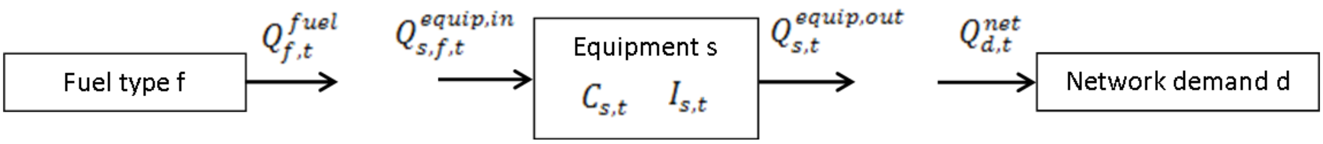

Fig. 2 - Illustration of units and streams in the model

This information is then passed on to the slave optimization, which aim is to minimize the operating costs by fixing the utilization $F_{s,t}$ (in MW heat output) of each equipment *s* for each time segment t within a given boundary (between $F_{min,s}*U_s$ and U_s), while respecting the balance equations and constraints. A balance equation is applied to each layer of the model (there is one layer for each fuel type and an additional layer for heat).

The knowledge of the utilization of each equipment at each time segment, obtained through the slave optimization, permits the calculation of the objective functions (heat price and CO_2 content). The heat price takes into account the fuel and electricity costs (P1), the operation & maintenance costs (P2/P3) and investment costs (P4) of the equipment and network, structural costs, taxes, subsidies, and operators' profit. CO_2 taxes are however excluded.

The objective functions are sent back to the master optimization and evaluated. The master optimization then modifies the decision variables and runs another iteration. The number of iterations depends on the complexity of the case (i.e. number of decision variables) and has to be specified by the user at the beginning.

Post-processing phase

The aim of the post-processing phase is to analyse results once the optimization phase has been completed and reached the Pareto optimal frontier. The Pareto frontier is a trade-off between economic and environmental targets, and can support decision making for selecting the optimal system configuration. As each solution included in the Pareto frontier is optimal with respect to the chosen objectives, it is not obvious which solution is the best. Additional tools, also developed in the model, can help give additional information, such as automatic clustering of results by similar configuration and global sensitivity analysis.

RESULTS

The developed methodology has been applied to a case study on an existing DHN in France, used to supply heat and domestic hot water to mostly residential buildings, and a few administrative and office buildings, as well as a school. The network has to face two major changes:

- Firstly, there will be a network extension and new clients will be connected, leading to an increase in heat demand.
- Secondly, the currently installed combined heat and power (CHP) plant will have to be replaced, as the contract with the power company which bought the electricity is coming to the end of its term.

These modifications imply that new heat production units will have to be added as the currently installed equipment are not sufficient to face the increase in heat consumption. Another aspect which has to be addressed is the renewable share of the heat production. In the present state, there is no renewable energy. To gain access to tax reduction, it is necessary to have at least 50 % renewable share. When investing in new equipment, this will have to be taken into account. Our methodology will help decision-makers identify which configurations are most suited, both from an economic and CO_2 impact point of view.

Before applying the methodology to the study case, it is tested on the reference case (i.e. the original network before the modifications), using the heat consumption data for a specific year, and compared to the operator's data for that same year.

Reference case

The main characteristics of the network are given in Tab. 1. The heat demand profile and load duration curve for the tested year is shown in Fig. 3 (black curve). Those yearly profiles have been reduced to 9 typical days, each of which is divided into 3 time segments, using the methodology proposed in [3]. The whole year is therefore represented by only 27 time segments. Those segments are also represented on Fig. 3 (coloured dots).

Tab. 1 - Main characteristics of DHN in the reference case

Network length (km)	3
Annual heat demand (GWh)	12
Maximum heat load (MW)	5,2

In the reference case, the heat on the network is produced by the following equipment:

- A combined heat and power (CHP) gas engine
- Two gas boilers, one of which is equipped with a condensation scrubber

The main characteristics of the equipment are given in Tab. 2. The CHP is only working between November and March, because the electricity produced can only be sold to the power company during this period according to the contract. Moreover, during the electricity production period, the CHP is working at 100 % of its nominal power outside of maintenance periods (in which case it is completely stopped). If the heat production exceeds the network demand, then the excess heat is dissipated with a cooling tower.

Tab. 2 - Main characteristics of the existing equipment on the network

	CHP gas engine	**Gas boiler 1 with condensation scrubber**	**Gas boiler 2**
Max power (MW)	2.7	7.5	3.6
Thermal efficiency	47 %	99 %	95 %
Electrical efficiency	35 %	-	-

The reference case simulation results are given in Tab. 3. The heat production of each equipment obtained using the tool is compared to the operator's values for the same year. It is to be noted that the heat for the CHP plant is the useful heat used by the network (it does not include the dissipated heat). The comparison with the operator's values shows that the CHP gas engine production is slightly overestimated with the simulation. This is counterbalanced by an underestimation of the gas boiler production. The 2nd gas boiler is never used (it is a back-up boiler). The difference can be explained by the fact that our tool does not take into account the operating availability of the CHP plant (i.e. there is a certain percentage of the time when the plant is not operating at full load or not operating at all). Moreover, the slight difference in total heat production comes from the approximation incurred by the use of typical days in the simulation.

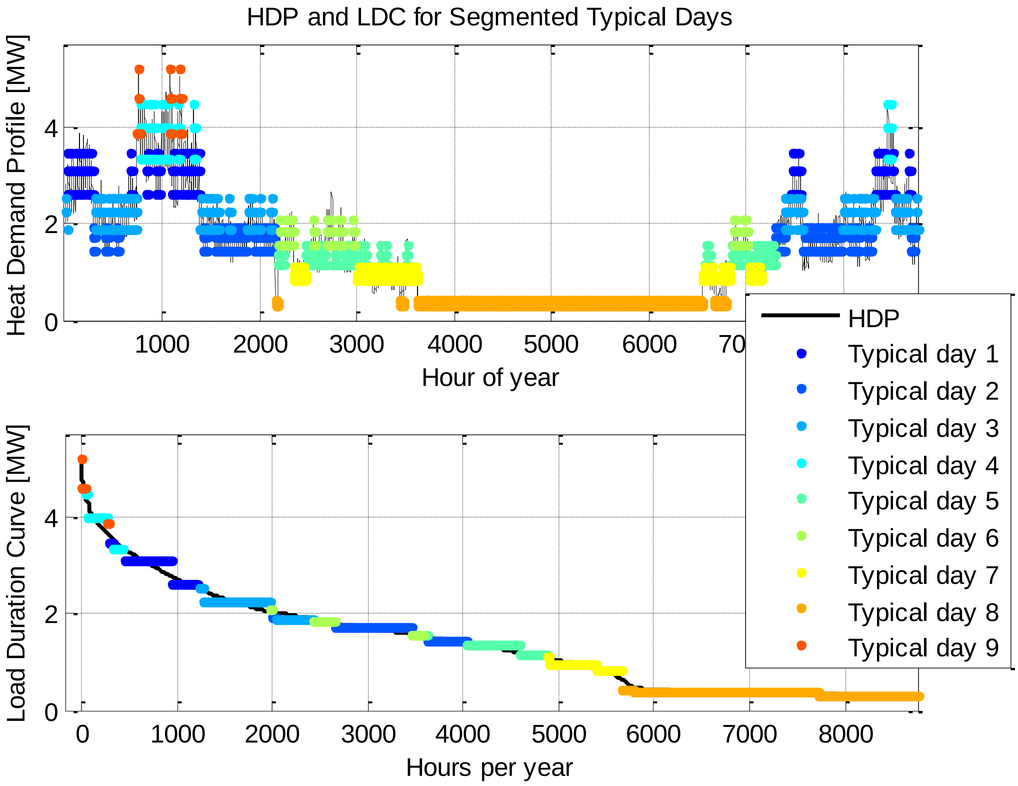

Fig. 3 - Heat demand profile and load duration curve of the network in reference case and typical days representation

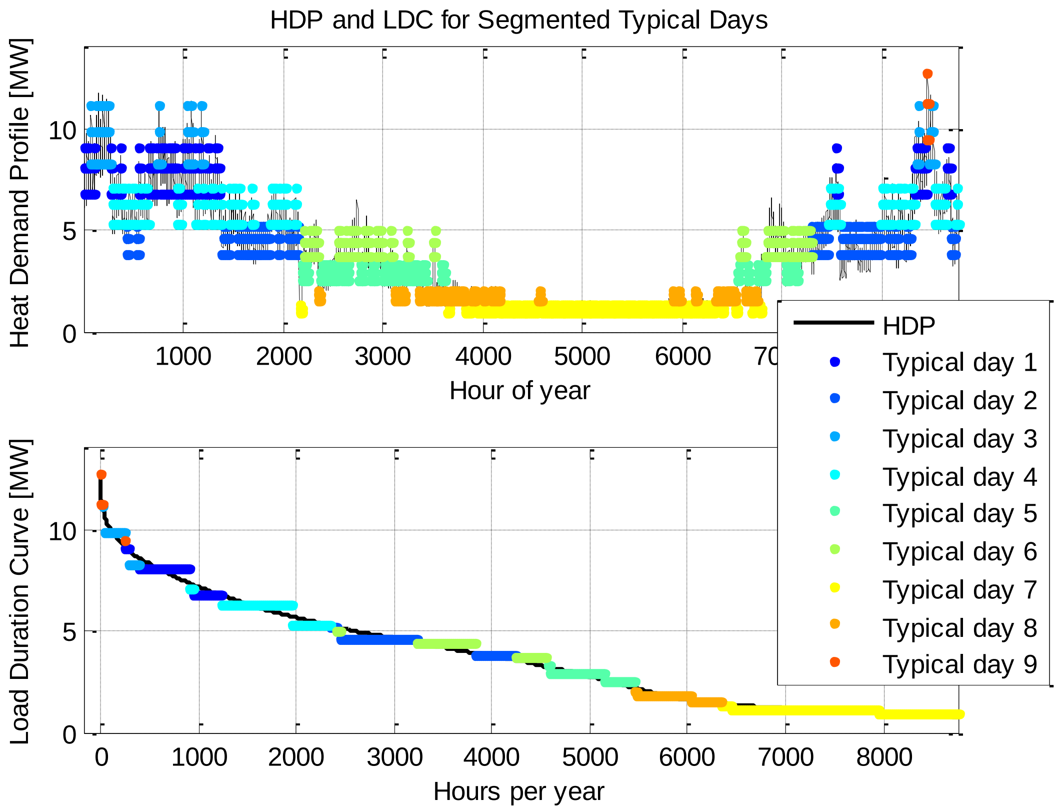

Fig. 4 - Heat demand profile and load duration curve of the network after modifications and typical days representation

Tab. 3 - Heat production in MWh of each unit obtained by optimization and the operator for the reference case

	CHP gas engine	**Gas boiler 1 with condensation scrubber**	**Gas boiler 2**
Simulation	7 801	4 385	0
Operator's values	7 214	4 929	0
Deviation	+ 8 %	- 11 %	0

Case study

The methodology is now applied to the case study, in which the previous network has been modified by adding new clients and extending the network. The characteristics of the network after those modifications are given in Tab. 4. This leads to an 11 GWh increase in heat demand per year, as well as an increase in maximum heat load by 7.6 MW. In the same time, the CHP plant is removed. One or more new equipment will have to be added to the network as:

- the current gas boilers are not sufficient to cover the peak load (1.7 MW missing)
- to obtain tax reductions, the renewable share of the network has to be at least 50 %

Tab. 4 - Characteristics of the DHN after modifications

Network length (km)	6
Annual heat demand (GWh)	33 (+175 %)
Maximum heat load (MW)	12,8 (+146 %)

The new heat demand profile and load duration curve, as well as the corresponding typical days, are shown on Fig. 4. The year is also represented using 27 time segments.

The list of available equipment that has been chosen for the multi-objective optimization is given in Tab. 5. The table also gives the sizing range U_s for each equipment, and indicates if the equipment produces electricity.

For the operating costs and investment costs, Veolia's databases are used. Subsidies are taken into account for the investment cost of the biomass boiler, geothermal heat pump, biomass CHP and the network extension if and only if the renewable share is over 50 %.

The fuel characteristics that were used are given in Tab. 6. The electricity selling price has been set at 126 €/MWh for all CHP plants subject to feed-in tariffs. These can only be activated during the electricity production period (between November and March). The biomass CHP with Organic Rankine Cycle (ORC) is an exception, as it can work at any time during the year, but the price is set at 50 €/MWh (standard spot market value) as it is not subject to a feed-in tariff (assumption). Moreover, the avoided CO_2 emissions corresponding to the electricity sold from CHP are deduced from total emissions (official value for France: 356 gCO_2/kWh [5]).

Tab. 5 - List of available equipment and sizing range

	U_s^{min} / U_s^{max} (MW)	Electricity production
Biomass boiler	1 / 5	No
Gas boiler	0,5 / 5	No
Gas engine (CHP)	0,5 / 5	Yes
Gas turbine (CHP)	2 / 5	Yes
Fuel cell (CHP)	0,5 / 2,5	Yes
Geothermal heat pump[1]	0,3 / 0,3	No
Biomass CHP (ORC)	1,8 / 5	Yes

Tab. 6 - Fuel characteristics

	Cost (€/MWh)	CO_2 impact (gCO2/kWh)
Biomass	22	0
Gas	44	205
Electricity (grid)	101	180

Fig. 5 represents the CO_2 content as a function of heat price for the optimal set of solutions. These solutions form the so-called "Pareto frontier". Each point on this figure represents a given configuration, defined by the type and size of the selected equipment. There are a total of 636 solutions on the Pareto frontier. These have been split into 3 clusters, which are shown by the colour of the points in the figure. The heat production share on the network among the different equipment is represented by a pie chart for the extreme and centre solutions of each cluster. The size of the selected equipment for these solutions is represented in Fig. 6.

[1] Geothermal source characteristics : Depth :30 m; Flowrate : 50m3/h; Temperature : 10°C; Distance from network : 300 m

DISCUSSION

The cheapest solutions, defined by cluster 1, are obtained by investing in a gas engine close to the maximum allowed power (5 MW). In that case, over 50 % of the heat on the network is produced by the gas engine. The rest of the heat is mostly produced by the existing gas boilers, except for extreme point 2, where the optimization chooses to invest in a small biomass boiler of around 1.7 MW, which produces 31 % of total heat. That cluster also has a high CO_2 content and a low renewable share (always inferior to 50 %).

There is a huge gap between cluster 1 and cluster 2 regarding the CO_2 content (drops from 124 to 43 g/kWh) for a negligible increase in heat price between extreme point 2 and 3 (<1 %). However, there is a high rise in investment costs (+42 %). The gap in the Pareto frontier can be explained by:

- the imposed minimum size of the equipment
- and the fact that the heat price is reduces through tax reductions and network extension subsidies only for solutions with over 50 % renewable share.

In cluster 2, the optimization chooses to systematically invest both in a biomass CHP plant and in a gas engine. As the heat price increases and the CO_2 content decreases, the biomass CHP plant size and heat share increases, and gradually replaces the gas engine. The CO_2 content even becomes negative after a certain point. This is because the CO_2 emissions are compensated by the avoided CO_2 emissions through selling electricity, and has to be put into perspective of the assumption used for the CO_2 content of this electricity. The existing gas boiler is used as back-up.

The transition between cluster 2 and cluster 3 runs much more smoothly. Indeed, the biomass CHP plant size and contribution continues to increase until the maximum allowed size is reached (5 MW). At the same time, the gas engine power decreases and it is completely removed for the solutions with lowest CO_2 emissions. The optimization replaces the gas engine with a biomass boiler, which size rapidly increases to reach the maximum allowed value (5 MW). Once this is achieved, most of the heat (>99%) is produced by the biomass boiler and CHP.

It is to be noted that the gas turbine, fuel cell and new gas boiler are never chosen in the optimal configurations. The geothermal heat pump is chosen for a small sub cluster of solutions (around C1 in Fig. 5), but its contribution is quite small (7 % at most).

OUTLOOK

The described methodology has here been applied to a specific case study. However, it is extremely flexible and can be used in a large variety of situations, be it entirely new DHN, network extensions, unit replacement or connecting several DHN together.

Other functionalities have been developed that were not presented here :

- integrating a heat storage tank [6];
- global sensitivity analysis [2];
- taking into account the geographical location of the equipment and network, so that the optimization not only chooses what units are to be implemented, but also where they should be located [7].

CONCLUSIONS

In the present work, a methodology for the multi-objective optimization of a district heating network was presented and applied to a test case in France. The computer tool which applies this methodology allows decision makers to identify a set of optimal configurations (i.e. type and size of equipment on network), both from an economic and CO_2 point of view. To help the decision makers choose among the optimal solutions, clustering and sensitivity analyses can also be carried out. The method has already been applied to several test cases in France and Europe.

One of the main advantages of this method is that optimal solutions can be pointed out from a large set of possibilities (a varied combination of technologies and sizes). Moreover, the operating strategy of selected units is optimized for each configuration, while respecting local constraints (fuel availability, electricity selling contract period etc.).

The tool is extremely flexible and can be applied to a large variety of studies:

- existing network operating strategy optimization
- new network development
- existing network extension
- study of possibility of connecting two or more networks together
- replacing one or more plants within a district heating network
- selecting the location of new units and network layout
- studying the effect of adding a heat storage tank on an existing network

The tool can be very useful in early project development to give a few possible orientations for a network development or when answering calls for tender. The limited number of solutions can then be analysed more in detail with the appropriate simulation tools.

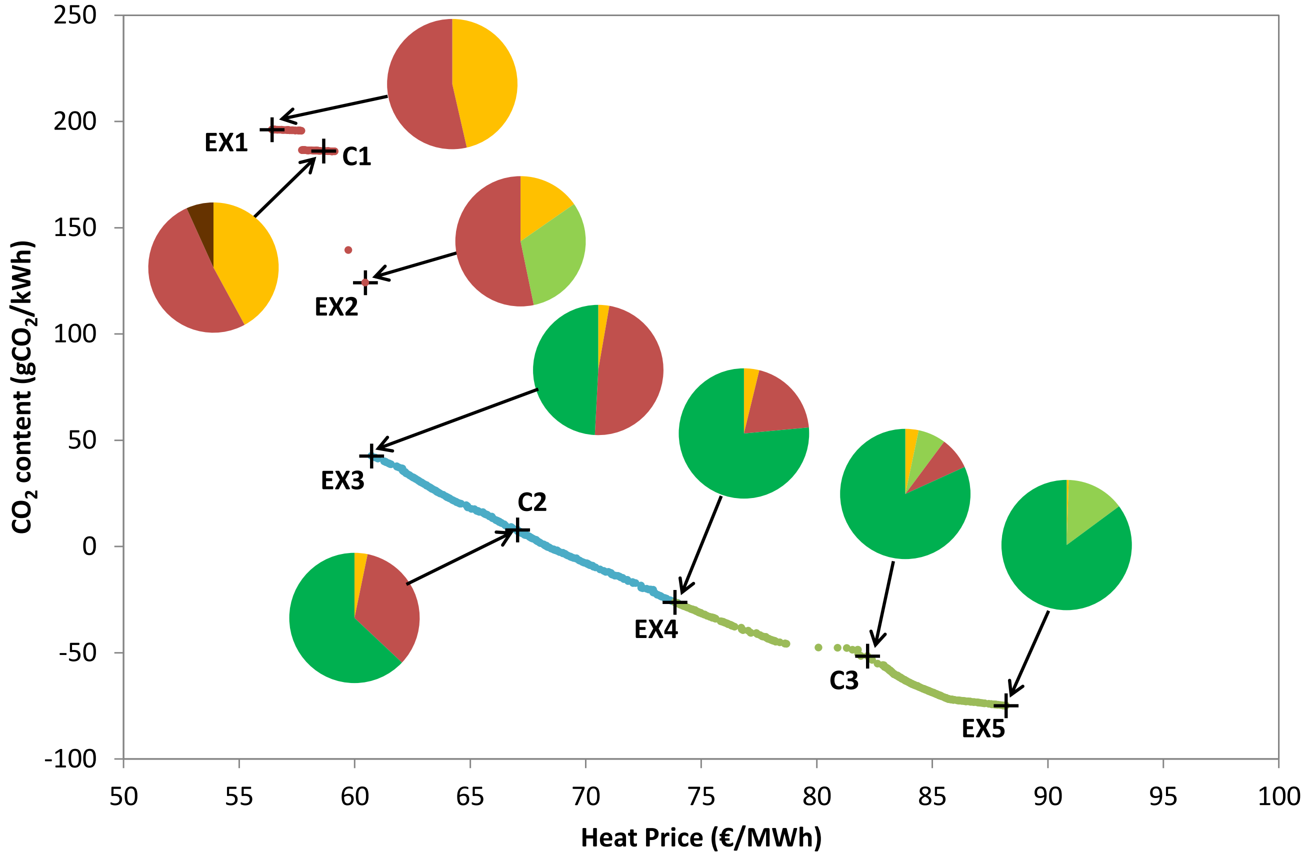

Fig. 5 - Heat price vs. CO_2 content representation of the optimal solutions and contribution of each equipment for cluster centre and extreme points (cluster 1 : red points ; cluster 2 : blue points ; cluster 3 : green points)

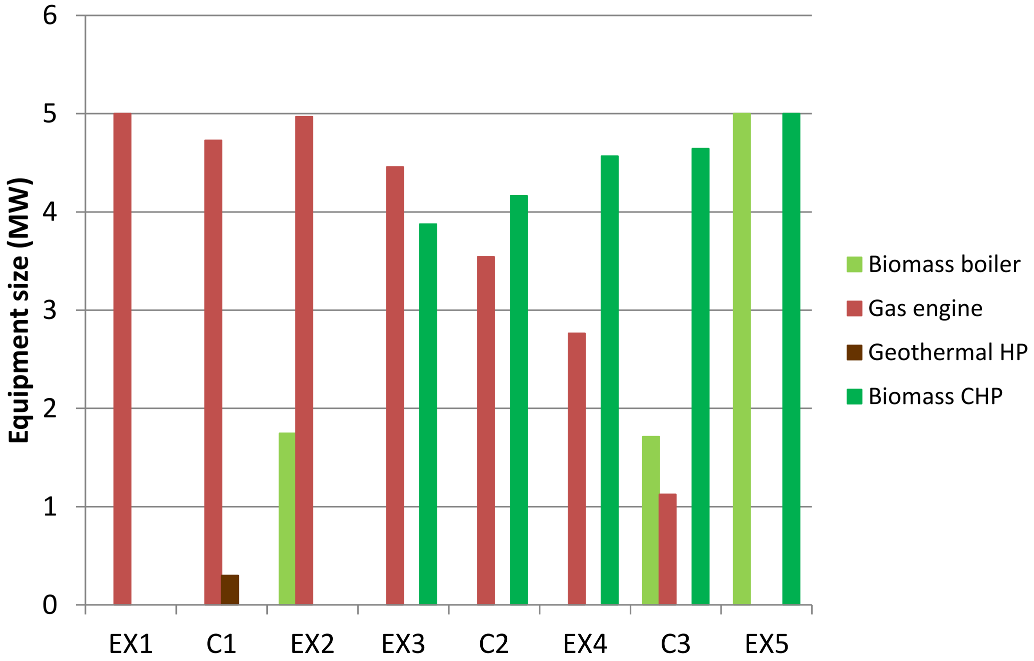

Fig. 6 - Equipment size of chosen equipment for cluster centre and extreme points

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SESSION 3

Resource efficiency and environmental performance

DISTRICT HEATING AND COOLING MEASURES FOR A SUSTAINABLE SOCIETY

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ABSTRACT

Our current use of energy is a major part of the sustainability challenge. To rapidly develop sustainable energy systems is crucial for the whole society's transition towards sustainability. Swedish district heating and cooling (DHC) systems have been very important for increased system efficiency and reduced climate impact and can continue to play an important role in society's transition towards sustainability.

Converting to DHC in a system with combined heat and power (CHP) gives an increased basis for electricity production. Since coal condensing is today the marginal production of electricity in Europe, conversion to DHC can contribute significantly to lower global emissions of CO2, in particular if the DHC and CHP systems are based on renewable energy sources.

However, in a sustainable society, where there is no longer a systematic increase of CO2 (and no other sustainability problems), the benefits of DH are less obvious.

The aim of this study is to develop a prototype for a methodological support for sustainable district heating systems development. Action research and case studies have therefore been prominent scientific methods in the project. We have studied the challenges and opportunities of district heating in Blekinge and Stockholm. These are two rather different cases, which leads to greater generalization. Our work is based on Blekinge Institute of Technology's (BTH) knowledge and competence in the field of strategic sustainable development and Linköping University's knowledge and competence in the field of energy systems analysis. The integration of these areas has largely taken place through the case studies and the development of the methodological support. These case studies have also provided examples of how the support can be used, some of which have been included in the support for pedagogical purposes.

INTRODUCTION/PURPOSE

Humanity is facing its greatest challenge ever – to transition society towards sustainability. There are many historical examples of local communities that perished due mismanagement of the ecological and/or social systems that they depended upon. Now, for the first time the entire global human civilization is threatened. This challenge is, of course, extremely serious and frightening. At the same time it holds strategic opportunities for proactive companies, municipalities and regions. By systematically reducing their contribution to the problem and by early on start to instead become part of the solution to the problem, they accelerate the transition, become more attractive in the increasingly sustainability-driven market and as such good examples they also encourage others to be proactive and strategic about sustainability.

Our current use of energy is a major part of the sustainability problem. To rapidly develop sustainable energy systems is crucial for the whole society's transition towards sustainability. Increased system efficiency and reduced climate impact are important parts of this. Swedish district heating systems have been very important for increased system efficiency and reduced climate impact and can continue to play an important role in society's transition towards sustainability. However, making environmental and economic assessments of additional investments in district heating systems have become more complex. For example, the great benefit from a climate perspective that district heating linked to combined heat and power generation (CHP) is often credited for today, is to a large extent based on the fact that the rest of the energy system is unsustainable (with coal based electricity generation at the margin). But when the entire energy system, and the entire society, will undergo a paradigm shift, how can we then discuss and assess investments in district heating? How can we ensure that we have a wide enough perspective in both space and time and as regards societal sectors? How can actions in different parts of the energy system and society be generated and coordinated so that they mutually support each other, or at least do not preclude future necessary steps within the subsystems? How could new competence that combines strategic sustainable development and energy system analysis be built and how could a methodological support look like that helps businesses, municipalities and regions to manage the increased complexity in the energy sector? These issues, with a special focus on district heating, formed a background to this project.

STATE OF THE ART

Previous studies have shown how a methodology for strategic sustainable development – based on backcasting from sustainability principles – can stimulate generation of innovative ideas and guide strategic planning and decision making for viable transitions towards sustainability within companies, municipalities and regions [1]. It has also been shown how this basic methodology can be used to assess the strengths and weaknesses of other methods and tools for sustainable development and to coordinate the use and maximize the benefits of such methods and tools [2]. Other previous studies have shown the power of using energy system analysis tools for a more detailed investigation of various alternative measures and energy systems investments [3], [4], [5], [6]. The basic idea of this project was to combine these competence areas, as an attempt to address the above issues. Potential benefits of such a combined approach would thus include stimulation of district heating stakeholders to co-create innovative solutions, new business models and attractive early steps for viable transition paths towards sustainability, i.e. transition paths that minimize the risks of sub-optimization due to a too narrow perspective in space or time or as regards societal sectors.

METHODS/METHODOLOGY

In this project a generic and unifying framework for planning and decision making towards sustainability (Framework for Strategic Sustainable Development; FSSD) has been used as the overall methodology. This has been integrated with methods and tools for modeling, simulation and optimization in the energy system field. Below we describe the core methodologies and how they have been integrated through action research and case studies.

Framework for FSSD

The Framework for Strategic Sustainable Development (FSSD) is designed to give guidance in how to develop any region, organization, project or planning endeavor towards social and ecological sustainability in an economically viable way. It has been under continuous development in a 20-year scientific consensus process including theoretical exploration, refinement and testing in iterative learning loops between scientists and practitioners from business and society. To plan and act strategically in complex systems, a clear intellectual differentiation between five different (but interacting) levels is helpful (see also figure 1):

1. The system level. This level describes the overall major functions of the system, i.e. the biosphere with its human society, organizations, value-networks, etc., our knowledge on stocks, flows, biogeochemical cycles, biodiversity and resilience, human needs, and the basic relationships between human practices and their impacts. The current systematic degradation of this system (unsustainability of the global human society) is the rational for the coming levels. In order to plan and act strategically, more and more detailed knowledge about the system is not necessarily helpful in itself. It is essential to also have a robust definition of "purpose/success" or "overall objective". Such a robust definition of the objective can then provide a basis for backcasting planning and provide a lens for the further study of the system, i.e. identification of the relevant and essential aspects of the system that need to be further studied with regard to reaching the defined objective.

2. The purpose/success level. This level specifies the definition of the objective – success of the region, organization or other subject of the planning within the constraints of a sustainable society. Basic principles are used to define (frame) a sustainable society. In the sustainability context it is more helpful to backcast from a principled definition of success than a fixed detailed scenario, for several reasons. For example, it is often difficult for many stakeholders to agree on a detailed objective that is far into the future. Also, since, e.g., technical and cultural evolution continuously change the conditions for the planning endeavor in a way that cannot be predicted in detail it is best to avoid overly specific assumptions of the future too early in the transition process. A principled vision offers more flexibility than a detailed scenario because success can be achieved in a variety of ways (as long as the principles are met). Organizational learning experts have observed that these types of constraints stimulate creativity. Applying an analogy; to checkmate one's opponent is the purpose/success in chess, which can happen in almost uncountable combinations all complying with the same basic principles of checkmate. To be functional for strategic sustainable development, the set of principles must be necessary (but not more) to avoid unnecessary restrictions and to reduce distraction over elements that may be debatable and sufficient (and not less) to cover all aspects of sustainability. In addition, the set of principles should be general to make sense for all stakeholders and thus allow for cross-disciplinary and cross-sector cooperation, concrete to inspire and guide innovation, problem solving and actions, and distinct (non-overlapping) to enable comprehension and facilitate development of indicators for monitoring. The next level requires this key second level.

3. The strategic guidelines level. This level specifies the guidelines for how to approach the objective strategically. This implies a step-by-step approach towards the objective in a way that ensures that financial, social, and ecological resources continue to feed the process. In chess, moves serve as strategic steps to checkmate. Trade-offs, in chess or in the "game of sustainable development", are selected from their capacity to serve as platforms towards complying

with principles of success (level 2), rather than as choices between inherent evils.

4. The actions level. This level is about putting concrete measures (e.g. investments) into stepwise action programs in line with the strategic guidelines at level 3.

5. The tools level. Concepts, methods and tools are often required for decision support, monitoring and disclosures of the actions (4) to ensure they are chosen strategically (3) to arrive stepwise at the objective (2) in the system (1). Examples in sustainable development are modeling and simulation tools, management systems, indicators, life cycle assessments, etc. The FSSD is designed to not compete with any other concept, method or tool, but to be structuring and unifying to aid people in making the best use of any other concept, method or tool, depending on purpose and context.

It is the rigor by which levels (1)-(3) are described and allowed to inform each other that determines how confident users can be when developing/choosing appropriate actions (4) and appropriate complementary concepts, methods and tools (5).

The FSSD uses an application procedure with four general steps. In the first step, (A) participants learn and apply the FSSD to share and discuss the topic or planning endeavor and agree on a preliminary principle vision of success, framed by sustainability principles (SPs). In the second step, (B) participants explore the current situation in this context. They list the main current challenges in relation to the objective they want to reach, informed by the SPs applied as boundary conditions, as well as current assets to deal with those challenges. Thereafter, (C) participants turn to brainstorming, whereby they suggest possible future solutions to the challenges and scrutinize them only with respect to the vision within the SPs, temporarily disregarding constraints related to the current situation, e.g., constraints related to the current infrastructure, the current energy system, the current financial capacity, etc. In the final step, (D) the strategic dimension comes to the fore when participants prioritize solutions, e.g., investment decisions from the previous step. In this D-step, priorities are set with an intuitive logic. It means a stepwise approach, ensuring that early steps are designed to serve as (1) flexible platforms for forthcoming steps that, taken together, are likely to bring society, the organization and the planning endeavor to the defined success, by striking a good balance between (2) direction and advancement speed with respect to the defined success and (3) return on investment to sustain the transition process. The logic creates the opportunity for pragmatic leadership, not only looking at the promise for an improved bottom-line in the future, but also considering short-term profits designed in a way that opens up the potential for the longer-term profits. The FSSD allows for a self-benefit of sustainability proactivity to be captured by, e.g., companies.

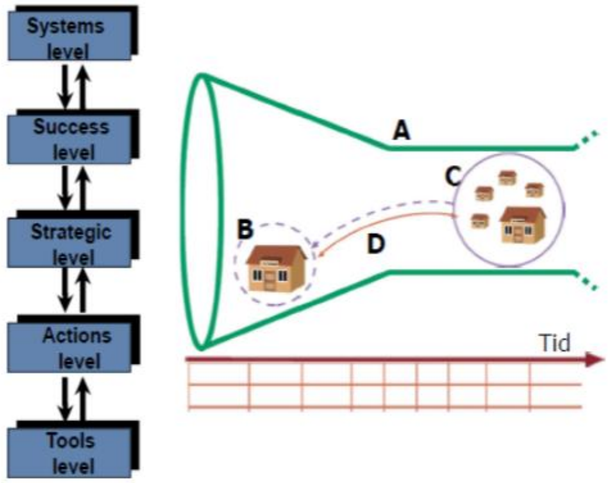

Fig. 1 The five level model and the ABCD planning procedure of the FSSD.

Modelling /Simulation/Optimization

In this project modellig, simulation and optimization have been used as a "tool" within the FSSD. An advantage of using models is to be able to answer questions about the studied system without performing any real experiments. Those are sometimes impossible to perform, too expensive, or ethically doubtful. Working with models is especially advantageous when there are several factors to consider. The effects of all the factors one by one may be clear but the totality is not. However, it is important to remember that any model is only an approximation of the real system. Practically all technical analyses and design work is dependent on models. Models' usefulness depends on how well the model describes the real system. It is important to clarify a model's range of validity and to verify the model [7], [8].

A number of modeling and simulation tools have been developed for analyzing energy systems. Examples include MODEST [9], MARKAL [10], EFOM [11], MESSAGE [12] and TIMES [13]. According to [7], a model should fulfill the following requirements: systematic, efficiency, validation, model conditions and generalization. A model for analyzing energy systems should also be able to represent [9]: many energy forms, investment costs and fixed and variable operation costs, demand-side measures, flexible, seasonal, monthly, weekly and diurnal time division, optimal operation and marginal costs.

In this project, mainly the MODEST tool has been used. The reason for choosing MODEST was, above all, the possibility to model a flexible time division. The MODEST model (short for Model for Optimisation of Dynamic Energy System with Time-dependent components and boundary conditions) was developed to fulfill the above-mentioned fundamental criteria as well as other criteria, see [9]. The MODEST model is briefly described below.

Modest

MODEST is used for minimizing the cost of existing and potential new plants [9], [14]. It is a model framework developed for simulation of municipal, regional and national energy systems and is based on linear programming. The aim of the optimization is to minimize the total cost of supplying the demand for heat and steam by finding the best types and sizes of new investments and the best operation of existing and potential plants. The total system cost is calculated as the present value of all capital costs of new installations, operation and maintenance costs, fuel costs, taxes and fees. The system is optimized over a given period of time. Each year in the optimization model is divided into seasons, which are then divided into daily periods.

The method assumes that the demand for district heating and electricity is known and the capacity of the plants is available. MODEST is not primarily a model for operational optimization, even if such optimization can be made in an approximate manner. MODEST has no other objective than total cost minimization, i.e. it has no objective of minimization, e.g., emissions or the use of certain energy forms.

As pointed out above, the validation of a model is important since the validation will indicate how well the model describes reality. Comparing the model with the real system's behavior can validate a model. MODEST has been tested for modeling electricity and district heating supply for approximately 50 local utilities, for biomass use in three regions and for the Swedish power supply [15], [16].

For the studies in this project, the results of the optimizations have been thoroughly checked by analyzing the reasonability of both input and output data and by communicating and checking those data with local energy utilities.

RESULTS

A general result of the project is a methodological support for the sustainable district heating development (Resource Kit). In the workshops and other dialogues we have had with district heating stakeholders, we have seen how early versions of the Resource Kit have provided support for, e.g., analyses of the current situation of local and regional energy systems in relation to sustainability, self-assessment of maturity in terms of strategic sustainability work, clarification of the strengths and weaknesses of current business models and how this has stimulated the generation of solutions and new business models. By on the one hand using today's systems and trends as a point of departure, and on the other hand using a vision of a future situation in which society has achieved sustainability, and by thinking about how investments in district heating could contribute to bridging this gap in an economically viable manner, the perspective is broadened and creativity is stimulated.

Examples of measures identified as interesting in workshops and reference group meetings during the project which we have studied in greater depth with methods and tools for energy system analysis include cooperation on the supply of district heating, the introduction of combined heat and power generation (CHP), absorption cooling and the production of biofuel. In the cases we have studied, investments in, e.g., cooperation on the supply of district heating and CHP have proven to be of particular interest as prioritized early measures. For example, heat cooperation between a regional energy utility and an industry, combined with investments in new bio-based CHP, could lead to approximately 100 % reduction in global CO_2 emissions when compared to the current situation (assuming coal-based power as marginal electricity production). Several examples of specific results are provided in the next section. We have also seen how the methodological support has stimulated more radical ideas during our workshops with district heating stakeholders. One example is the idea of changing the value proposition from "heat" to "indoor climate" and building up stakeholder collaboration and business models around it.

Case studies

As examples of how the methodological support developed in this project can be used in practice, and as a way of developing the methodological support, different case studies have been performed. Below are short descriptions of some of the case studies.

Modeling district heating systems in Blekinge

The overall objective of the study is to give suggestions to improve the economic performance of district heating systems in the county Blekinge of Sweden while reducing the global CO_2 emissions of the system. Presently, the district heating in Blekinge is mostly produced by biomass based heating plants and waste heat. One of the plants utilizes waste heat from the local pulp industry and there is one recently started biomass based CHP plant in Karlskrona.

The research is carried out by using computer programs and literature study. Two computer programs are used in the thesis. PVSYST is used to estimate the effective solar irradiation and MODEST is used to model the local district heating system.

The results show that connections between the networks would give more economic benefit when there are more imbalanced fuels input or production facilities. If the connections were introduced into the existing DH system, the heat flows through them would be low and the economic profitability would not be significant. However, with the new CHP plant in the system, the introduction of the connections would reduce the system cost by about 50 % and the global CO2 emission of the system would be reduced by 93,440 tons annually.

The new installed solar collectors with an area of 10,000 m2 in Olofström's DH network would produce 3,7 GWh, corresponding to 29 % of the total district heating supply in Olofström. Moreover, if the biomass prices would increase in the future, the solar district heating production would become more interesting [17].

Sustainabillityself-assessment and business model-design

There is a large degree of consensus regarding the potential business impact of sustainability. However, most companies either are not acting or are falling short on execution [18]. Relatively few companies consider innovation for sustainability substantially rewarding. Suggested solution for this includes better access to frameworks for understanding sustainability and value creation and the business cases thereof [18]. Furthermore, it is well-known that support for generation and selection of ideas and for formulating goals and strategies is especially important to have during the early phases of the innovation process [19].

The usual absence of an operational definition of sustainability is still a major barrier to corporate strategic sustainable development [20]. A sustainability definition that can guide assessment of the current situation and stimulate generation of ideas for upstream solutions and strategic guidelines that can aid prioritization of early smart actions are among the most promising leverage points. A framework including those features is being developed in an international consensus process since twenty years. Among other things, this framework for strategic sustainable development (FSSD), clarifies the self-interest in sustainability work and thus supports more widespread and proactive sustainable innovation.

In this study, the FSSD is used as the main basis for a new tool to be used in early phases of the innovation process for self-assessment of an organization's current maturity and performance from an overall strategic sustainability point of view and for stimulating generation of ideas for business models design. We present a prototype version of such a tool and results from initial tests of this tool performed in four organizations. We study in particular whether the outlined tool is perceived by the organizations to be: (i) easy to comprehend, (ii) relevant, (iii) capable of differentiating the organizations in a comprehensive way, (iv) helpful for discovering insufficiencies that the organizations are not already aware of and (v) helpful for generation and selection of ideas for upstream solutions, business model innovation and for formulation of goals and strategies [21].

The role of district heating for sustainable development

In Sweden, DH is quite well developed and is already mainly based on non-fossil fuels. Increased use of DH is therefore considered as a way of phasing out fossil energy for heating purposes. Furthermore, increased use of DH provides an increased basis for CHP.

Considering that coal condensing is the marginal production of electricity in Europe, increased use of bio-fueled CHP leads to even greater reductions of global CO2 emissions. However, in a sustainable society, where there is no longer a systematic increase of CO2 (and no other sustainability problems), the benefits of DH are less obvious.

The aim of this work is to explore the impact of DH and CHP in the development towards such a society. A local energy system is studied for five different time periods from 2010 to 2060 with different marginal technologies for electricity production. Results show that when the local energy utility cooperate with a local industry plant and invests in a new CHP plant for waste incineration the global CO2 emissions for the whole studied time period will be reduced with about 48 000 tons, which corresponds to over 100 % of the emissions from today's system for the same time period.

When considering that biofuel is a scarce resource, and that the amount of CO2 emission linked to waste probably will be lower in sustainable society, the global CO2 emissions will be about 250 % lower compared to the system of today (assuming coal-based power as marginal electricity production). The studied DH related cooperation and introduction of CHP will reduce the system cost for the whole studied energy system with 2 500 MSEK for the studied period. In general, the results indicate that the modeled measures will not have any major sustainability advantages over other heating technologies in a sustainable society but that it can play a vital role for the development towards such a society [22] – [23].

DISCUSSION

The importance of integrating strategic sustainability thinking into the core business of companies is becoming more and more pronounced around the world. The systematic guidance for how to do this by using a framework for strategic sustainable development (FSSD), could therefore be of significant value for business and society. Using this together with methods and tools for energy system analysis – as presented in this project – will assist district heating stakeholders to decide on actions that support sustainable development of the whole society and at the same time strengthen their own organizations.

In the workshops and other dialogues we have had with district heating stakeholders, we have seen how early versions of the Resource Kit have provided support for, e.g., analyses of the current situation of local and regional energy systems in relation to sustainability, self-assessment of maturity in terms of strategic sustainability work, clarification of the strengths and weaknesses of current business models and how this has stimulated the generation of solutions and new business models. By on the one hand using today's systems and trends as one bridge head, and on the other hand using a vision of a future situation in which society has achieved sustainability as a second bridge head, and by thinking about how investments in district heating could contribute to bridging this gap in an economically viable manner, the perspective is broadened and creativity is stimulated.

Examples of measures identified as interesting which we have studied in greater depth with methods and tools for energy system analysis include cooperation on the supply of district heating, the introduction of CHP), absorption cooling and the production of biofuel. In the cases we have studied, investments in, e.g., cooperation on the supply of district heating and CHP have proven to be of particular interest as prioritized early measures. For example, heat cooperation between a regional energy utility and an industry, combined with investments in new bio-based CHP, could lead to approximately 100 % reduction in global CO2 emissions when compared to the current situation (assuming coal-based power as marginal electricity production). But the advantages of heat cooperation and new CHP are less clear in a sustainable society in which all electricity is produced by renewable and sustainable energy sources – where we thus have no marginal electricity production in coal-fired condensing power plants. Under certain conditions, these measures can still play a crucial role in the development towards a sustainable society. It is however difficult to give any generally applicable or standard measures, as the conditions vary for each district heating company and region. It is therefore more appropriate and important that the stakeholders in question build up their knowledge and competence and get access to a methodological support, enabling them to clarify the grounds for – and likely implications of – their decisions, based on the prevailing conditions in the specific cases.

OUTLOOK

The scope of this work is most vital to study for DHC system in the whole Europe. The prerequisites for DHC differ between European countries which is important to take into consideration for further analyses.

Also, to further develop the prototype for the Resource Kit into a more complete and user-friendly support, future work is necessary between development and usage, preferably in more regions and municipalities in order to test and secure a high degree of generalization.

CONCLUSIONS

We have concluded that energy modeling, simulation and optimization tools can be useful in all steps of the ABCD procedure of the FSSD. In the A-step they can be used to facilitate learning, in the B-step they can support the analysis of the current situation, .e.g., by clarifying orders of magnitude of various contributions to societal violations of the sustainability principles of the FSSD and in the C-step they can aid stimulation of creativity for the generation of possible solutions. However, the main utility of those tools is in the D-step. Here the solutions from the C-step need to prioritized into a strategic plan, with some early steps that are designed to serve as (1) flexible platforms for forthcoming steps that, taken together, are likely to bring society, the organization and the planning endeavor to the defined success, by striking a good balance between (2) direction and advancement speed with respect to the defined success and (3) return on investment to sustain the transition process. This involves many “what-if-simulations” to compare alternatives with respect to their performance in relation to these prioritization questions.

The Resource Kit prototype that has been developed in this work is an attempt to guide this integration of competence areas, to support sustainable district heating development. The main target group is energy utilities, but also consulting companies, authorities, municipalities and universities can benefit from this methodological support. The Resource Kit is suited primarily for somewhat larger organizations. The user should preferably have a unit for strategic planning and development, which is usually the case for district heating companies with more than about 20 employees. With a more comprehensive external expert assistance, also smaller organizations can benefit from Resource Kit. The first time it is used, and if there is not already competence within the organization in strategic sustainability thinking and energy system analysis, it is recommended that external support is used.

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SUSTAINABLE STEEL CITY: HEAT STORAGE AND INDUSTRIAL HEAT RECOVERY FOR A DISTRICT HEATING NETWORK

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Keywords: industrial heat recovery, heat pumps, heat storage, CO_2 emissions.

ABSTRACT

Energy intensive industries need to adapt in order to play an important role in the low-carbon economy. Efficient use of energy resources and the minimisation of wasted heat will be important. The role of the steel industry in recovering recycled metals means these industries are important for a sustainable economy, providing employment and supporting manufacturing.

The aim of this project is to investigate the potential uses for heat storage in Sheffield, UK for capturing heat which is produced intermittently at a steelworks for both re-use of heat on site at various temperatures and for heat supply to a city-wide heat network. Site visits were followed by calculations using data provided. Heat storage options were investigated to ensure that waste heat could be re-used effectively. The feasibility of using the district heating network in the city to carry low grade heat away from the plant was considered. Around 4.7 MW of useful heat could be generated from two steelworks sites in Sheffield and a further 10.9 MW from a site in nearby Rotherham. 22,500 tonnes of CO_2 could be saved per year by fully exploiting this waste heat resource.

1. INTRODUCTION

With a growing global population placing pressure on resource supplies and increasing knowledge of the role of greenhouse gases in climate change, it is important to develop businesses with minimised environmental impacts. Much work has already been done within UK industry to optimise systems. For heat-intensive industries such as steel, maximising energy efficiency may involve the capture of low-grade waste heat for distribution through district heating networks.

In the United Kingdom, industry contributes a quarter of the national CO_2 emissions [1] and the government is working to help industry lower the carbon footprint of heat. It is also looking at how heat demands across all sectors can be met at lower cost and environmental impact with technologies including district heating [1].

Sheffield has for decades been a pioneering city in the UK in terms of developing district heating to provide heat at lower cost and environmental impact to the city. The city-centre network is supplied with up to 60 MW of heat from an Energy from Waste combined heat and power (CHP) station marked as site 1 in Figure 1.

In addition, a new CHP power station using biomass is being constructed by E.On at site 2 in Figure 1 and this will supply heat through a new district heating network to sites closer to Sheffield city centre. The new network will be extended to supply new customers and may connect to the city-centre network. The new network also offers the prospect of recovering heat from the city's industrial sector. Finney et al. [2] identified potential for at least 10 MW of industrial waste heat for the city's expanded district heating system. Sheffield and nearby Rotherham have an estimated annual output of 1.07 million tonnes of steel produced each year from four electric arc furnaces; the location of these three sites are marked in Figure 1.

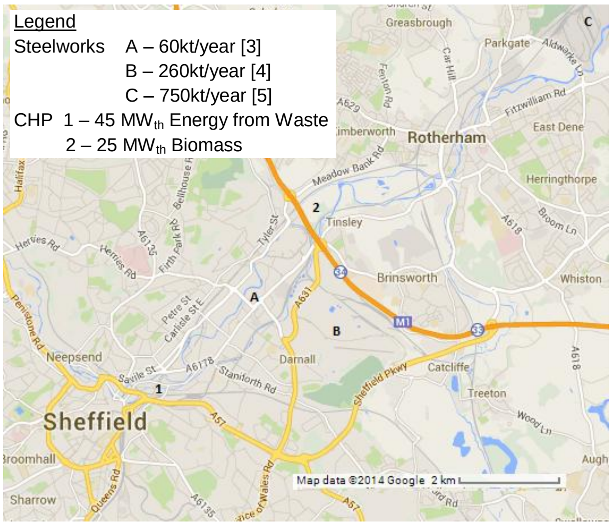

Figure 1: Map of Sheffield and Rotherham with three steelworks and two district heating CHP stations marked.

Approximately 500 kWh of electricity is used in the furnace for each tonne of steel produced [6], meaning an average of around 60 MW of electricity consumption and indirect CO_2 emissions of the order 280,000 tonnes per year from electricity alone. These processes are necessarily heat-intensive in order to melt the scrap metal, and the use of an electric arc allows the process to be carried out in batches of around 100 tonnes in four compact furnaces on these three sites.

2. STATE OF THE ART

2.1 High Temperature Heat Recovery and Storage

The furnace flue gases from steelworks are very hot, in the range 600 to 1500°C and, although they are dust-laden, flue gas heat recovery systems in industry are increasingly common, with one example at Port Talbot steelworks [1]. Tenova Group have developed waste heat boilers for electric arc furnace flue gas heat recovery at sites in Germany and South Korea; both examples include the generation of steam. One of the heat recovery systems uses steam to supply heat to a 2.5 MW organic Rankine cycle (ORC) generator [7]. Higher temperature (higher exergy) energy could be used for power generation or through work processes such as vacuum creation in a steam jet ejector.

High pressure steam accumulators are widely used to balance supply and demand on sites for steam and can be used for storing recovered heat. Regenerator materials mainly made from ceramics are already used on many gas-fired furnaces to recover heat; these materials capture the heat of the exhaust air leaving the furnaces and, when the flow direction periodically changes, use that heat to preheat incoming combustion air. Recuperator systems are an alternative, allowing increased efficiency by exchanging heat from exhaust air with incoming air; this involves a heat exchanger and the heat is not stored.

2.2 Medium Temperature Heat Recovery and Storage

It is possible to recover heat from cooling water on industry sites, for example in the water that cools the electric arc furnace walls or the water that cools the hot gas extraction ducts. Residual heat may also be available from steam processes that operate typically at 200 to 250°C. In Graz, Austria heat is recovered from a gas-fired reheat furnace along with high-temperature cooling water at around 90°C from two electric arc furnaces [8].

Buffer tanks could be used in this instance to store water at temperatures in the range 70 to 110°C which are suitable for district heating. If the water is above its atmospheric pressure boiling point then the tank needs to be pressurised, usually including a cushion of steam or nitrogen at the top of the tank to allow for thermal expansion and contraction processes.

2.3 Low Temperature Heat Recovery and Storage

Many industry sites have relatively low temperature cooling systems that are adapted from, or in some cases still use, river water cooling. Circulation of water to cooling towers reduces the need to import cool water. In some cases, cooling circuits with water treatment are necessary to prevent contaminants in the water from escaping. This water is often not hot enough for building heating but heat pumps could be used to draw useful heat from that water.

Water tanks can be used to store the cooling water ranging from ambient temperatures up to possibly 70°C if the cooling systems are adjusted to run at higher temperatures, but large capacities are needed for lower temperature stores. Underground thermal energy storage is another option that uses the thermal capacity of the ground and can be useful for storing large volumes of low-temperature heat for long periods.

2.4 Using Low Temperature Heat: Heat Pumps

Heat pumps can be used to draw heat from the atmosphere, ground or bodies of water and supply it at a higher temperature suitable for heating. The coefficient of performance (CoP) for the heat pump describes its performance (Equation 1). The emissions factor for UK electricity will determine the environmental impact of a heat pump using electricity. One recent example in Norway draws heat from the fjords in order to supply a district heating system at 90°C [9]. Sheffield's district heating operates at 110°C and delivery of heat from heat pumps at these temperatures is difficult and suitable technology is at an early stage.

$$\text{CoP} = \frac{\text{Heat Delivered}}{\text{Energy Consumed}} \quad (1)$$

The Norwegian heat pump uses ammonia as refrigerant which has its critical point at 132°C and pressures of 41 bar are required for the ammonia heat pump condensers to work [9]. By definition, the latent heat for vapour phase change diminishes as you increase the condensation (heat delivery) temperature towards the critical point from 90°C, as shown in Figure 2, and the working pressures increase too.

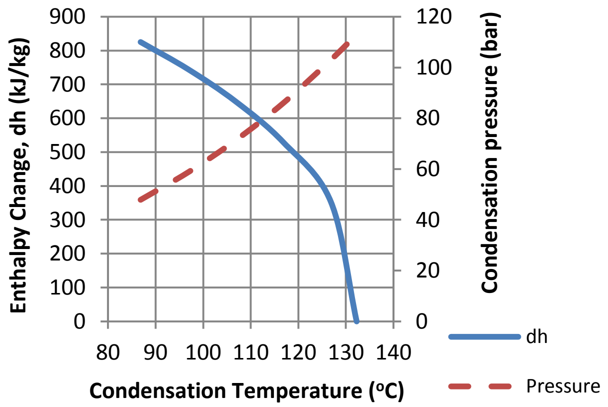

Figure 2: Condensation temperatures, pressures and enthalpy changes for ammonia, data from [10].

3. METHODOLOGY

3.1 System Optimisation

Industrial sites typically have a range of heating and cooling needs depending upon the stage of the industrial process being carried out. Finding ways to pass heat effectively between parts of the process can save a lot of heating or cooling energy. This method is termed process integration, and the practicality of such steps was considered. The use of district heating opens up opportunities for using waste heat streams for a new purpose and this could become more widespread in future, particularly in the UK. The many options for system arrangement, including how components such as heat storage are integrated, create uncertainty over the optimal way to achieve economic and environmental goals.

The method used here comprises a model built in the C++ programming language to investigate how system components interact. This modelling environment was chosen in order to give high flexibility over component arrangement as well as providing means to adjust appropriate parameters such as the heat storage capacity and the prices of energy under different future scenarios. It is these cost and environmental benefit estimates that will guide decisions.

Understanding the potential for using heat pumps is important, they give potential to extract heat from cooling water at the steelworks. If an ammonia heat pump is being used then it may be more effective to only raise the water to 90°C, as high pressures are needed for temperatures above that. The output temperature could then be topped using heat from the flue gases.

3.2 Heat Source Modelling

A site visit to one of the steelworks was undertaken to assess the potential for heat capture. The waste heat sources are primarily flue gases from furnaces (at high temperatures) and the cooling water from the electric furnace (at low temperatures).

The electric arc furnace melts scrap metal at very high temperatures and removes impurities. It produces hot and dusty off-gas which must be extracted and filtered before release. Typically, one extraction duct captures gas from close to the furnace, while a canopy duct captures any fugitive emissions from around the furnace (Figure 3). Some furnaces preheat scrap metal in the extraction duct allowing energy to return to the furnace when the scrap is loaded; this reduces electricity consumption but the nature of processes at the sites in Sheffield makes this approach difficult.

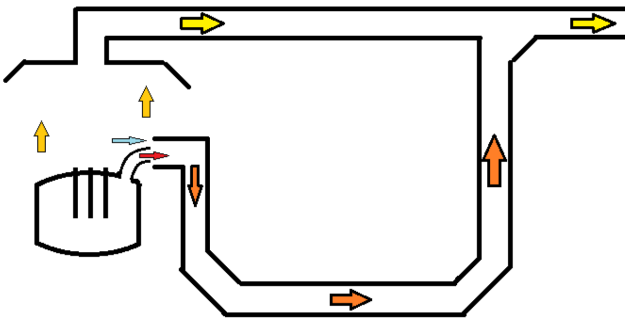

Figure 3: Schematic for the arc furnace (lower left) and its gas extraction ducts.

There are also gas fired furnaces and cooling water where heat could be recovered as detailed in Table 1. Various approaches were investigated in the models.

Table 1: The main features of heat sources on site.

Heat Source	Features	Useful Sources
Electric Arc Furnace (EAF)	• Heating process uses a lot of electricity. • A lot of heat is carried off at high temperatures in the flue gases [12][13]. • Waste gas stream is dust laden, but such problems have been solved for waste incinerators with heat recovery. • 10% of the total input energy is assumed recoverable.	Dixon and Bramfoot (1985) [11] Jones (1997) [12] Zuliani et al.(2010) [13]
Gas fired reheat furnaces	• Maximum fuel burn rate equates to around 10 MW on large furnaces. • For furnaces with a recuperator, around 24% of fuel energy input leaves via the exhaust [14]. • Exhaust temperatures will be variable. • A heat recovery of 5% of the input energy is assumed. • Bringing the exhaust gas to temperatures below 150°C increases the risk of acid corrosion on the heat exchanger.	Tenova Group (2014) [14]
Cooling systems	• Water cooling systems protect the lining of the arc furnace. • Cooling towers dissipate some of this heat, as does river water subject to environmental permitting constraints. • 7 to 17% of energy input to arc furnace leaves through cooling [12][13] • Cooling also needed for steam processes on site.	Walling and Otts (1967) [15]

3.3 Heat Storage Options

High temperature heat is already stored on sites using regenerator materials and in a steam accumulator. The accumulator matches steady production of steam from boilers to the short discharge needs of the vacuum processes. If more heat is to be recovered then the thermal capacities of the ceramic regenerators or the steam accumulator could be used to balance supply and demand of waste heat, although modifications will be needed to make such connections. If flue gas heat is recovered for generating steam then using existing steam storage facilities may be sufficient.

Medium to low temperature heat could be stored using hot water tanks which can be linked to district heating networks. If the water in the store is circulated in the network then this prevents temperatures losses through heat exchangers. However, the water quality needs to be sufficiently high and the temperatures and pressures of operation need to be compatible with the network. In the case of Sheffield's district heating, the store would need to operate between 70 and 110^{o}C.

For low temperature waste heat, underground thermal energy storage could be used and would give potentially a high heat capacity at low cost. Storing the cooling water is an option, but low temperatures mean a large volume of storage would be needed and this increases expense. If electricity is needed to run a heat pump and upgrade this heat at the time of use then this may be costly if it is needed at peak demand times.

3.4 Environmental Analysis

Any heat recovery project needs be evaluated, not just in economic terms, but also in terms of its environmental impacts. This can help industry meet environmental objectives and there are economic incentives in the UK supporting good practice. It is important to calculate overall impacts on CO_2 emissions while also for looking at how other gas emissions and resource use levels would be affected.

3.4.1 Assigning CO_2 Emissions

If heat is recovered and used to generate process steam then this displaces use of gas-fired steam boilers. If *x* units of gas avoid being burned then the carbon dioxide saving is given by equation (2). The standard gas boiler is assumed to operate with efficiency of 81% and using a fuel of 0.185 kg CO_2 equivalent per kWh, bringing the total to 0.228 tCO_2 per MWh delivered to the customer, as laid out in UK carbon reporting regulations [16].

$$\mathrm{CO_2\ saved} = x\ \mathrm{MWh}\ \times 0.228\ \mathrm{tCO_2/MWh} \qquad (2)$$

If *y* MWhs of heat are recovered for distribution through a heat exchanger and along district heating, this displaces the traditional use of gas boilers saving carbon. Heat losses with district heating are typically 5% and this replaces a gas boiler emitting 0.228 kg CO_2 per kWh of heat delivered. The CO_2 equivalent saving in this situation is given by equation (3).

$$\mathrm{CO_2\ saved} = y\ \mathrm{MWh}\ \times 0.95 \times 0.228\ \mathrm{tCO_2/MWh} \qquad (3)$$

When using a heat pump to supply *z* MWh of heat, the picture is more complicated, and if the heat pump is electricity-driven then the carbon emissions associated with that electricity need to be accounted for, the figure used here is for the UK electricity in 2011 and assigns 0.484kg CO_2 equivalent to each kWh consumed [16]. The electricity consumed relates to the output heat energy using equation (1), and overall carbon dioxide saving is calculated using equation (4).

$$\mathrm{CO_2\ saved} = z\ \mathrm{MWh}\ \times 0.95 \times 0.228\ \mathrm{tCO_2/MWh} - \frac{z\ \mathrm{MWh}}{\mathrm{CoP}} \times 0.95 \times 0.484\ \mathrm{tCO_2/MWh} \qquad (4)$$

3.4.2 Other Emissions

Modern industry recognises the need to monitor, control and minimise emissions of particles and harmful gases from their processes. One example of an emission that is closely monitored is dioxins, and while over 90% of human exposure is from dioxins present in food [17], industry is regulated to minimise dioxin emissions. High temperatures of over 850^{o}C are required to destroy these particles [17], and there is a chance of reformation between 500 and 250^{o}C. Many steelworks use quenching of gases with water spray to pass this critical temperature zone [18]. With flue gas heat recovery, heat exchanger design should account for this issue.

Another important issue for heat recovery is the flue gas level of sulphur oxides, if these gases combine with moisture they create acid and this can corrode any heat exchanger increasing maintenance needs. In some instances, lime can be used to counter acidic gases, and activated carbon can be used to capture dioxins and heavy metals.

3.4.3 Water Use

The amount of water consumption at a steelworks is another issue with environmental implications. approximately 14 to 28 m^3 of water is required per tonne of steel produced in electric furnaces [15][19]. For some processes, the water is limited to a certain temperature rise in the cooling circuits to prevent corrosion, and high water velocities are needed to prevent particles from settling in cooling systems [15].

The adjustment of cooling systems is a complex issue and will require detailed work by engineers to consider consequences before proceeding, however use of high temperature cooling has been achieved in some instances [8] and this would carry benefits in terms of transferring heat to district heating as well as reducing water use. Even the current low temperature cooling could provide water suitable for a heat pump.

3.5 Economics of Heat Recovery

Fuel prices for UK industry have been rising over recent years as shown in Figure 4. For example, industrial gas prices rose 10% between 2012 and 2013 (8% when accounting for inflation) [20]. The economics of heat recovery in future years will depend upon the price of natural gas over the lifespan of the project, since natural gas is the alternative for industrial heating and main competitor to district heating.

If preheating of scrap were possible this would reduce the amount of electricity needed. The recovery of heat to generate steam would significantly reduce use of natural gas in the steelworks. The larger steel sites (B and C) in this instance are further from the district heating networks swinging the favour in the direction of electricity generation using technologies such as organic Rankine cycles (ORCs). Furnace processes are more continuous on the larger sites further increasing feasibility; for example on one site the electric furnaces runs for six days per week [5]. The processes at site A are unlikely to be sufficiently continuous to justify the production of steam for electricity generation.

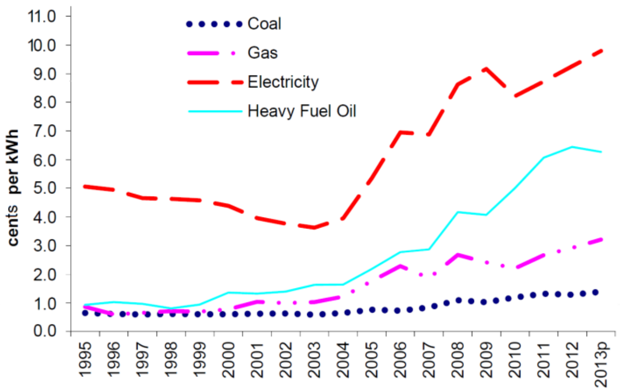

Figure 4: Industrial energy prices in the UK from 1995 to 2013, in euro cents. Source: DECC [20].

Site A is already adjacent to a district heating pipe, therefore heat feed in would be relatively easy. To connect site B to the district heating network will require around 1.5 km of new district heating trench but there may be potential new customers along the way. Connecting site C to a heat network will only become feasible if Rotherham develops a heat network infrastructure, which may happen in the long term. Then, perhaps 2 kilometres of extra trench would be required from a town centre network. District heating extension costs are approximately €630 to €1.390 per metre in the UK depending on the circumstances [21].

In areas with clustering of industry steam networks may be viable for trading heat, and new industries could be located nearby to take advantage of this. However, the timing of steam supply and demand may not match up and the pressure and temperature required by different customers also may not match.

There are many policy incentives in the UK driving improvements in environmental performance, comprising four main elements [1]:

- EU Emissions Trading System;
- Climate Change Levy;
- Climate Change Agreements;
- Carbon Reduction Commitment Energy Efficiency Scheme.

There are also support mechanisms for funding energy efficiency projects such as exemption from Enhanced Capital Allowances on energy efficiency equipment as well as funding opportunities from the UK's Green Investment Bank or the EU Regional Development funds [1]. Finally, the UK's Renewable Heat Incentive gives financial support for ground source heat pumps and from 2014 will allow these to access the heat in industrial waste heat streams [22].

4. RESULTS

Values for technically recoverable heat were developed based upon estimated annual production figures that were in the public domain and these were combined with estimates for energy consumption per unit produced along with how much heat could be recovered from different waste heat streams. The results are summarised in Table 2 for these three sites.

Table 2: The estimates for technically recoverable heat at the three sites.

Annual Output (tonnes)		Flue Gas Heat Recovery		EAF cooling water heat recovery (MWh/year)
		Gas furnace (MWh/year)	EAF (MWh/ year)	
A	60,200	2,000	3,000	3,000
B	260,000	8,700	13,000	13,000
C	750,000	24,200	37,400	37,400

The amount of heat that can be recovered depends upon how that heat is to be used, for example if the heat is to be used to generate high pressure steam then only heat above a certain temperature will be useful. A two-part heat exchanger could be used in order to generate hot water for district heating from the partly cooled flue gases allowing for a greater level of heat recovery. These would be aspects to consider in the detailed design of heat recovery equipment.

It is assumed here that where cooling water heat is recovered for district heating, a heat pump coefficient of performance (CoP) 3.0 is used. Vapour compression heat pumps require electricity to run a compressor and the high carbon intensity of UK grid electricity leads to only a small carbon saving. There is roughly twice as much heat in the EAF flue gases as is needed for steam generation and correspondingly that heat is divided between steam and hot water production. The use of waste heat and the carbon savings calculated using equations (2), (3) and (4) are given in Table 3.

Table 3: The expected carbon dioxide savings for heat recovery.

Heat Recovery Project	Site	Heat output (MWh/ year)	Annual CO_2 Saving (tCO_2)
Steam from EAF flue duct.	A	1,500	342
	B	6,500	1,482
	C	18,700	4,264
Hot water from EAF flue duct.	A	1,500	325
	B	6,500	1,408
	C	18,700	4,050
Hot water from gas furnace flue duct.	A	2,000	433
	B	8,700	1,884
	C	24,200	5,241
Hot water from cooling water heat pump.	A	4,500	285
	B	19,500	1,235
	C	24,200	1,533
TOTAL		136,500	22,482

Instead of electricity, steam from flue duct heat recovery could be used to drive an absorption-type heat pump; then the carbon savings would be much greater. Finding an appropriate heat pump technology able to deliver at the right temperatures with a low carbon footprint is vital for making a significant environmental saving while the UK grid electricity emissions factor remains so high.

For the contribution of heat to district heating a new heat store would be required. If the heat is just used when demand is available, and discarded when demand is not then this avoids the need for heat storage however it also reduces the environmental benefits. A hot water store could be off-site if connected via district heating, although the feed-in temperature and rate needs to be carefully controlled if feed in to the heat network is instantaneous. If the heat store is operational as part of the network then it can also provide services to the district heating operator.

Table 4 shows the estimated storage needs for different heat recovery scenarios. The cost of the additional storage needed for recovering cooling water heat, and the low economic and environmental gains make that option the least appealing and therefore unlikely to be practical.

Table 4: The nature of heat storage need in each heat recovery scenario.

Waste Heat	Production Variability	Storage Need
Steam from arc furnace flue gas	Produced and used 4 days/ week at site A, around 1,500 MWh/year.	Use existing steam buffers
Hot water from arc furnace flue gas	Produced and used 4 days/ week at site A, around 1,500 MWh/year.	20 MWh ($600m^3$) Pressurised hot water store
Hot water recovered from reheat furnace flue gas	Most likely to be economically recoverable at site A, around 2,000 MWh/year	20 MWh ($600m^3$) Pressurised hot water store
Cooling water	Recoverable if heat pump solution is practical	35 MWh hot water store at site A or on the DH network

5. DISCUSSION

The carbon footprint of an electric steelworks depends heavily upon the carbon emissions associated with using grid electricity. This is currently high in the UK, but is likely to fall in the medium term from its current value of around 0.484 kg CO_2/kWh as the amount of low-carbon energy generation increases. However, the emission intensity is already much lower in competitor countries such as France and Sweden.

To effectively use industrial waste heat the operational principles need to be established early with the district heating operator, including what charges and payments apply for supplied heat as well as when and how much heat can be fed-in at various times of day. There will be knock-on effects for other heat sources on the network. For example a flexible CHP unit can be switched from electricity to heat production and therefore the injection of industrial heat increases the capacity to add electricity production to the grid. However, the relative amount of heat and power production can affect the eligibility for renewable energy incentives in the UK. If electricity is used for a heat pump then heat injected to district heating, this could have a negative effect on emissions associated with delivered heat and the way this is accounted will be important.

Investment in heat recovery has to compete against other possible investments that can help with energy saving. For example, sites B and C have invested in variable speed drives for the flue gas extraction systems in recent years and this may also be a possible energy-saving investment for site A. If placing a heat exchanger into the flue gas duct increases the electricity consumption of the extractor fan then the process of energy recovery increases the overall carbon emissions. Also, if the process efficiency is negatively affected (for example the slower dust removal means the melt takes longer and therefore heat losses from the furnace increase).

Altering operational temperatures on the heat network would make the recovery of heat more feasible but the temperatures need to be sufficient to satisfy the needs of all the customers. If the new network connects to the old one then the water needs to be hot enough to be used by an absorption chiller unit in the city centre. In the long term, lower temperatures could assist the integration of geothermal and solar energies too.

Overall, it is quite probable that the energy spent in running a heat pump is inhibitive to the economics and therefore that only the flue gas heat which is much hotter can be recovered. However, if significant charges are associated with river water use for cooling then saving water by recovering heat may have better economics. The amount of heat that is recovered will depend upon the economics of the project and the sale price which heat can achieve through the network.

6. OUTLOOK

The expanding heat networks have the potential to provide a heat sink for excess heat created on these three sites and there may be other companies in the city that are generating waste heat which could also feed into the heat network. The UK has advantages in that there is likely to be significant expansion of heat network use in future; planning heat networks to run close to industry sites and early investigations of possible heat customers along those routes can help to reduce investment uncertainty. Co-location of industries is another important option, particularly with high-temperature heat which can be distributed over small distances using a steam network rather than a hot water network.

In order to minimise costs of feasibility studies, forging a partnership between these companies to investigate and invite consultants may lead to greater chances of success, even for the sites some distance from the district heating network there may be benefits for recovering heat for use in steam generation although there is understood to be significant excess steam produced by heat recovery. A shared expertise in operating and maintaining heat recovery equipment between these sites may lead to a significant cost saving on staffing.

7. CONCLUSIONS

Recovering heat from high-temperature industrial heat sources can boost the overall system efficiency and give environmental advantages; however there are barriers to making this feasible. In particular, the up-front cost of constructing district heating networks means that connections to industry can be capital-intensive. High-temperature heat pumps are a quickly developing technology, but some designs have practical limits on delivery temperatures which may limit their applications. In the UK, the high carbon intensity of grid electricity reduces the environmental advantages of electricity-driven heat pumps. Adjusting district heating networks to run at lower temperatures in future will increase both efficiency and volume of recoverable industrial waste heat. Working to maximise heat recovery will help energy intensive industry contribute to reducing the economy's carbon intensity.

8. ACKNOWLEDGEMENTS

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CHINA'S ANSHAN PROJECT- A GOOD EXAMPLE TO IMPLEMENTING SCANDINAVIAN DH TECHNOLOGY AND ENVIRONMENTALLY FRIENDLY HEAT SOURCE TO UPGRADE THE DH SYSTEM

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ABSTRACT

Coal as dominate fuel in China's district heating (DH) section has brought out a series of environmental, healthy, and economic challenges. Central government of China makes great efforts to seek better solutions to improve overall DH system efficiency and reduce energy consumption as well as control the emission of pollutants and greenhouse gas (GHG).Optimisation of multi-heat sources such as the collectives of surplus heat from industrial processes, renew energy, combined heat and power (CHP) and heat only boilers (HOBs) for example is a good consideration. Research showed that if surplus industrial heat would be utilized to a great extent, it could cover up to 70% of the heat demand in northern China's legal heating regions. In addition, urbanized city areas always have developed DH pipeline infrastructure. The city of Anshan is a great example how industrial surplus heat from the ANGANG (AG) steel plant can be used in the Anshan DH network. Anshan is currently undergoing a major upgrade of DH system by implementing Scandinavian technology and way of thinking for achieving considerable energy and environmental emission reductions at the same time as the comfort for the consumers is raised. These could include the establishment of multi-heat sources by utilizing waste heat, pooled operation and automatic controls applied for the DH systems. This paper will present the inspirations from the Anshan project to illustrate the potential benefits of China's DH systems if they are brought up towards the Scandinavian level.

1. INTRODUCTION

China's DH technologies originally learned from the Soviet Union, heat is supplied mainly for space heating(SH), minor domestic how water (DHW) systems, actually less than 5%[1], are integrated into the DH systems. That means typical DH system operates only in winter, namely heating season. Geographically, China is divided into North China and South China along the dividing line: Qinling Mountain Range and the Huaihe River. All 13 provinces and cities are the legally "heat-required" areas and located in the north of the dividing line. Most of areas belong to the cold and severe cold climate zones[2] with at least 90 days of average outdoor temperature at or below 5°C.

Anshan is the third largest prefecture level city in Liaoning province with the population of 3,584,000, and covers an area of about 9,252 km^2.[3] Geographically, Anshan locates in north east China and belongs to severe cold climate region. The heating season lasts around 150 days. Anshan city has very representative DH system in China, since it can reflect the generally existing problems or could say to be excavated potentials for most of China's DH systems.

Generally, 1).heavily dependent on fossil fuels, mainly coal, as well the associated with pollution and high GHG emission issue; 2).Low efficiency leading to the high energy consumption;3).Manually operate or control the system brings out the faults and low efficiency. These issues stand for the typical problems currently existing in the China's DH systems, whereas they also can be found in Anshan DH system.

According to the data from China's State Statistics Bureau, in 2008 the national heating sector consumed 145.4 million tons of raw coal - about 91% of the total energy supply to the sector, around one third of which is used in low efficiency, heat-only boilers [4]. Coal combustion and uncontrolled coal-fired boilers are often significant sources of high concentrations of SO_2, and fine particulars (PM10, PM2.5, and even finer particulate Matter). Air pollution is an enormous challenge in China today, which could compromise the gained economy achievement and also imply more financial investment to govern the environment and protect people's health.

Another challenge is the energy supply security. The development of DH in China has gone hand in hand with rapid urbanization and economic growth in the last ten years. China's urban building area nearly keep 11.1% average annual growth rate, and reach 21123.4 million square meters of 2010, and DH covers about 70% the building area in northern China which is the mandated heating areas[5]. The rapid urbanization speed means continuously growing the heating areas and associated rising energy consumption.

Furthermore, technical difficulties exist in how to improve the efficiency of overall DH system. For instance, one of the challenges of Anshan city's DH system reflects on the hydraulic imbalance and consequent problems, such as insufficient available head between supply and return pipe, high return temperature, high electricity consumption of pumps, unsatisfactory indoor comfort level etc. Meanwhile, a general lack of automatic control devices in DH system has caused over manual operation workload, imprecise and empirical control, it is said the DH system can't automatically regulate the heat output according to the weather change rather than the operator's personnel experience or judgment. Therefore, request and demand can't match well, which heavily influences the efficiency and flexibility of DH system. Moreover, some old buildings with poor-insulated pipes and disrepair shut-off valves have led in the quite amount of water leakage and heat loss. Since the heat bill is charged by the fixed cost according to the floor space, the heat consumers have not incentive to save energy consciously. On the other hand, in order to improve the satisfactory degree of heat users, and make heating fee to be paid on time, DH companies have to supply excessive heat to satisfy the distal heat consumers, which makes the proximal heat users get much more heat than needed. Hence, renovation of automatic control system are urgent, which should penetrate the entire DH system including primary network, substation, secondary network and end users.

Under this background, the stresses from environmental pollution and increasing rate of energy consumption as well as low efficiency of DH system issues force China's government to think about the DH development strategies, whereas efficiency improvement and modernizing DH with clean energy technologies have the maximum synergy between energy supply security and air pollution abatement.

This paper takes Anshan DH project as example to state the potential benefits of China's DH systems and illustrate the specific technical measures with fusing Scandinavian DH elements or experience, which aim to improve the overall efficiency of DH system and the overall control strategy application.

2. STATE OF THE ART

2.1 Background introduction

Denmark is one of the most energy-efficient countries in the world. A wide range of pro-active, energy-saving measures have decreased energy consumption and increased the use of renewable energy and technological development. Since the 1980s, Denmark's energy consumption has consequently remained steady, while the economy has continued to grow. The widespread use of DH (DH) and combined heat and power (CHP) has made a major contribution to Denmark's drive towards efficiency and energy self-sufficiency[6][7][8]. It could say Denmark has state of the art of DH technology, whereas the achievements are learnt from yesterday's lessons.

1970's energy crisis alerted Denmark to break away the heavy dependant on oil. Afterwards, a series of energy regulations by attaching the corresponding subsidy and tax policies had led the country to wisely utilize the energy. The heat supply legislation is specifically stated "the utilization of energy must be carried out in the best possible way from both an economic and an environmental point of view." [9] At the same time, development CHP (both large-scale in the populated metropolitan regions in centralized mode and decentralized CHP plants in small cities) and DH had been given high priority. Today, CHP supplies 77% of the heat in Denmark, and DH share would increase from now more than 60% to over 70% for the next decade[10][11].

2.2 Copenhagen DH system

Among Danish numerous DH systems, Copenhagen's DH system is as one of the largest DH system in the world, would be the representative to present the state of the art of Danish DH technology. The DH system of Greater Copenhagen has approx.34,500 TJ (9,600 GWh, 32,700 GBtu) annually heat consumption including the heat loss in 2012 and covers around 35.5 million square meters building stock. The system also involves 18 municipalities, 25 DH companies and 500,000 end users. It meets approx. 20 % heat demand in Denmark[12]. Moreover, the system operates for the whole year to supply SH and DHW simultaneously. Especially in the municipal Copenhagen, the length of 1,500 km double-piped DH network covers more than 98% of heat demand, and the request of DH connection still keep rising[13]. The system is featured as multi-heat source options by considering flexible and high level energy supply security in economic and eco-friendly way; high efficient transmission network and distribution system are connect by the heat exchanger and pump stations, the number and the location of these stations have been chosen with a view to achieving the best possible technical and economic solution for the entire DH system; high-level automatic operation system ensuring the control, regulation and monitoring, even maintenance of DH system to be carried out by computer system; as well as the significant reduction the adverse effects of energy consumption on the surrounding environment. By tracking the development of Copenhagen DH system, the successful experience is worth to spread and learn by other DH application counties.

2.2.1 Multi-heat sources system

The Copenhagen DH system was initiated in the mid of 1920s, nearly 100 years technology evolutions brought out a remarkably sustainable energy production model. CHP-based DH makes it possible to increase the total efficiency of the heating process, also benefits fuel flexibility, energy savings and pollution reduction. There are 10 different CHP plants and other additional heat plants by utilizing industrial surplus heat, geothermal and solar etc. to produce heat for the DH system. According to the data from CTR (Centralkommunernes

Transmissionsselskab I/S), in 2012, 92% heat production is from surplus heat of CHP plants and industrial processing. No fossil fuel accounted for 44% in the DH fuel consumption structure. Table 1 shows the heat production in Copenhagen's DH system from various different units by burning different fuels with different heat capacity.

Table 1.Heat production units of Copenhagen DH system[14]

	Supply units	Fuel	Heat Capacity (MW_{th})	Electrical Capacity (MW_e)
CHP Plants	Avedore, Unit 1	Coal	330	250
	Avedore, Unit 2	straw / wood pellets / natural gas / fuel-oil	570	585
	Amager, Unit 1	Wood & straw pellets (coal back-up)	250	80
	Amager, Unit 3	Coal	330	250
	Svanemolle	Natural gas	138	71
	H.C. Orsted 7	Gas/ fuel-oil	224	88
	H.C. Orsted 8	Natural gas	42	24
	Amagerforbraending	Waste	120	29
	Kara/ Noveren	Waste	12	71
	Vestforbrænding	Waste	31	219
	HOBs	Natural gas	1300	–
	Heat accumulator	Thermal storage	330	–
	Geothermal heat plant	Geothermal energy	13	–
	solar plant	Solar energy	0.28	–
	Surplus heat from waste water treatment plant	Industrial waste energy	?	–

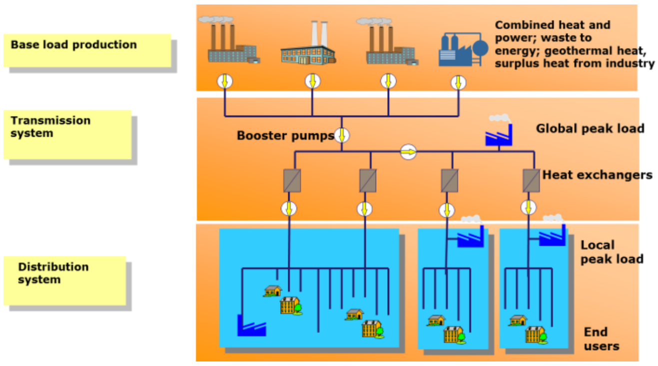
Except for these heat production plants, heat accumulators, as the thermal storage facilities, also play an important role. On the one hand, heat accumulators reduce the total installed capacity by either storing or supplying heat at times of off-peak or peak period respectively. On the other hand, they can also specifically be the adjustment facilities in CHP plants to optimize the output of electricity and heat at certain time. For instance, mainly for electricity generation when revenue from electricity sales is highest and allowing the heat generated to be made available at a later time when electricity revenue is not as favourable.

This kind of multi-heat source options create the very flexible heat generation system with high level energy supply security and minimum the influence of fluctuating world energy price. At the same time, it also ensures the DH system to operate in the best economic performance and eco-friendly way as well as the optimization production of heat and electricity.

2.2.2 Transmission network

Tracing back the formation of transmission network, it could say the legislation framework promoted the utilization of CHP, waste heat and renewable energy, and created the opportunity for this kind of hybrid energy production system. While the liberalized electricity market enforces the energy production enterprises to balance the output between power and heat in an economic way. Since the expansion of DH network had high priority in the heavily urbanized Greater Copenhagen area, the existed small-scale DH networks and the expansion need for electricity production facilitated a coherent DH transmission network for the entire area eventually. From a socio-economic point of view, the supply area was divided into two major transmission companies: CTR and VEKS (Vestegnens Kraftvarmeselskab I/S). These two companies' pipe networks were connected internally in order that heat could be exchanged in the most advantageous manner possible. Figures 1. illustrate the design concept of transmission network.

Figure 1.The design concept of transmission network[15]



The system concept virtually separates production, transmission and distribution as three divisions in order to optimize the energy production of the entire DH system in the most economical and environmental way while considering the system as a whole. Waste incineration plant has the first priority in heat generation, which keeps operating for all the hours. Then CHP cover the rest heat demand as the greatest extend as possible. General heat demand estimation, e.g. for CTR, is drawn up based on the forecasts from the Danish Meteorological Office. The heat supplied by the solar thermal and geothermal plants is upgraded using heat pumps to be supplied to the DH network. Detailed parameters regarding transmission network, might be seen in Table 2[15]. End users are also included in this table to present the temperature level in the internal building heating system and stressed that Danish DH system has integrated SH and DHW together.

Table 2.Parameters in the transmission network

Transmission		
Design parameters	120°C,25 bar	Variable flow and temperature control Symmetric pressure
operation parameters	95-115°C/45-60°C (supply/ return)	
Distribution		
Design parameters	120°C,6.5-10 bar	Variable flow and temperature control
operation parameters	supply:80-105°C, return:40-50°C	
End consumer		
Space heating	70/40°C (supply/ return)	Heat is exchanged via building or house level stations which contain the systematic controllers
Domestic hot water	55-60/10°C (supply/ return)	

2.2.3 Computers control the system operation

In Copenhagen DH system, the obvious advantages of extensive use of computer technologies present as: 1).minimum the staff number; 2).optimize the energy consumption;3).establish hydraulic balance of the system;4).remote metering of DH substations.

1).In Copenhagen DH system, the extensive use of computer technology has minimized the staff number, manual operation and the associated potential errors. The example is the computer system of CTR, this company supplies heat to 275,000 households in five municipalities around Greater Copenhagen areas. From the general perspective, there is a central control room to monitor and regulate heat supply by using advanced computer technology, and other 5 main stations are located in 5 municipalities individually. Each of the municipal main stations is responsible for seeing to the actual operation and maintenance of those parts of the system that have been established in its municipality, and close monitoring of a number of heat substations within the supervision range area. In this way, all process control functions take place in independent sub-stations which can be operated independently from the rest of the system and which can carry out automatic regulation and sequent control. Communications between the stations are carried out by double (one is back-up) long fibre optic network. Additionally, in order to realize the control, regulation and monitoring of DH system, approx.10000 signals are installed to inform the process. In this way, the operation centre monitors the production, transportation and delivery of the heat to the end users. At the same time, as many of the daily control room tasks as possible have been automated. Therefore, very possibly, the system can run by following the planned operations which have been installed in the computers, while continuously adapt the operations based on the currently applicable conditions. This means, most of time, the operational personnel only need to intervene the arising alarms.

2).Another advantage of the automated control system is optimisation of energy consumption by adjusting the supply temperature as lowest as possible. As known, supply temperature in the DH system tends to be higher than necessary, while this correspondingly increases the heat losses and operational cost. Copenhagen's DH system solutions are: based on the historical data from SCANA system, load forecast is produced in the form of supply temperature, return temperature, flow, heat load, outdoor temperature and wind speed together with weather forecast data. The temperature optimisation module takes into account the accumulated energy in the net, and the changes needed as a result of the weather forecast. This can be carried out by the common operational changes, such as valves being opened or closed, large consumers with varying consumption, and variations during weekends and holidays and as well unusual operational interruptions. Practice has proved, an exceptionally detailed regulation of the temperature of the system can lead to appreciably large savings.

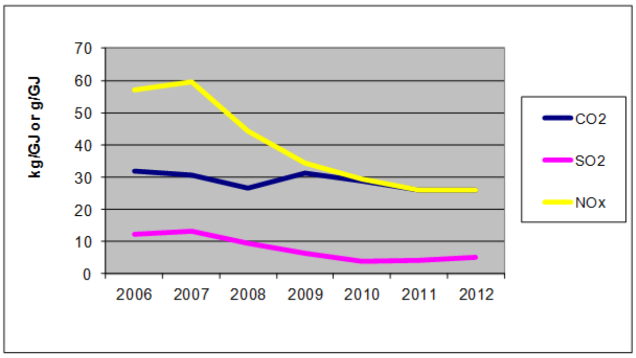
3).In addition, pressure or flow controllers are installed in the substation to establish the hydraulic balance of DH system, which can control the differential pressure to a level necessary for operating the substation and thereby controlling the flow rate in individual branches of the system.

4).And remote metering of DH substation not only measure the energy consumption, also uses for monitoring of substation to detect of malfunctions and improve the performance of the substations, e.g. reduction of return temperature. This kind of heat metering mechanism based on actual consumption also an effective method to encourage end users to save energy consciously.

2.2.4. Economic environmental benefits

In a normal year, 5 million MWh is delivered from the 50 km long CTR transmission system through 29 heat substations to the distribution networks. The annual heat loss in the transmission system is 1%. The heat is produced in an optimal way by waste-to-energy. Therefore, by using renewable energy and reducing cooling losses from the power plants, the fossil fuel consumption for the heat is only 0,3 MWh fuel per MWh thermal energy. The CO_2 emission is only 96 kg/MWh heat delivered to each distribution network and it is still being reduced by integrating more renewable energy in the production. Moreover the shift from small local boilers to large CHP plants with efficient flue gas cleaning, incl. removal of SO_2 has had a very positive impact on the air quality in the Greater Copenhagen area. Figure 2 shows the yearly reduction of CO_2 emission and mainly pollutants from fossil fuel combustion. The environmental benefits are significant by CO_2, SO_2, NO_x yearly reducing rate of 3.0%, 9.8%, and 9.1%.

Figure 2.The yearly reduction of emission and pollutants[15]



2.3 Discussion

The history of Danish DH is more than 100 years and still very much a part of modern society and the future. During 100 years' development and expansion of DH systems in Denmark, the intense research was carried out, and associated policies, legislations and laws were developed to orient the development direction of DH industry. It could say the general objective was DH system should provide more efficient operation and contribute to the overall energy saving targets while considering environmental influence. Copenhagen DH system could be a good example to present the achieved results which were appreciated world-wide. Even though, China just started to develop the DH industry since 1950s, it could say Denmark and China are at different development stage of DH industry, these two countries also very different national conditions, these are not the main obstacle to apply the practical DH technologies and absorbable inspirations for China to learn from Danish experience and lessons.

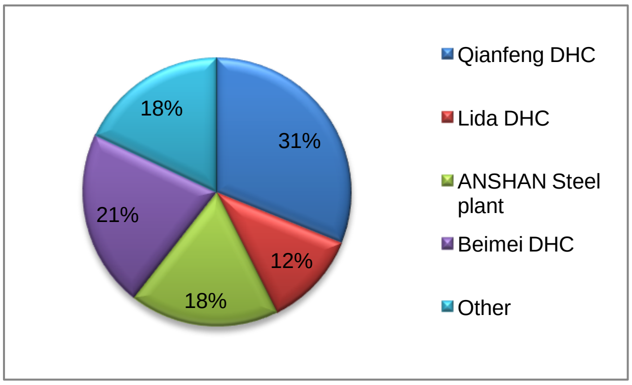
3. METHODS/METHODOLOGY

3.1 Introduction

Currently, coal-fired HOBs are the main heat sources of Anshan DH system. According to the data from ANSHAN government, the existing heat areas are 61 million square meters in ANSHAN city. Two municipal DH Companies (DHC): Qianfeng (31%) and Lida (12%) can meet over 40% heat demand of the city, which both account for 26 million square meters heating areas. ANGANG (AG) steel plant supplies heat to 18% of the total existing heat area in the city, mainly for industrial buildings, office buildings and residential buildings within AG steel plant area range. Beimei DHC is a private heating enterprise and supplies 21% of the total existing heat areas. The rest 18% of the total existing heating area mainly is supplied by scattered or small scale heating systems which are mainly powered by coal-fired boilers, see Figure 3, which shows the profile of DH enterprises in Anshan city.

Like many other northern China's cities, coal is the dominant fuel for DH systems in winter, whereas this issue have brought out a series of environmental, economic and healthy challenges. Under this background, Anshan government decides to precede the renovation and upgrade of the city DH system from two municipal heating enterprises: Qianfeng and Lida DHC. In 2013-2014 heating season, Qianfeng DHC delivered heat to 19 million square meters heating areas through 8 coal-fired DH plants. And Lida had supplied space heating to 7 million square meters heating area via 4 district heating plants. The medium in DH network for both of DHCs is hot water, coal-fired HOBs are the unique heat generation units, most of them only operate in winter time and produce hot water for space heating.

Figure 3.Current DH enterprises profile in Anshan



On the other hand, ANSHAN is also a mining city and a centre of heavy industry in China. It is home to the Anshan Iron and Steel Group (AG steel plant belongs to this group), one of the largest steel producers in China. Generally, burning coal is the common way to power the industrial production processes. Therefore, air pollution issue is severe in Anshan, the situation could be even worse in winter, because more coal is consumed in heating season to simultaneously power the industrial production and DH system. According to[16] ,the research showed air quality issue of Anshan is the typical coal smoke pollution. It also presented dust, PM10 and SO_2 concentration exceeded the national standard greatly, while the source of SO_2 is mainly from coal combustion.

Additionally, Anshan DH industry has grown rapidly in past ten years. The continuous expansion of heating area and the improvement of life quality both request high comfort level for SH and DHW. It implies not only even higher energy consumption, but even severer pollution issue if the DH system is not renovated. Except for the high pollution, high emission and high energy consumption, Anshan also faced the challenge from the low efficiency of DH network as mentioned above, which was partly caused by hydraulic imbalance.

Therefore, the undergoing major upgrade of DH network in Anshan aims to achieve considerable energy and environmental emission reductions, by focusing on these aspects:

- Exploitation of local waste energy
- Control, regulation and monitoring integrated system
- Improvement of the overall efficiency of DH system
- Achievement of the hydraulic balance of DH system
- Application of Intelligent devices in DH system.

While the renovation of Qianfeng and Lida DH systems would be in the pilot project.

3.2 Available local waste energy in Anshan

In Anshan DH renovation project, utilization of local waste energy has the first priority. The local waste energy refers to surplus heat from industrial process of AG steel plant, and shifts the existed power plants in AG steel plant range to CHP plants so that efficiency of power plants would be improved as well as the associated environmental benefits. Table 4 shows the available waste energy based on the initial investigation of AG steel plant.

Table 3.Available waste energy within AG steel plant range

Waste energy type	Item	Waste energy sources	Heat capacity（MW）
Waste energy from CHP	1	2nd power plant	400
	2	1st power plant and North power plant	200
	3	Back-pressure turbine	240
	4	Qikuang power plant	50-100
Waste energy from industrial surplus heat	5	Cooling water of blast furnace wall and slag flushing water from steelmaking plant	466
	6	Waste gas from coking plant and waste heat from coke-oven gas	226
	7	Waste heat from clean cycled water	268
	8	Waste heat from used cycled water	105
Total			1955-2005

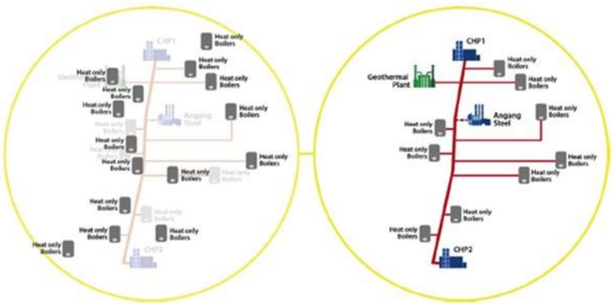
These above waste heat resources could be exploited and utilized within 2-8 years, and predictably meet over 50% base load of space heating of Anshan city. According to the data of Table 3, surplus heat from industrial process accounts for 55% of the total waste heat, whereas these kinds of industrial waste heat can supply the low-grade heat with temperature level less than 35 ° C (Item7,8), and 75 ° C(Item 5,6) respectively. Based on this scheme, the number of operating coal-fired HOBs (HOBs) could be reduced significantly, and transferred as peak-load or back-up heat generation units. Moreover, since CHP plants would be requested to install desulfurization and denitrification facilities, thus not only the pollutants, which generated by burning coal, can be correspondingly reduced, also the emission of CHP plants can be controlled. As for energy transportation, currently, there are 4 available transport routes, and 3 exploitable transport routes, total 7 transport routes will deliver waste heat to 4 city districts in the shortest distance, lowest investment cost, and the fastest effect. In addition, Anshan government also have the plan to exploit local geothermal resources as DH fuel in the future.

3.3 Transmission network

Surplus heat from industrial processes of AG steel plant, waste heat from CHP plants, the existed HOBs as peak load units, as well as the potential geothermal resource, Anshan city have the conditions to utilize multi-heat sources to power the DH system. While establishment of waste heat collection and transmission system will be a decisive factor if waste heat could be transported to the desired points in an appropriate way. Concerning this issue, Copenhagen DH system's experience is drawn on, and the transmission line approach is presented here. Figure 4 show the transformation of Anshan DH system by utilizing the transmission network approach. The left shows the situation before DH system transformation, and the right shows after the transformation: numerous coal-fired HOBs are either completely removed or replaced as peak load units, multi-heat sources are integrated into the DH system to greatly improve the energy flexibility. On the other hand, the entire DH system is divide three separate divisions.

- Transmission system (1st ring): Collect waste heat (including waste heat from CHP and surplus heat from industrial processes) from different locations of AG steel plant, then adjust hot water to a reasonable temperature level, then transport the waste energy to each boiler house through transmission network. Waste resource units would have the parallel connection with the existed boilers. During the heating season, waste energy is used to meet the base load, and boilers are as the peak load units.
- The primary network (2nd Ring): the thermal energy gotten from waste heat and boilers are driven by circulation pumps to each-substation,
- Secondary network (3rd ring): The sub-stations exchange energy from primary network to secondary network via heat exchangers, and eventually delivers to the end users.

Figure 4.Comparison of before and after transformation of Anshan DH system



The waste heat as a base load of DH system (approximately 60-70%), has the first priority. Since so, the situation of coal-fired HOBs as the unique heat source will be changed and the associated environmental damages will be alleviated greatly.

3.4. Integrated Control, regulation and monitoring into the operating system

Anshan project plans to establish the integrated control, regulation and monitoring operation system. And before, the systematic control and management of DH system are insufficient, even depend on quite big amount of manual work. In order to realize these functions, real-time operating data is detected through a variety of monitoring devices which are embedded in the acquisition systems. And these real-time operating data will be transferred to upper computer and lower computer via communication system; after analysis, calculation and optimisation, the instructions are issued to each execution unit. Since so, the control, regulation and monitoring can be implemented in the DH system.

Controlling the operation of DH system consists of hardware on the physical level, and software on the information level. In order to improve the overall operation efficiency, it is essential to fully play the advantages of both of them. Generally, software includes upper and lower computer system, and hardware includes parameter detection, imaging, transmission, and execution as well as control equipment. Uploaded and issued the data between software and hardware system is achieved via the communication system.

And the topology of control system can be simply described as follow:

1).DH system monitoring is based on a public communications network platform to create a heat production, transmission, distribution and data/information sharing platform. All the data from heating plants, heat transfer sub-stations, mixing-loop units, pipe network are gathered and directly brought together into this platform. 2).From the network structure point of view to analysis, SCADA monitoring system is standard four-level network architecture. The first level is monitor and control centre (MCC) of the whole central heating system; the second is the heating plants monitoring centre; the third is the remote terminal stations; the fourth is the site execution devices. 3).Lower heat substation to upper control centre (Each heat plants) establish a VPN communication link by taking use of public network platform (ADSL or wireless 3G network).Monitoring data streams and video streams are transferred through this link from the lower heat substation to upper control centre. The monitor and control instructions also are sending by this link.

3.5 Hydraulic balance of DH network

As mentioned above, Anshan DH systems encountered the hydraulic imbalance issue, which presented both in the primary side and secondary side of sub-station.

3.5.1 Implementation of hydraulic balance in the primary side

Taking Jiefanglu boiler house as example, which is one of heating plants within Qianfeng heating range. At the present, there are totally 48 substations connected to the Jiefanglu boiler house. Among them, 25 sub-stations are sub- manufactured with good quality components as a whole unit; the rest 23 stations are simply assembled with separate components together. Furthermore, this DH system is in hydraulic imbalances in the primary network of the substations: the differential pressure between supply and return pipes is insufficient, flow distribution is uneven between stations, it is namely either insufficient or overflow to fulfil the heat demand of each substation, as well as long-term manual work and high electricity consumption of the pumps. The energy output of heating plant can't be adjusted according to weather change.

In view of the above problems, the renovation technical proposal for hydraulic balance in the primary network is to install the self-acting differential pressure controllers in the branch pipelines in the primary network of substation; installation sub-station, instead of simply assembling the separate components together, in order to improve the overall quality and performance. At the same time, the essential control functions, remote monitoring, and the weather compensation are taken into account in the substation. By doing these, the expected effects are to eliminate the hydraulic imbalance among the substations; reduce electricity consumption of circulation pumps in the boiler house,; increase the differential temperature to get lower the return water temperature, thus reduce the heat loss of the pipe network; reduce manual workload to save the maintenance costs; saving the space and assembling time of heat stations. Figure 5 illustrates the outlook and the work diagram of sub-station.

Figure 5-1.Outlook of sub-station

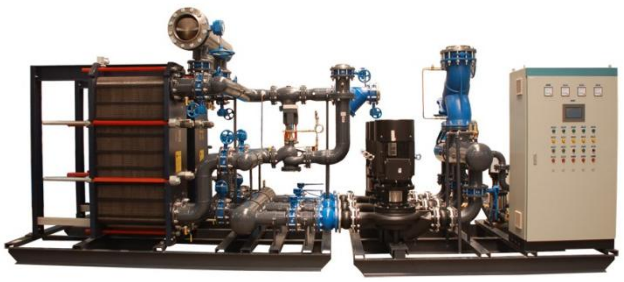
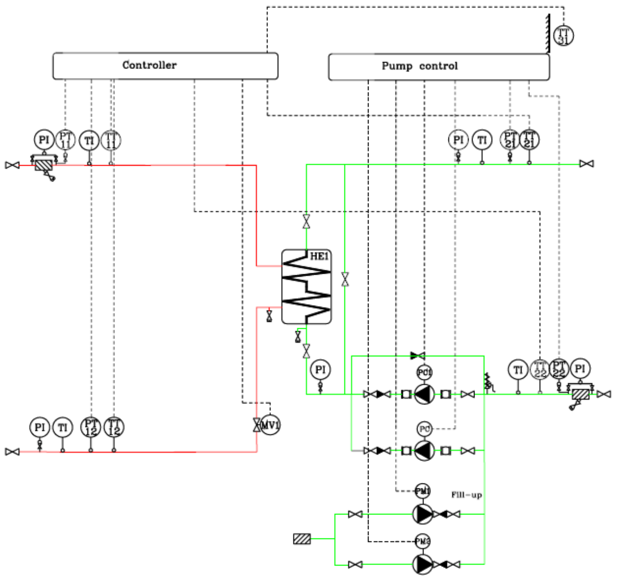


Figure 5-2. Work diagram of sub-station



3.5.2 Implementation of Hydraulic balance in the secondary network

For the secondary network system of Jiefanglu boiler house, the total heating area is nearly 4,000,000 square meters. Most of buildings are relatively old and the underground pipe-network system has complex transportation routes and connected with various manual valves by accompanying the operation difficulties and water leakages. For some of the new buildings, the secondary network system has no or less appropriate and effective flow regulation measures, it results in the regulation and maintenance have to be done manually on site and workload is huge, time-consuming and ineffective. The network is less flexibility, higher energy consumption and unsatisfactory comfort level of end users. In addition, Almost all of the secondary network system is under running with the large flow, small differential temperature ,the differential temperature of supply and return is only 5-7 ℃, this has result in the higher electricity consumption of pump.

In order to solve these problems, some technical measures are applied in the thermal entrance of the certain buildings, such as the application of self-acting differential pressure(dp) controller units, see Figure 6-1, and mixing-loop units, see Figure 6-2. The latter has the practical and comprehensive control functions, such as climate compensation, timing-operation and so on.

Figure 6-1.Self- acting dp control units

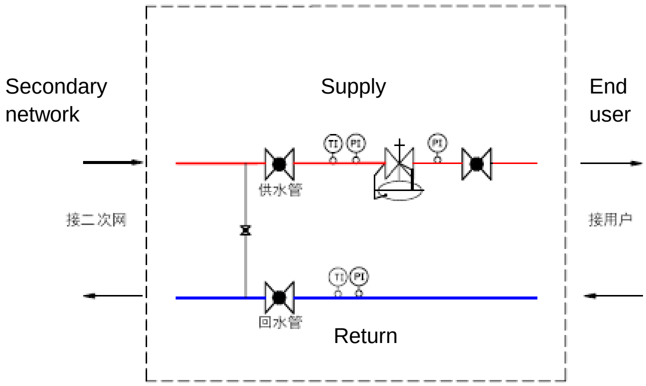
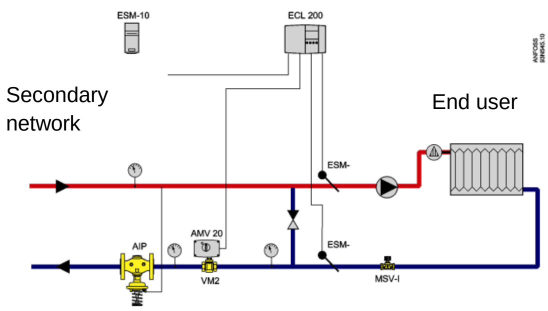


Figure 6-2.Mixing-loop unit



3.6 Economic and environmental benefits

It is a little earlier to say the apparent economic and environmental benefits of this project. But one could predict the potential concerning environmental and economic aspects. When tracing back Lida DHC's energy consumption and emission data during 2012-2013 heating season, it can partly get some evidence to support this point. For Lida DHC, past heating season lasted 152 days, from November 1, 2012 to March 31, 2013. During this period, these 4 DH plants, with a total of 11 coal-fire HOBs heated 5,956,800 m^2 of floor space, and burned 175,000 tons of coal, which is equivalent to 2,485TJ energy consumption. The DH systems were composed of 158,000m^3 of water and consumed 9,010,000 kWh of electricity. Meanwhile, CO_2 emissions were around 500,500 tons, along with 1487.5 tons of SO_2 and 1295 tons of NO_x, see Table 4. Predictably, in the next 5-10 years, the heating area will increase to 19,200,000 m^2. One can image that energy supply security and environmental issues will encounter even greater challenges. However, if the renovation and upgrade of DH system in Anshan city can be implemented successfully, around 50% energy consumption will be saved, and the associated reduction of pollutants and CO_2. But it is also important to remember: here Lida DHC is taken as the example to present the potential, whereas this company only met 12% heat demand of Anshan city in 2013. Therefore, the potential to save energy and reduce pollution is greatly significant in Anshan future. Furthermore, this hypothesis regarding DH industry also can be expanded to the whole of China.

Table 4. 2012-2013 heating season energy consumption and emission data of Lida DHC

DH plant	Heated floor area (m^2)	Coal consum-ption (ton)	CO_2 emission (ton)	SO_2 emission (ton)	NOx emission (ton)
Tao-shan	2,200,000	68,000	194,480	578	503.2
Ling-shan	1,800,000	51,000	145,860	433.5	377.4
Jian-guolu	1,203,600	34,000	97,240	289	251.6
Shuang shan	753,200	22,000	62,920	187	162.8
Total	5,956,800	175,000	500500	1487.5	1295

OUTLOOK

Anshan waste heat utilization and energy-saving demonstration project will be a good example for more other cities' DH projects in China, and provide the guidance and experience to them. It mainly reflects on these aspects: full utilization of local waste energy resources; combination the advantages of the intelligent software and hardware together to implement of integrated information management, controlling and monitoring; specific targets to ensure optimal operation of the whole DH system, to reduce energy consumption and emission, protect the environment, improve the energy efficiency, enhance supplied-heat quality of heating and satisfactory degree and comfort level of end users.

DISCUSSION AND CONCLUSIONS

DH is a systematic engineering and need to consider the overall solutions from a global perspective. At the same time, based on the local conditions, practical and implementable planning should be determined.

It is essential to make the full analysis, investigation, exploration to integrate the local resources before the existing central heating system is going to be optimized.

It is necessary to absorb the modern technology the development of science to rationally utilize the advanced and effective technical measures , and take the improving system operational efficiency as eventual target.

One of main tasks for China's DH system is to establish the integrated control, regulation monitoring system, and fully play the advantages of software and hardware in order to improve the management level, reduce the operational cost, improve the control precision, and enhance the comfort degree of end users.

Hydraulic balance is a key factor to influence the efficiency of DH system. Improvement of hydraulic imbalance issue of China's DH system should apply the practical solutions by focusing on the specific problems. As long as the measures are effective, the potential of energy-saving could be huge.

Because Waste heat utilization has its own characteristics, numerous factors need to be taken into account, they are not only limited as "thermal quality, parameters, stability of heat source, and the system's economic costs and benefits, as well as the influence on production process, system capacity and so on.

Usually, the actual benefits of relatively large waste heat utilization project can be reflected after long period due to the complexity and the needed long operation time.

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DEVELOPMENT OF A POLYGENERATION DISTRICT HEATING AND COOLING SYSTEM BASED ON GASIFICATION OF RDF

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ABSTRACT

A polygeneration district heating and cooling (DHC) system may produce not only cold, heat and electricity but also added-value product(s) depending on the technology selected. A promising choice as energy source for a polygeneration DHC system is refused derived fuels (RDF). RDF can be transformed into a useful fuel (syngas) through gasification, which originates also solid products. The syngas can be used as the main fuel for the combined heat and power system, and the solid products may originate important added-value products, such as char coal. The main objective of this study is to examine the potential of using RDF as the main fuel for the polygeneration DHC system. To this end, thermodynamic, exergy and economic models were developed and applied to the proposed system. The results reveal the technical and economical potential of using RDF in polygeneration systems.

INTRODUCTION AND STATE-OF-ART

A district heating and cooling (DHC) system comprises a combined heat and power generation plant, distribution networks (heat and cold) and consumers (households, municipal buildings, etc.). Such a system provides thermal comfort to final costumers, and it is rather important in countries with cold winters, though it may be also suitable for countries with the relatively moderate climate as well. The conventional DHC system consumes considerable amounts of fossil fuels. This unfavorable consumption might be reduced by upgrading the conventional DHC system to a polygeneration DHC [1], [2]. The polygeneration system relies on different energy sources, including renewables. In this case, the DHC polygeneration system may produce not only cold, heat and electricity but also added-value product(s) depending on the technology selected.

A promising choice as energy source for a polygeneration system is refuse derived fuels (RDF). Basically, the term ‘RDF’ stands for a wide variety of comparatively high calorific products derived from municipal solid waste (MSW). Until very recently the common practice for the MSW utilization was landfilling with or without a pre-step of incineration. Recently, the European Union introduced regulations (Directives 2006/12/EC and 1999/31/EC) to restrict the solid waste landfilling with the goal to utilize MSW with the minimal impact on the environment and to intensify energy/resource recovery. One option is to process the MSW in order to obtain RDF, which can be used as either raw material or fuel.

Biomass, which includes the RDF, might be transformed into a useful fuel through two major processes: thermo-chemical or biological (anaerobic digestion and post-composting) [3]. The thermo-chemical treatment includes processes such as combustion, pyrolysis, gasification and direct liquefaction. Of those, the pyrolysis and the gasification present a great potential to be used in polygeneration DHC systems, while the liquefaction process is currently too complex and expensive to be a suitable solution. The combustion of biomass is the oldest and the most prevalent method of the biomass conversion [4], though its use in DHC polygeneration systems may limit the manufacturing of added-value products. Of the technologies listed above, gasification seems to be the most promising since it originates a syngas (CO_2, CO, H_2, CH_4 and others), and solid products (char and tar) [4]. Thus, the syngas can be used as the main fuel for the combined heat and power (CHP) system, and the solid products may be regarded as important added-value products. For example, the formed char coal could be used as a partial substitution of raw $CaCO_3$ in the cement industry [5] or as fuel for energy generation [6].

The main objective of this study is to examine the potential of using RDF as the main fuel of the polygeneration DHC system. Studies on RDF applications to polygeneration district heating and cooling systems are very scarce in the literature. The proposed system should be able to provide heat/cold and electricity for a region of Lisbon, called EXPO, and added-value products. The RDF conversion process used here is the gasification technology, which yields a syngas along with added-value products (char coal).

METHODOLOGY

The proposed DHC polygeneration system was designed based on an existing one; specifically, the Climaespaço DHC system, located in Freguesia of Santa Maria dos Olivais, Lisboa. This unit is a trigeneration system with a CHP working on natural gas with cold and heat distribution networks 60 km long [7]. The CHP output data were obtained from the Climaespaço unit, and the proposed DHC polygeneration system scheme includes the following major units: a gasifier, a gas turbine, a boiler, and an absorption chiller. Fig. 1 shows a schematic of the proposed DHC polygeneration system.

To evaluate the performance of the present system thermodynamic, exergy and economic models were developed in EES (Energy Equations Software) environment, which includes a detailed database of thermochemical properties for various substances.

Nomenclature

E – exergy, kJ

ΔH – heat of reaction (formation and etc), kJ/kmol

i – discount rate

Ir – irreversibility

q – energy, kJ

x – mole fraction

Abbreviations

CF – cash flow

ER – equivalence ratio

GT – gas turbine

HHV – higher heating value

HRSG – heat recovery steam generator

Inf – inflation

LHV – lower heating value

NCF – net cash flow

S/C – steam to carbon molar ratio

Subscripts

ash – ash

ch – chemical

cold – cold

com – compressor

exh – exhaust gases

ext – exterior

f – formation

gas – gasification

heat – heat

in – input

los – loses

out – output

p – isobaric

ph – physical

r – reaction

t – year

syn – syngas

Thermodynamic modeling

In order to model the system, a number of assumptions have been introduced such as:

- The system is regarded as stationary, with all processes being adiabatic and in equilibrium.
- Losses do not vary during the CHP operation so that equipment efficiencies are constant.
- The gas turbine works at the full load constantly, thus outlet exhaust gases characteristics do not change during operation.
- The system supplies heat and cold demands completely, while the electricity is produced also for selling to the grid.
- The major electricity consumers are the syngas compressor and the compression chiller.
- RDF is the main fuel and natural gas is used as the back-up fuel.

In this work the gasifier was modeled using the stoichiometric equilibrium model [4]. During the pyrolysis stage large biomass molecules disintegrate into smaller molecules of organic liquids (mostly tar), gases, char and ash without any interaction with the gasifying medium. In the gasification stage, gases and char in the presence of the oxidizer undergo through several major reactions, which determine the final syngas composition. Desrosiers [8], as it was reported by [9], indicated that, within gasification temperature range (600 K to 1500 K), CO_2, CO, H_2, CH_4, H_2O and char are the only products that exist with concentrations higher than 10^{-4} mol%. Assumptions similar to those listed in [9], [10] were also applied here.

According to [11] the typical gasification temperatures for RDF are within 1073 K and 1173 K; in this temperature range the following reactions are common [4]:

$$C + CO_2 \leftrightarrow 2CO \quad (1)$$

$$C + H_2O \leftrightarrow CO + H_2 \quad (2)$$

$$C + 2H_2 \leftrightarrow CH_4 \quad (3)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (4)$$

Equilibrium constants for reactions (3) and (4) may be found in references [12] and [13], as it was stated by [14]. In addition, it was assumed that char is pure carbon with mole ratio yield equal to 0.04.

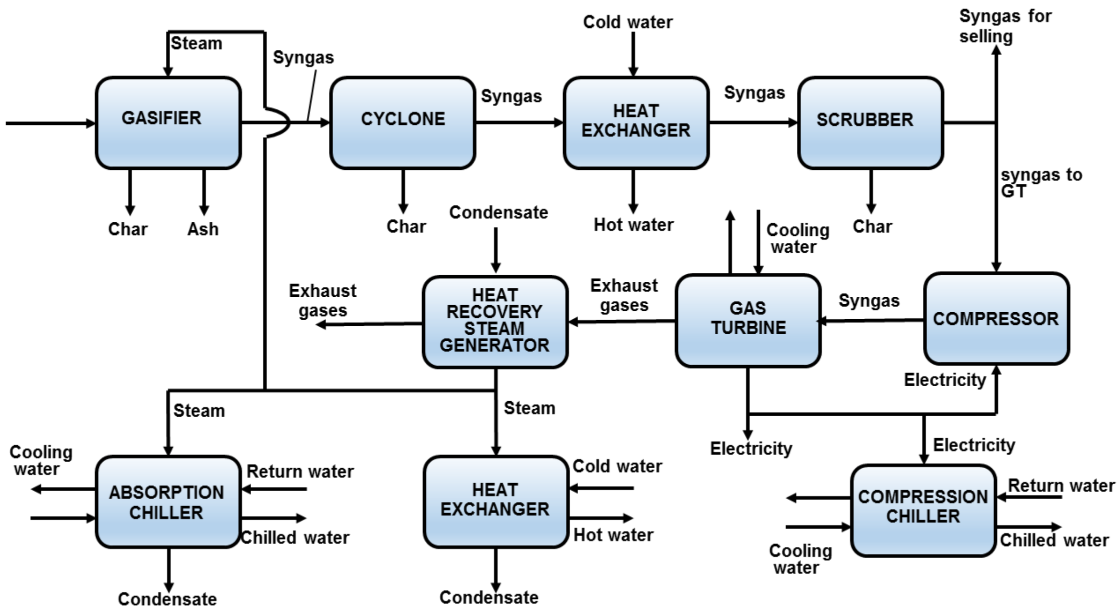

Fig. 1. Schematic of the proposed DHC polygeneration system.

An energy balance to the gasifier can be written as:

$$LHV_{RDF} \times m_{RDF} + q_{RDF} + q_{H2O} + q_{air} + q_{ext} = q_{syn} + q_{char} + q_{losses} + q_{gas} + q_{ash} \quad (5)$$

where the value of LHV of RDF was taken from reference [15].

The thermal energy of the gases was calculated through the expressions given in reference [16].

In Eq. (5), q_{gas} represents the net heat, which needs to be delivered/diverted to/from the reactor and can be calculated as [4]:

$$q_{gas} = \Delta H_{T\,r} = \Delta H^0_{298\,r} + \left[\sum \int_{298}^{T} x_{out}\, c_{p\,out}(T)dT - 298 Txincp\, inTdT \right. \quad (6)$$

where the RDF heat of formation can be calculated as [17]:

$$\Delta H^0_{298\,f\,RDF} = LHV_{RDF} + \frac{1}{M_{RDF}} \sum x_j \times \Delta H^0_{f,j} \quad (7)$$

The remaining enthalpies of formation were obtained from [18].

The modeling of the gas turbine, boiler, absorption and compression chillers and others minor units was performed based on existing equipment. Table 1 presents the characteristics of these units.

Exergy modeling

The main drawback of the first law analysis is that it characterizes different energy flows (heat, cold and electricity in the present study) as equal without taking into account their quality and their real potential towards the reference system. In addition, for the system balance it does not allow to consider the material flows (charcoal and syngas in the present study) as energy carriers. These shortcomings might be overcome by the exergy analysis. For this analysis the following assumptions were introduced:

- the system is quasi-equilibrium;
- the reference model does not undergo through changes in time;
- all gases behave ideally;
- kinetic and potential exergy changes are negligible.

The exergy balance for the polygeneration DHC system could be written as:

$$E_{RDF} = E_{syngas} + E_{char} + E_{exhaus} + E_w + E_{heat} + E_{cold} + \mathrm{E}_{ash} + Ir \quad (8)$$

and the chemical exergy of RDF (organic part) might be calculated as follows [25]:

$$e_{RDF\,org\,ch} = \beta \times LHV_{RDF}$$
(9)

Economic modeling

The economic evaluation of the system performance was based on the discounted net cash net flows criteria [26]:

$$NCF = \sum_t \frac{CF_t}{(1+i)^t} \quad (10)$$

The cash flow for each year (in USD), with the exception of the first year, consists of annual revenues from electricity, heat, cold, syngas and char coal sales with the substraction of the annual expenditures (maintenance, operation and insurance). Costs such as consumables were excluded from the model.

Table 1. Characteristics of the proposed units.

Equipment	Parameter	Value	Ref.
Compressor	Polytropic efficiency	80%	-
	Mechanical efficiency	97%	-
Gas turbine	Exhaust temperature	783 K	[19]
	Engine efficiency	31.5%	
	Output power	5670 kWe	
HRSG	HRSG outlet temperature	421.95 K	[20]
	HRSG efficiency	67.1%	[21]
	Steam pressure	10 bar	-
	Steam temperature	473 K	-
Absorption chiller	COP	1.12	-
Compres-sion chiller	COP	5.25	-
Conventional cyclone	Collection efficiency	90%	[22]
	Pressure drop	10 kPA	
	Temperature drop	10 K	
Air-to-water heat exchanger	Efficiency	90%	[23]
	Pressure drop	5 mbar	
Venture scrubber	Collection efficiency	100%	[24]
	Pressure drop	0.5 mbar	
	Working temperature	303 K	

The net cash flow for the first year has also investment costs. Furthermore, all costs associated with district heating/cooling networks and installation, civil and project engineering are excluded from this model since the proposed plant is intended to be constructed on the existing site.

The equipment costs were estimated following the method proposed in references [27] - [29]. The costs were updated to the level of the 2013 inflation by means of the chemical engineering plant cost index (CEPCI) [30]:

$$Inf = \frac{CEPCI_{2013}}{CEPCI_{year}} \quad (11)$$

The project lifetime is assumed to be 20 years in agreement to the lifetime of a typical CHP plant working on natural gas.

The fuel price is a crucial parameter for the economical model establishment. According to reference [31] prices of RDF vary from 0 to 40 euro/ton. Moreover, it should be stressed that currently there is no well-established market for RDF.

RESULTS

Thermodynamic analysis

According to reference [32], RDF specifications depend highly on the production line scheme and their origin. In the present study the RDF characteristics were taken from reference [33]. Table 2 shows a comparison between the predicted syngas composition with the present model and that obtained from experiments [33].

Table 2. Comparison between predicted syngas composition with the present model and that obtained from experiments [33].

Volatile gas	Content (%v)	
	Model	**Experimental**
H_2	42.6	42.7
CO	14.5	15.8
CO_2	9.2	17.9
CH_4	2.0	17.6
C_2H_4	-	5.6
C_2H_6	-	0.4
H_2O	31.5	-
N_2	0.16	-

Despite the model predicts well the contents of H_2 and CO, it fails to predict accuratly the contents of CO_2, CH_4 and H_2O. These deviations can be attributed to a number of factores, namely, syngas composition assumed in the model and char content assumed at the output of gasifier.

As syngas LHV is significantly lower than the natural gas LHV, the syngas mass flow rate fed to the GT must increase in order to produce the same electricity output at the generator terminals. As a consequence, the flue gases flow rate from the syngas combustion increase significantly as compared with the natural gas combustion, which causes an increase in the steam generation capacity.

The thermodynamic study reveals that the produced amount of steam in the proposed system covers completely the required head load, unlike the current system installed at Climaespaço. Additionally, the steam produced by the proposed system is enough to supply the absorption chiller so that less than 0.001% had to be provided by the compression chiller. Moreover, for the maximum heat and cold production the proposed system is produces steam in excess that can be used for other purposes.

It should be noted that the annual thermodynamic trigeneration efficiency varies marginally with the gasification temperature.

Exergy analysis

Fig. 2 shows the annual exergetic efficiency as a function of the steam to carbon ratio at a gasification temperature of 1073 K. It is seen that the exergetic efficiency augments as the S/C ratio increases. Although the syngas LHV decreases with S/C ratio for a given ER due to incomplete combustion, its decline results in higher mass flow through the GT and HRSG and, consequently, in higher cold fraction generated in the absorption chiller with the same thermal input.

It is interesting to note that an increase in the ER leads to a similar result, that is, a growth in the exergy efficiency due to the related reasons.

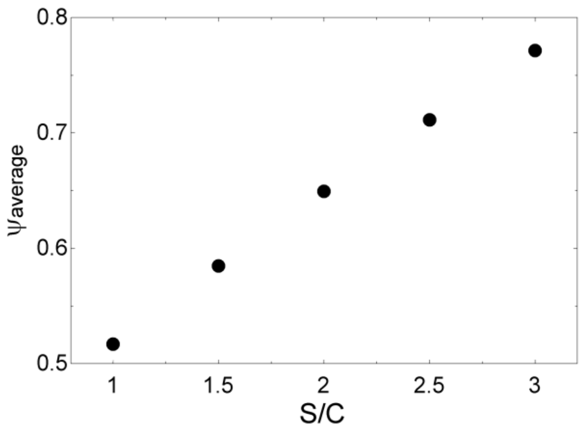

Fig. 2. Annual exergetic efficiency as a function of the steam to carbon ratio at a gasification temperature of 1073 K.

Economic analysis

Table 3 presents the key results of the economic analysis and optimization.

A parametric study carried out revealed that within the considered RDF price range, the net cash flow and the discounted cash flow for the first year are not sensitive to price changes. Fig. 3 shows the net cash flow as a function of the syngas produced for selling. It is observed that the increase of the syngas for selling results in lower payback periods along with growth of the net cash flow for 20 years.

Table 3. Key results of the economic analysis and optimization.

ER = 0.0034; S/C = 2; T_{gas} = 1173 K	
Parameter	Value
Annual average exergy efficiency	0.62
Annual average trigeneration efficiency	0.76
Annual average cogeneration efficiency	0.46
Net cash flow for 20 years, mln USD	318.4
Revenue char, mln USD	0.03
Revenue syngas, mln USD	28,3
Payback period, years	2

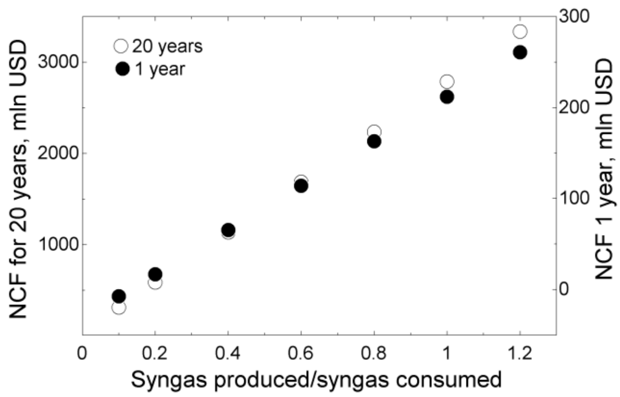

Fig. 3. Net cash flow as a function of the syngas produced for selling.

DISCUSSION

The existing conventional DHC system was retroffited with a gasifier and RDF was introduced as the main fuel on the system instead of natural gas. Both modifications of the tradional system transformed it into a polygeneration DHC system producing simultaneously electricity, heat, cold and value-added products (char coal).

Despite the RDF conversion technology proposed in this study (gasification) being still under development, there are already a number of facilities or pilot plants operating successfully [34]. However, it should be pointed out that the RDF gasification may face dificulties related with the heterogeneous nature of the RDF.

It is important to note that currently there is no well-established market for RDF in Portugal [35]. This poses two important problems. Firstly, the absence of a RDF market will not guarantee security of supply, and, secondly, the RDF price may be subject high uncertainties.

Furthermore, syngas and charcoal as value-added products could be classified as products with specific and non stable demand. Thus the price ranges might be unpredictable.

OUTLOOK

Further investigation will include refining of the present models and detailed validation against experimental data. Moreover, the knowledge of the impact of the RDF heterogeneous characteristics on the gasifier performance has to be carefully evaluated. To this end, the design and construction of a laboratory RDF gasifier will be considered.

CONCLUSIONS

This work examined the potential of using RDF as the main fuel, instead of natural gas, in a polygeneration DHC system in Lisboa, Portugal. To this end, thermodynamic, exergy and economic models were developed and applied to the proposed system. The results revealed that the full replacement of natural gas by RDF is technically and economically feasible. The new fuel is relatively cheap and yields relatively low payback periods for the project implementation. Complimentary added-value products such as syngas and char coal brings additional profit to the system, almost doubling the net cash flow. Furthermore, the proposed system reduces the impact of MSW on the environment and allows recovering energy from it. Finally, the system provides final costumers with energy without direct carbon emissions.

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SESSION 4

Key elements in District Heating and Cooling systems

PEAK REDUCTION IN DISTRICT HEATING NETWORKS: A COMPARISON STUDY AND PRACTICAL CONSIDERATIONS

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ABSTRACT

In district heating networks, peak heating loads of different consumers are usually occurring at the same time of the day. This leads to a cumulative peak in heat generation (typically morning and evening peaks) and requires the intervention of additional peak boilers, usually operating with fossil fuels at high costs.

From a review of published research works in the field of peak reduction in district heating systems a general classification scheme of the theoretical and existing measures is derived. The analysed measures include supply side measures (using the network as storage by adaptive temperature control, integration of centralised and distributed storage tanks), demand side measures (load control) and the implementation of new tariff systems. Practical relevance of the abovementioned measures to district heating networks, technical limitations and barriers in the implementation and potential improvements are described as well.

As proof of concept, a district heating network is modelled in the simulation environment Modelica/ Dymola and the results of the computational network simulations for different peak saving mechanisms are assessed using economic and ecological indicators. The usage of the volume of the network as storage and the demand side load shifting for the largest consumers under these constrains resulted the most economic feasible measures.

INTRODUCTION/PURPOSE

Significant peak loads (especially in the morning and evening) are challenging for the operation of district heating systems. In most cases, peak load generation units have to be kept on stand-by to cover the peak demand. For economic reasons, these are usually boilers based on fossil combustibles (gas or oil without combined power generation). Due to the high specific heat costs through low utilization ratio and expensive combustibles, operating these peak demand boilers compromises the economic and environmental performance (high specific CO_2 emissions) of district heating systems.

In this paper network operation and control strategies for peak load reduction will be described and compared. For this scope, different supply and demand side measures were defined and assessed for the chosen model of a district heating system of Salzburg AG (an ESCO) in a medium size village of the "smart grids model region Salzburg" (www.smartgridssalzburg.at)

STATE OF THE ART

Introduction of supply and demand side measures for load shifting

Based on a review of research work in the field of peak reduction in district heating systems a general classification scheme of theoretical and existing measures is derived. These measures are classified as:

- Demand side measures:
    - Refer to measures that can be applied on the demand side, thus with the support from the consumer.
- Tariff model measures:
    - Refer to measures that are introduced by the network operator and endorsed by the consumer to increase the efficiency of the system.
- Supply side measures:
    - Refer to measures that can be applied on the supply side, thus by the network operator.

The abovementioned measures are in detail explained in the following sections and they have been applied to an Austrian case study with the exception of the tariff model measures.

Demand side

Demand Side Management (DSM) is generally one of the main strategies to influence and improve the performance of energy systems, e.g. [1], [2], [3] and [4]. The night setback is a common DSM used to reduce heat demand. The application of this measure could result in significant energy savings up to 30% on yearly basis, e.g. [5], [6], [7] and [8]. However, when a large number of buildings connected to a district heating network adopt similar night setback settings, large peak can occur.

A significant contribution to the peak load results from domestic hot water (DHW) production due to showering in the morning. To reduce this effect, the loading cycle of available DHW tanks could be shifted to off peak times. Due to the relative small volume of many DHW tank and the priority circuit of the DHW preparation (avoidance of legionella), a coincidence with the peak load sometimes cannot be avoided [9].

One measure to reduce peak loads would be a deactivation of the night setback [10] for all or for significant customers. Since that would result in higher energy costs for the customers, their motivation for implementing it is rather small. Distinguishing tariff systems could support the measure, but this would require distinguished measurements of the heat consumption with high time resolution (see section "Tariff model measures").

More promising is the application of load shifting strategies: In different publications the effect of using the building thermal mass for load shifting has been assessed and verified [11], [12], [13] [14], [15] and [10].

In [16], [17] and [18] the potential of peak load reduction by using the building thermal mass has been assessed at large scale, e.g. for a city wide district heating network. Therefore, a large database of validated heating up time for different types of building standards and outdoor conditions was developed. Depending on the heat up time of the building from night setback to day set point, the start time of the heating phase can be arranged in order to reach the desired room temperature within a predetermined period of time and reduce the cumulative peak load as much as possible. An optimization algorithm considering certain flexibility in reaching the day set-point was applied (see Figure 1). As a result, a reduction of the daily peaks of up to 35% was achieved, with about 2% additional heat production.

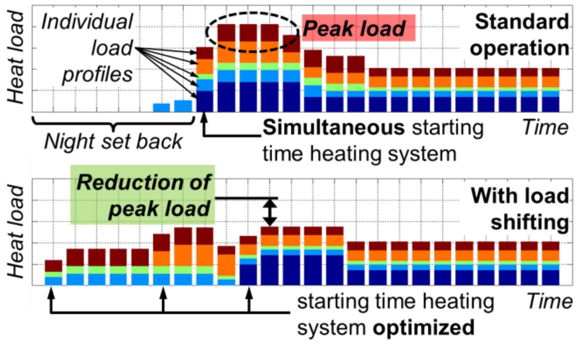

Figure 1: Optimisation of the cumulative heat load profile in a simplified case with 5 buildings, upper picture: no load shifting strategy is applied reaching high heat load peaks, lower picture: the starting times of the heating systems is optimised reducing the heat load peaks

A systematic analysis of different network settings shows, that a high number of buildings with low heat up time is beneficiary for peak load reduction due to load shifting. This is the case for a) buildings with a low thermal mass and b) buildings with oversized substation capacity (wrong calculation of heat load/ no adaptation of the substation after thermal retrofitting). As a result, retrofitted buildings without adaptation of the substation capacity have a high flexibility and are beneficiary for load shifting. On the other hand, retrofitted buildings with adaptation of the substation capacity have a lower flexibility, but also contribute less to the overall peak load.

A prerequisite for implementing a centralized load shifting strategy is the possibility of remote controlling the set points of the heating systems of the buildings connected to the district heating network. A first implementation attempt (using a small number of buildings in the Altenmarkt district heating network via remote control of the secondary supply temperature) was largely unsuccessful due to a secondary control in the buildings: The room thermostats opened the regulating valves as soon as the secondary supply temperature was reduced.

Tariff model measures

In the district heating sector different tariff models have been developed to increase the efficiency of specific networks. Nevertheless they refer to models helping in reducing district volume flow rate consumption or return temperature from customers, e.g. [19], [20] and [21].

The introduction of a time dependent tariff system would represent an incentive to the customer for modification of the set points of the heating systems in order to shift their heat load. Such tariff systems would require the measurement of instantaneous heat load together with fix scheduling for tariff costs over the time of the day. Thus requiring in the implementation from the one hand the problem of the complexity of the billing system and on the other hand the issue on privacy, common for instance to the electricity grid.

Additionally, applying the same tariff signal for many customer results in the risk of synchronisation of the heating times and thus creates additional peak loads.

Unfortunately no examples of the time dependent tariff model were found in literature confirming efficiency improvement. Because of the abovementioned technical difficulties this measure was not considered in the study.

Supply side

Integration of centralised and distributed storage tanks

Preliminary note: in the framework of this paper, following types of storages are defined (see Figure 2): central storages are large storage tanks installed nearby significant producers. Decentralised storage units are large storage tanks installed outside any producers and distributed storages are smaller storages distributed in the network.

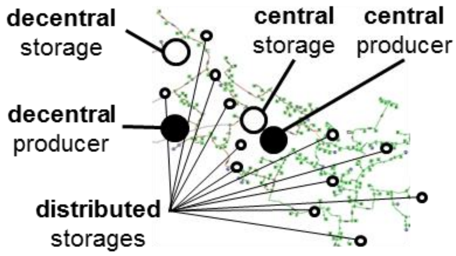

Figure 2: Examples of centralised, decentralised and distributed storages

One of the most common measure to reduce peak loads is the integration of storage tanks into the network. Besides reducing peak loads, centralised storages are also used for back-up reasons, decoupling heat and electricity production in CHP (combined heat and power) plants [22] and support the integration of fluctuating renewables (e.g. solar thermal energy [23]) or wind and photovoltaic energy (power-to-heat [24]).

An alternative to the centralised storage is the usage of distributed storage. Compared to centralised storage, distributed storages at the customer substation have a higher thermal storage density since the temperatures at the secondary side are lower. Therefore distributed storage tanks need a lower volume at constant storage capacity. Additionally, distributed storages have the potential to reduce peak loads directly at their origin and as a result reduce pumping energy. However, since they are in general very costly intensive compared to large scale storages [25] and the installation is connected to difficulties due to limited access to the customer side and missing business models, centralised or decentralised storages are often preferred.

A variant of a distributed storage is to replace the substation with a storage tank, see Figure 3. The heating of the secondary side is done by a primary side heat exchanger. The control of the substation would be identical with a standard substation control using a flow control valve. This set-up is currently tested in the DH network of Salzburg, but no results are available up to now.

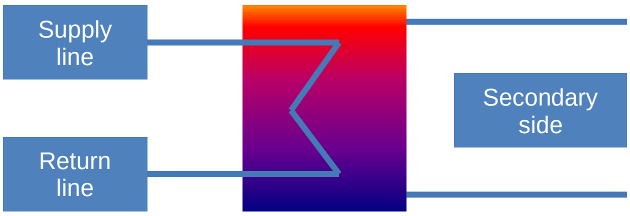

Figure 3: Using storages place of the substations

Using the network as storage by adaptive temperature control

The water volume contained in the DH network piping can be used as storage. Usually this is done by increasing the supply temperature a sufficient time before a peak occurs. Just before the onset of the peak, the supply temperature will be decreased to its initial value. This measure is well known by many network operators, e.g. [26] and it requires negligible investment costs.

However, the storage capacity is limited due to the induced adaptation of the building side mass flow: Once the supply temperature step reaches a customer, its substation control will reduce the mass flow from the network (constant heat demand and return temperature of the customer). As a consequence, the overall mass flow in the network is reduced successively.

In [27] a control algorithm allowing a higher storage capacity is investigated: opening bypasses between the supply and return line and controlling the mass flow rate will allow using the return pipe for storing additional heat by increasing the return temperature. Although, the return temperature should be as low as possible to decrease the pumping energy and the heat losses and increase the supply efficiency (relevant e.g. for ORC processes and processes with flue gas condensation), temporary increasing the return temperature will decrease the power demand during peak loads. The negative effects due to higher return temperatures and the reduction of the use of peak load boilers has to be compared for each system individually.

The effect of the optimised control strategy in a typical winter day is presented in Figure 4 ("final controller"). For the specific case, a peak load reduction of about 14% can be reached. The related distribution losses due to the higher network temperatures increase about 0.1%.

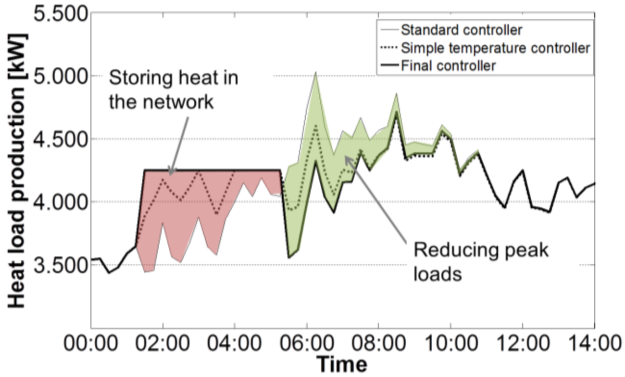

Figure 4: using the network as storage, results of the network simulation for the sample network in Altenmarkt: heat production from reference scenario, "simple temperature controller" and "final controller".

In [16] this measure was applied in a simulation study to different DH networks with varying linear power densities (ratio of the maximum peak load to the network length). Here, the effect of different charging times and temperature steps dT were investigated, see Figure 5. It can be seen, that a low linear power density (typically for rural networks) results in a high storage capacity and thus enables on to reduce the peak load by up to 10% by using the network as storage.

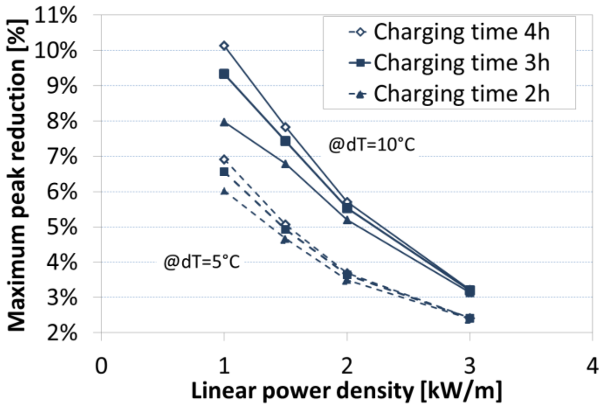

Figure 5: using the network as storage, results of the network simulation for different linear power densities

In general, the following barriers for the measure emerge:

- A higher storage capacity by using the return line can only be reached when remote controllable bypasses are installed in the network;
- Some producers cannot reach higher supply temperatures (e.g. industrial waste heat), the temperature changes cannot be reached in the required time (e.g. coal power plants) or their efficiency will be reduced (e.g. solar thermal);
- In meshed networks with multiple producers, the pervasion of the temperature step(s) is not easy to predict since the flow direction is not always known;
- Since the thermal expansion due to the temperature changes causes additional stress in the pipes and other system components, the lifetime of the network could be decreased.

Later barrier was assessed in [16] using a simplified low cycle fatigue analysis. The results show that the measure adds 10 full temperature cycles in 30 years and as a result could be considered as not relevant for the life time of the network, since they are usually designed for 1000-5000 full temperature cycles [28]. However, for “historical” DH systems where the status of the pipes and the compensators is often unclear and/or plastic pipes are used which have a reduced resistance to stress cycles could be critical.

METHODOLOGY

Simulation set-up for assessing different measures

The analysis of selected demand and supply measures is carried out with the numerical model of the district heating network of Altenmarkt in Pongau (Austria). In this network, heat generation is done by three boilers classified as base load and peak load. The 5.5 MW base load is covered by two biomass heating boilers, one of them coupled to an ORC-process for electricity generation (not considered in this study). The peak load is covered by an oil fired boiler. The average yearly supply and return temperature are 90°C and 60°C respectively. 198 consumers were connected to the network in 2009 (47% single-family houses, 15% multi-family houses, 18% mixed residential/commercial, 11% hotel/guesthouses), with an overall installed capacity of about 10 MW. 15 min monitoring data are available for every customer.

The detailed model of the district heating network computing the dynamic response was developed in Modelica/Dymola [29], [30] based on models of the Modelica Fluid library [31] and on the DisHeatLib [32] developed at the Austrian Institute of Technology. This includes models of producer units, hydraulic schemes of substations and preconfigured pipe models.

To detect any model error the entire network was divided into three parts, see Figure 6.

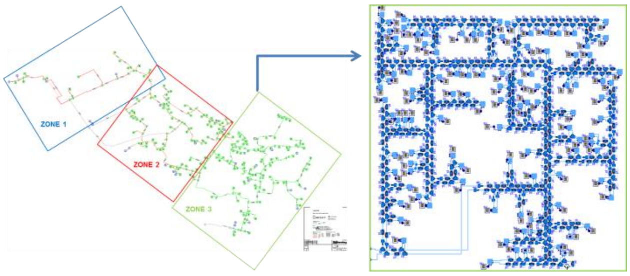

Figure 6: left: division of the district heating network of Altenmarkt into three zones, right: model of zone 3

In order to reduce the complexity of the network model for certain simulations and thus increase the efficiency of the numerical calculations, the network geometry was aggregated based on the work of [33].

Developed scenarios

In the following section the effect on peak load reduction from different supply and demand side measures is accessed for the described network model. The ”reference scenario” (Ref) considers the status quo of the district heating network without the implementation of any measures.

<u>Supply side measures</u>

1. *Network as storage, by adaptive temperature control*

In the controller the following limitations have been set:

- Maximum temperature at 115 ° C (based on the pipe specifications);
- Maximum temperature gradient of 2K/min (reduce additional stress on the pipes)

Based on a parametric study, a temperature step dT of 10°C and a charging time of 3 h were set for a maximum peak load reduction.

2. *Centralised and distributed storages*

The design of the centralised and distributed storage is done based on the annual load curve, Figure 7 shows the energy required, to cover the daily load peaks during the winter months and the available capacity of the biomass plant for the times at which the production profile exceeds 5.5 MW. From the analysis of the required storage capacity along the yearly time-span, following conclusions can be drawn:

1. In winter period when high peak loads occur, the potential of heat storage is limited because the biomass heat plant runs close to the full capacity;
2. In transitional period when enough capacity is available from the biomass heat plant, very limited peak loads have to be covered.

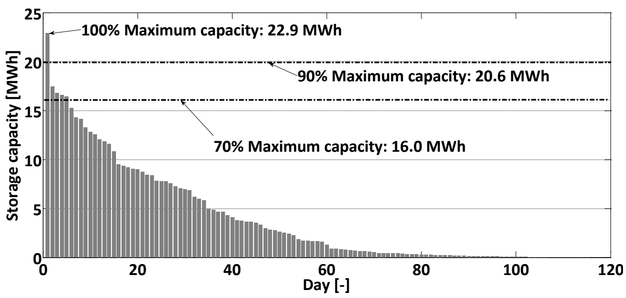

Figure 7: required storage capacity to cover the daily heat load peaks (sorted from the highest to the lowest value)

Following seven scenarios were considered based on the Figure 7 and including a scenario with a large storage tank able to shave all the peaks:

1. Centralised storage with a volume of 400 m³
2. Centralised storage with a volume of 550 m³
3. Centralised storage with a volume of 700 m³
4. Centralised storage with a volume of 1000 m³
5. Distributed storage with a total volume of 250 m³
6. Distributed storage with a total volume of 400 m³
7. Distributed storage with a total volume of 500 m³

<u>Demand side measures</u>

Load shifting

For this study, three different scenarios with increasing number of buildings subjected to load shifting are considered:

1. 10% of the largest consumers nominal capacity connected to the grid

2. 20% of the largest consumers nominal capacity connected to the grid
3. 30% of the largest consumers nominal capacity connected to the grid

RESULTS

The different measures explained in the previous sections are applied to the case study Altenmarkt im Pongau and the simulation results are evaluated with respect to the economic and ecologic indicators as reported in

Table 2. The assumptions for the economic evaluation are shown in Table 1; the assumptions for the ecologic evaluation are based on Austrian guidelines [34]. A possible influence on the ORC process is not considered.

Table 1 Assumptions for the economic indicators of the different scenarios

Parameter	Value	Unit	Source
Storage (central) Total cost	450	€/m³	[35]
Storage (distributed) investment cost	$18.18\, V[l]^{0.635}$	€	[25]
Storage (distributed) installation costs	200	€/Station	Assumption
Implementation of DSM	2.000	€/Customer	Assumption
Implementation of dT controller	15.000	€	Assumption
Fuel cost increase	3.0	%/Year	Assumption
Interest rate	4.0%	%/Year	Assumption

Table 2: Scenario comparison (yearly values)

Scenario	Base load [MWh]	Peak load [MWh]	Fuel costs [€]	Specific CO_2 emissions [tons/GWh]
Reference-scenario (**Ref**)	22.582	457,1	479.066	14,86
Network as storage (**dT**)	22.772	340,3	475.861	12,59
Storage 400 m³ (central) (**SC**)	22.975	222,5	472.840	10,30
Storage 550 m³ (central)	23.136	60,4	466.350	7,12
Storage 700 m³ (central)	23.168	43,9	466.002	6,80
Storage 1000 m³ (central)	23.227	-	464.542	5,94
Storage 250 m³ (dist.) (**SD**)	23.021	199,6	472.390	9,86
Storage 400 m³ (dist.)	23.172	60,4	467.062	7,13
Storage 500 m³ (dist.)	23.201	43,9	466.660	6,81
DSM 30% customers	22.824	327	476.082	12,34
DSM 20% customers	22.763	360	476.839	12,98
DSM 10% customers	22.690	376	476.383	13,29

The distribution of energy related to the base load and peak load is presented in

Figure 8.

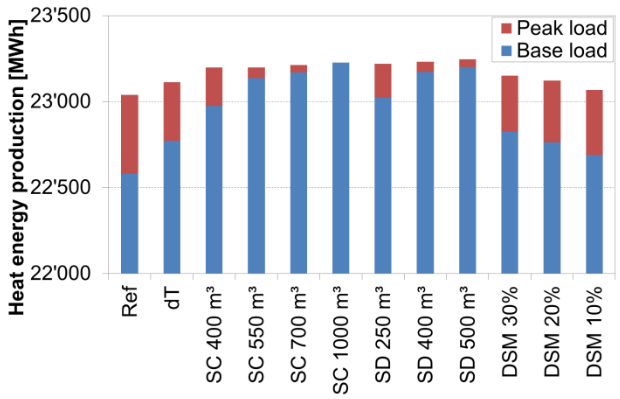

Figure 8: Distribution of heat load (base and peak load) for all scenarios

The specific CO_2 emissions for delivered energy are presented in

Figure 9.

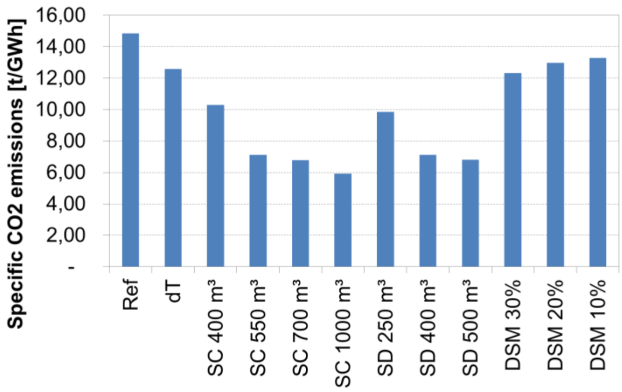

Figure 9: Specific CO_2 emissions for all scenarios

For the economic evaluation the amortisation time, (defined as the period needed for an investment capital expenditure to be returned), is used as indicator.

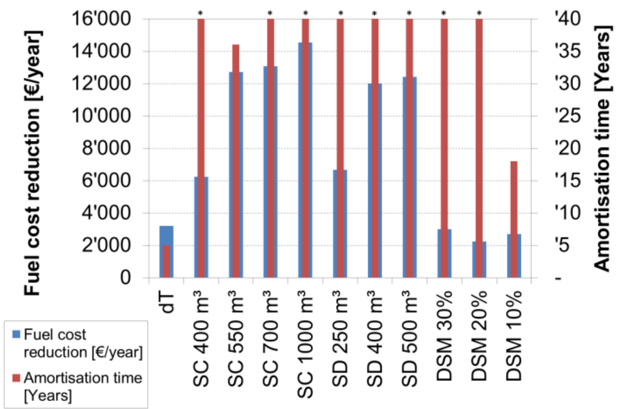

Figure 10: Fuel cost reduction (first year) and amortisation time. *Amortisation time > 40 years is not shown

DISCUSSION

Different demand and supply side measures for peak load reduction have been investigated, including:

Integration of centralised storages: This measure has a high relevance for DH networks, since centralised storages can be used also for other purposes (e.g. as back-up, for decoupling heat and electricity production in CHP and to support the integration of fluctuating renewables). In many networks, centralised storages are already integrated although the amortisation time for pure peak load reduction would be rather large in the investigated case study.

Integration of distributed storages: Whereas distributed storages have a higher storage capacity and the additional potential to reduce the pumping energy, central solutions have lower investment costs and are thus more favourable. Under the investigated boundary conditions, no solution was found with amortisation periods < 40 years. Additional, the installation is connected to difficulties due to limited access to the customer side.

Utilization of the network as storage: The volume of the pipes can be used as storage by temporary increasing the supply temperature. However, the storage capacity of the network is limited due to the induced adaptation of the building side mass flow. A higher storage capacity can be achieved by opening bypasses and controlling the mass flow rate and thus using the return pipe for storing heat. This measure is especially relevant for rural networks with a low linear power density and thus a high specific storage capacity. Additionally, the status of the network is often well known, allowing a better assessment of the risk for early failure due to the additional stress. For “historical” urban networks, this measure has a lower relevance since the storage capacity is lower and often a large number of producers exist, some of them cannot control their supply temperature. Restrictions on the network side allow only limited number of temperature changes.

Demand side load shifting: The thermal capacity of the buildings can be used in order to shift the heat load to off-peak times, and at the same time maintaining a comfortable room temperature. Decreasing the substation capacity reduces the flexibility of the buildings for load shifting, but also the individual peak load. For a large scale implementation, one has to consider that on the one hand the more buildings are subjected to load shifting the more the peak load will be reduced. On the other hand the start of many individual heating systems needs to be preponed to the early morning hours and thus the energy consumption will increase and the economic efficiency will be reduced. Additionally, the risk of comfort restrictions rises and the practical large scale implementation needs further investigation. As a consequence, the relevance of this measure is high only for the largest customers that can be more easily assessed and have a high load shifting potential. .

Deactivation of the night setback: This will result in a continuous heating during the night time and thus reduces peak loads almost completely but also increases heating energy consumption. As a consequence, the relevance of this measure is rather low, since it is difficult to attain a WIN/WIN situation for the customer and the supplier.

OUTLOOK

Future developments will include a general procedure for the selection of the most appropriate measures in district heating networks, supporting district heating operators phasing out peak loads. This will require enhancements for the most promising measures:

- Network as the storage
  - Adaptation of the methodology in case of multiple distributed producers with different supply temperatures.
  - Detailed analysis of the additional mechanical stress on the pipeline network, considering the large uncertainties regarding the bias of existing components (especially relevant for historic DH networks).
- Load shifting
  - Evaluation of an appropriate ICT infrastructure for remote control of customer equipment with the possibility for modification of the secondary-side control.
  - Develop a buildings information gathering methodology at district/city scale (set-point, occupancy time, buildings standard), and considering data uncertainties in the load shifting algorithm.

CONCLUSIONS

In district heating networks, the (cumulative) customer load profile resulting from the customer behaviour and the settings of the individual heating system exhibit often high peak loads (typically morning and evening peaks), reducing the economic and ecological performance of the system.

Based on a literature review and dynamic network simulations of the district heating network Altenmarkt im Pongau (AT), different demand and supply-side measures for reducing the usage of peak load boilers were developed and tested. This is including: the Integration of centralised and distributed storages, the utilization of the network as storage and demand side load shifting as well as the deactivation of the night setback.

Whereas large centralised storage tanks are already used in many DH networks for various reasons (as back-up, for decoupling heat and electricity production in CHP and to support the integration of fluctuating renewables) and represent a suitable measure for peak load reduction, smaller distributed storages at the customer side are very cost intensive and difficult to handle. Due to low investment costs, the utilization of the network as storage is promising, although restrictions on the network side allow only limited number of temperature changes. Implementing load shifting for larger loads (e.g. hotels, swimming pools, shopping centre) is another conceivable measure resulting in a cost effective reduction of peak loads, the practical implementation on a large scale needs further investigation.

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This project is part of the "Smart Grids Modellregion Salzburg". The aim of the Model Region programme is to aggregate different Smart Grid applications and issues (e.g. grid-integration of renewables, smart metering, e-mobility, demand-side-management and virtual power plants) into an integrated system. Several applications are developed and analysed in R&D projects in order to be field-tested and proved in real-life demonstration projects. Next to development and testing of technical solutions, research in the field of customer-acceptance and usability play a central role in the Model Region programme. The Smart Grid Model Region programme is supported by a team of experts in the fields of energy (Salzburg AG), housing industry (Salzburg Wohnbau), a technology provider (Siemens AG) and research partners (Austrian Institute of Technology, TU Vienna, CURE and Fichtner).

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HEAT LOSSES IN DISTRICT HEATING - ASSESSMENT AND LEVERS OF IMPROVEMENT - CASE STUDY ON WARSAW DH

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ABSTRACT

The level of heat losses is known in considerations on the district heating system as a whole, correct determination of heat losses separately for each section of the network is a much more difficult task. The article presents the methodology of solving this problem. Such an approach is designed to allow computation of potential energy savings during replacement of fragments of the network and forecasting the level of losses in consecutive years. Ultimately this solution is to support the investment strategy of the company with respect to energy efficiency of the district heating system.

The adopted method requires the use or development of computing models dedicated to each technology and configuration of heat pipelines (DN, location of pipelines, type of insulation, operation period, etc.). All these data on the district heating network are accessible in geographic information systems (GIS). Mathematical models used to calculate the heat losses from networks placed directly in the soil, in ducts or from ground networks are derived from literature. However, it is difficult to properly match all the parameters specified in these models, both in terms of material properties and the temperatures of the network water and the ambient temperature.

The properties of materials, particularly the thermal conductivity coefficient of the insulation, also in pipelines withdrawn from operation, were adopted based on laboratory tests carried out in our laboratory, and also on the experience of our employees and field measurements. Currently we place the strongest emphasis of precise definition of the properties of fiber insulation, both by means of field measurements and laboratory tests. Furthermore, the temperature of the heating water in each section of the pipe depends on the distance from the source of heat and this should be taken into account in the methodology of calculation.

This paper presents the results of calculations obtained for the existing district heating system in Warsaw, complete with conclusions and perspectives of the research project.

INTRODUCTION

The subject presented herein, used for calculating the heat losses in the district heating networks, is a part of a larger project focused on effective management of the district heating network. The major task of this particular part of the project consists in detailed definition of the parameters in each section of the network, and then on these grounds – calculation of the forecast amount of heat losses. The results obtained may be processed in any way: they may be generated as separate reports, maps, or they may be included into a financial analysis of individual sections of district heating pipelines earmarked for replacement.

STATE OF THE ART.

The total level of heat losses in the district heating systems is fairly generally known, but only for the whole system and over a longer period, mainly one year. It is calculated based on the volume of generated (purchased) heat, which is then sold to the customers. However, the amount of heat losses in each section of the district heating network is difficult to determine, due to the lack of reliable data on the state of repair of the given fragment of the heating pipeline. Only the design and as-built data are known, whereas the knowledge of the rate of degradation of the district heating network insulation is essential.

There are models designed to calculate the heat losses from pre-insulated and pipelines insulated with fibrous material. These may be analytical or numerical. However, reliable data are the most important element in any calculating model; in the case of the district heating networks these mainly include the thermal conductivity coefficient of the insulation and the thickness of the insulation.

Having run numerous laboratory tests we are in possession of reliable data on the polyurethane (PUR) insulation, both with respect to the new pipelines and those which have already been in operation for over a decade. Whereas information about the properties of the fiber insulation is only at testing stage.

METHODOLOGY

In order to achieve the major objective of the project described in this paper, i.e. to calculate the amount of heat losses for every section of the district heating network a method was developed, consisting of a number of elements:

a) Acquisition, selection and verification of data on sections of the district heating network from the data base (GIS),

b) Calculation (generation) of heat loss indicators for traditional and pre-insulated district heating networks at different ages of the networks,

c) Preparation of historical operating data from a real system (the Warsaw District Heating System),

d) Running the calculations with the use of a specially developed algorithm,

e) Generation of reports, maps included, on heat losses.

Figure 1 below presents the general diagram of the approach used. The general calculating method is simple, however certain aspects cause difficulties, which will be discussed further on in the paper.

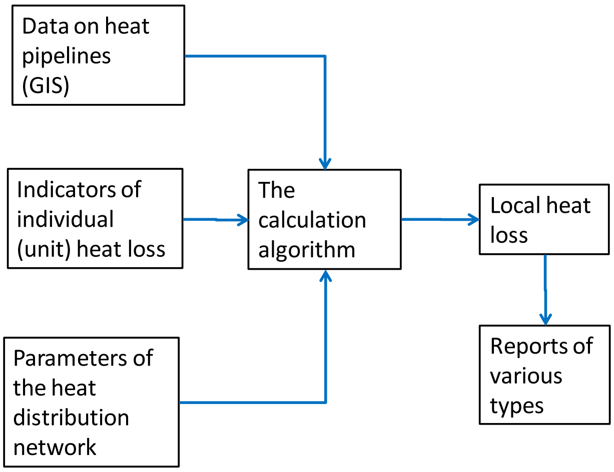

Fig.1. Diagram of the method of calculation applied.

RESULTS

During the work on the project several comparisons were done of the summary heat losses for all the studied sections with the annual data on the annual levels of heat purchase from the sources, sale of heat to customers and heat losses. At first these results were not satisfactory, the result generated by the model exceeded by over 20% the values provided by the Controlling Dept. Neither is the last result obtained very close to the official data, as it is lower by about 13%. That is why work is continued to improve the adopted heat loss indicators.

The figures 2 ÷ 5 below present the current results which comprise the summary heat losses and lengths for each nominal diameter.

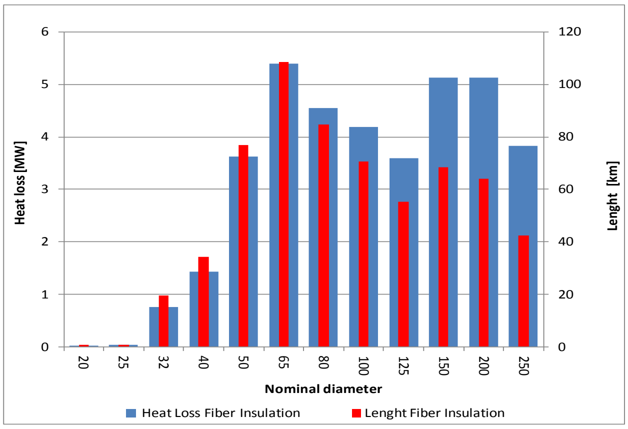

Fig. 2. Summary heat losses and lengths of sections of the traditional network for DN 20 ÷ DN 250 diameters.

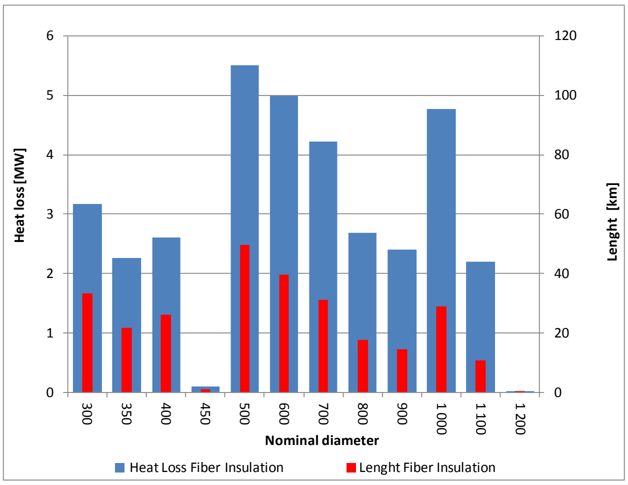

Fig. 3. Summary heat losses and lengths of sections of the traditional network for DN 300 ÷ DN 1200 diameters.

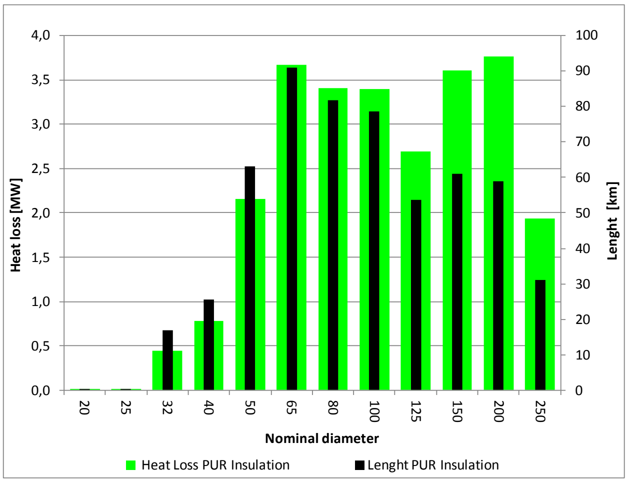

Fig. 4. Summary heat losses and lengths of sections of the pre-insulated network for DN 20 ÷ DN 250 diameters.

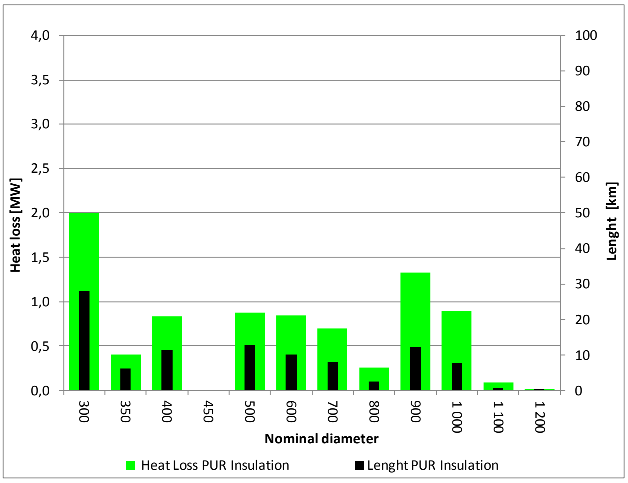

Fig. 5. Summary heat losses and lengths of sections of the pre-insulated network for DN 300 ÷ DN 1200 diameters.

The above graphs show that the network with smaller nominal diameters (particularly within the range of diameters DN 50 ÷ DN 200) is the longest. Both types of pipelines (pre-insulated and traditional) have similar length, however, the heat losses in the network with traditional insulation are higher by about 30%. In the case of the mains network (above DN 500) the length of the sections with traditional insulation is much greater, about four times. The amount of the heat loss in this network is higher by as much as about 50% (with consideration for the length of the network).

Calculation of the heat losses separately for every section allows visualisation of the results on maps, which may present numerous different data featuring the network sections. An example of such a map is presented in figure 6.

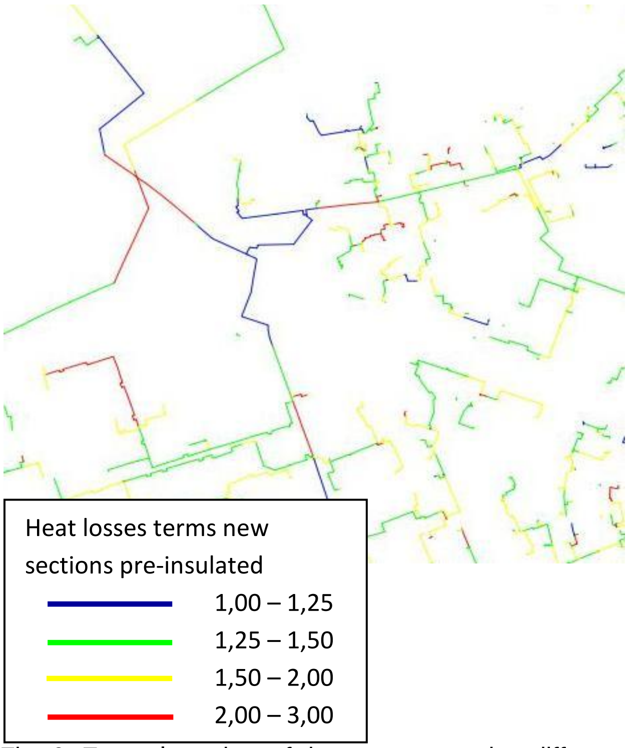

Fig. 6. Exemplary view of the map presenting different heat loss levels for individual sections.

There were several reasons for repeated generation of the balance, though basically they may be divided into three groups: the first: correcting errors in the calculation algorithm, the second: modification of the structure and value of the heat loss indicators, the third: modification of the values (updating) in the data base of the district heating network sections.

The large number of variables defining the sections of the district heating network and their high level of uncertainty (Table 1) were the reasons why it was impossible to avoid errors in constructing the calculation algorithm. There was a case of running calculations for all sections of the network from the data base, not only for the selected network (WDH). A considerable amount of erroneous or uncertain data, particularly among those related to the date of construction of the sections caused some complications, but at the same time forced the application of averages in the algorithm. For instance, in the case of obviously wrong date of construction of a section (e.g. earlier than the existence of district heating in Warsaw) it was necessary to artificially replace that date with a probable one. Similar errors appeared also for the pre-insulated network not only for the traditional one, but the substitute dates had to be different.

During the work on the project also the values of the heat loss indicators were modified (particularly for the traditional network) as well as their number and saving format. Every such modification required modifying the calculation algorithm, making it more complicated. At the beginning there was only a single set of heat loss indicators for the traditional network. Then it was decided there should be a separate set of indicators for networks designed to parameters 150/80°C and 130/70°C. Finally one more category was added – indicators for sections without insulation.

The GIS data base in Warsaw is continuously supplemented and verified which means the data base of the project described herein needs to be updated several times a year. Unfortunately there were also fairly considerable changes in the lengths of certain sections, exerting a significant impact on the results of the final balance.

DISCUSSION

The selection of the proper types of data and attention to the quality of those data are a very essential issue in each and every calculating project. As the district heating networks are structures with long history (in Poland it is over 60 years) and continuously modified, the accessibility of all data is an often encountered problem. It was relatively recently when all data on the district heating networks started to be collected on a current basis, before that not much attention was paid to this aspect. The form of data storage is another problem, as only data in digital form may be processed easily and quickly. In the Warsaw system, but also in many other systems in Poland the digital data bases are only at the stage of supplementing and verification of data. The project is based on the data comprised in the Geographic Information System (GIS), because it comprises all available data on the district heating network.

Because of the limited resources of reliable data the project used indispensable data and the most reliable data. It was adopted that the data indispensable to achieve the set target, i.e. determination of the heat loss for each section of the district heating network, included the following categories of data: the name of the district heating system, the heating agent, operating temperatures, the technology in which the section was built, the date of construction of the section, the nominal diameter, the length. The first three categories are necessary to distinguish, among all data, the sections of the high parameter water network of the main system (WDH). The remaining data are required for categorizing the sections or computing the specific heat loss values. In terms of the construction technology all sections were divided into two types: the traditional network (with fibrous insulation) and the pre-insulated network (porous insulation on polyurethane foam). The network construction date is another required data, allowing individual assignment of the insulation ageing factor to each section. Additionally, in the case of the pre-insulated network, the age plus the nominal diameter were used to identify the PUR foam foaming agent. In the Warsaw system there are pre-insulated pipelines foamed with carbon dioxide and cyclopentane, for a certain period both types of pipelines were used. It should be noted here that a part of the data on the age of the network is erroneous, as shown in greater detail in table 1. However, it was necessary to use even unreliable data, though this required the use of certain averages or substitute values in the calculation algorithm. The nominal diameter is also an indispensable datum, as the heat loss indicators are different for every dimension. The last datum, the length, allows conversion of unit heat losses into total values for the whole section. Table 1 presents pictorial data on the number and reliability of data on the Warsaw District Heating Network (WSC) used.

Table 1. Statistics data on sections of the network.

Datum / Size	**No of all sections**	**No of sections with reliable data**	**No of sections with unreliable data**
No of sections in the GIS	83905	75524 – WSC sections taken for analysis	8381 – sections of other district heating systems
Traditional network	45559	24713	20846
Preinsulated network	29965	19509	10456

The next essential element of the presented method consists in generation of the heat loss indicators for the district heating network. At the beginning the heat loss indicators were calculated for the new pipelines, in breakdown into two basic groups: for the traditional and the pre-insulated networks.

The values for the traditional network were calculated based on the norm PN-B-02421:1995, which defined the admissible heat losses for newly designed pipelines for different temperatures of the network water. Figure 7 presents the exemplary values derived from that standard. The same values of limitations were effective for networks designed and built in the earlier years.

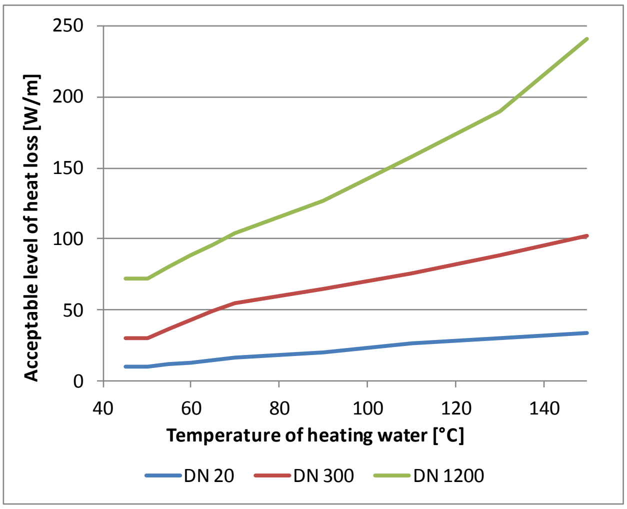

Fig. 7. Admissible level of heat losses for the traditional network acc. to the PN-B-02421:1995 standard.

Based on the limitations comprised in the said norm the design thicknesses of insulation were calculated for each nominal diameter. These thicknesses were determined for two design levels network water temperature: 150/80ºC and 130/70ºC, which were applied in the past in the Warsaw district heating system. For the 150/80ºC parameters, the thickness of insulation for the supply pipeline was between 60 and 160 mm, and for the return pipeline it was 40 to 90 mm. For the 130/70ºC parameters the thickness of insulation for the supply pipeline was between 40 and 120 mm, and for the return pipelines from 30 to 70 mm. It should be noted, however, that in the years when the design parameters were higher, the properties of the insulation were worse. For higher design temperatures the insulation coefficient λ was 0.052 W/mK, whereas for the 130/70ºC parameters the admissible λ coefficient was 0.042 W/mK. Differences in the thickness of the insulation and in its thermal conduction caused the differences in heat loss levels in the new network. An example of the heat loss values at design temperatures is presented in Figure 8.

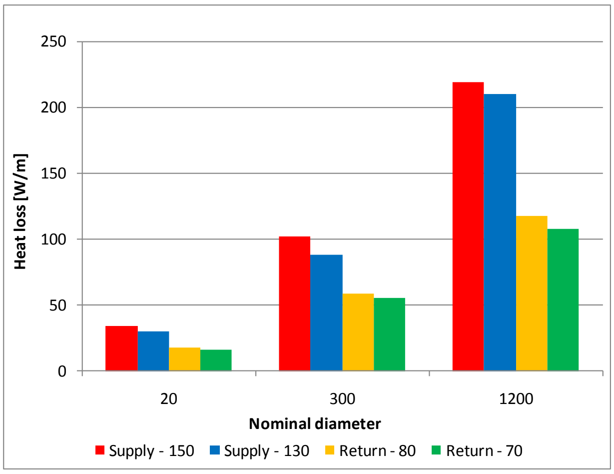

Fig. 8. Exemplary design levels of heat loss for fiber insulation.

The heat loss calculations were also carried out for the average operating temperatures of the network water. For the supply pipelines the temperatures were within the range of 73 ÷ 85ºC, and for the return pipeline within the range of 40 ÷ 55ºC. Values from these calculations were then used in the final algorithm for computing the mean annual heat losses for each section of the district heating network.

The heat loss indicators for the pre-insulated network were also divided into two groups in terms of different polyurethane foaming agents. In the nineties of the 20th century CO_2 was used to prepare foam for the insulation of pipelines, whereas following the enhancement of the insulating requirements cyclopentane came into use. The heat loss values were calculated for all nominal diameters within the temperature range of 45 ÷ 130ºC. Values from these calculations were then used in the final algorithm for computing the mean annual heat losses for each section of the district heating network.

All the described heat loss indicators referred to new insulation. However, with time every insulation is liable to ageing (degradation). The pre-insulated insulation is liable to degradation in two ways. Firstly, the foaming gas diffuses from the polyurethane foam cells and is replaced by air. The rate of this process is the highest during the first period of operation, to slow down later, with the diminishing volume of the gas inside the insulation. The diffusion phenomenon is well known, hence it is possible to forecast the process of ageing as a result of diffusion. Figure 9 presents exemplary values of the ageing coefficient for pre-insulated pipelines.

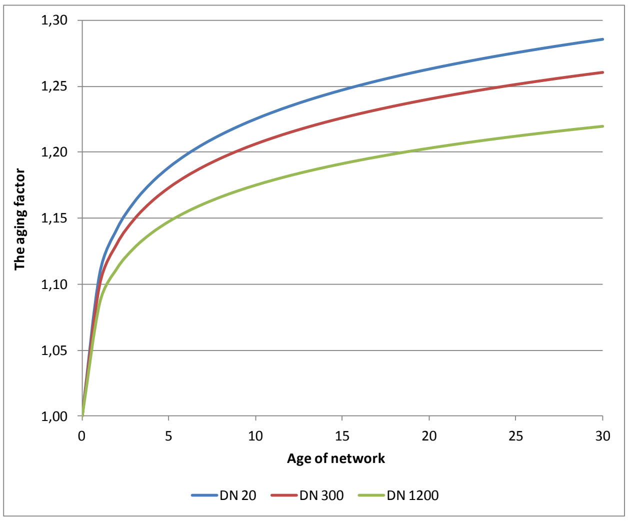

Fig. 9. Exemplary values of the ageing coefficient for pre-insulated pipelines.

In the case of smaller diameters, where also the thickness of the insulation is smaller, the rate of diffusion, i.e. ageing is greater, whereas in the case of larger diameters this process is slightly slower. Hence different levels of the ageing coefficient for each nominal diameter of pre-insulated pipelines.

Overheating is an additional factor degrading the polyurethane insulation. These insulations are not resistant to temperatures higher than 120ºC, when destruction of the structure of the insulation occurs. This phenomenon is less recognized and additionally it depends on the temperatures of the heating water applied, and therefore more difficult to determine precisely.

The fibrous insulations (traditional networks) are prone to ageing in a different way. They are resistant to the temperatures generally applied in district heating, hence they are not liable to overheating (scorching). However, the mechanical strength of fibres in these insulations is poor and for this reason with time they begin to crumble and fall off. Moreover, degradation of the fibrous insulation is considerably accelerated by water, which may appear in it in three ways. Firstly, in certain duct networks, insulation may be periodically flooded by precipitation or ground water. Secondly, water vapour may condensate in the ducts or the in the insulation. The last instance is the possible flooding of the insulation as a result of a network failure. The impact of these factors on destruction of the insulation has not been yet been recognized and additionally it is difficult to determine the frequency of occurrence of these phenomena. Therefore the fibrous insulation ageing coefficient has been averaged and adopted at a single level for all nominal diameters. In the past the value of this coefficient was adopted within the range between 1 for new insulation and up to 2 for 60 year old insulation.

Another element required for calculation of the heat losses – operating temperatures in the district heating network. For this purpose any value of temperature may be used from the range of actual operating parameters of the district heating system. However, in order to allow verification of the results obtained, the temperature must be adopted from the supply pipeline and the return pipeline in sections where the heat loss volumes are known.

The most reasonable approach consisted in generation of an annual heat loss balance for the Warsaw district heating network (WDH) at its mean annual operating temperatures. For this reason the following appeared with the selection of the required data for the project: name of the district heating system, heating agent, operating temperatures.

For the proper construction of the heat loss balance sheet it was also necessary to additionally calculate several indispensable values. The first of them is the value of annual heat losses caused solely by thermal conduction through the insulation, without heat loss in the heating water loss. The enterprise has data on the total annual heat loss, therefore estimate calculations had to be done for the heat lost with the heating water and then deducted. Further data included the supply and return heating water temperatures, average for the whole year. It should be noted that it was necessary to calculate the mean temperature of heating water in the network, not at the sources of heat. This was done on a dedicated spreadsheet where a histogram is preset of the heat source operating temperatures as well as the annual sums of generated heat (purchased at the source) and sold to the recipients. After balancing the whole sheet we may read the histogram of the mean temperatures of heating water in the district heating network or the annual average. In the case of the WSC the mean temperature of supply water in the network (throughout the year) is lower by about 3.7°C than the mean temperature at the sources. In the summer this difference increases even to about 6°C, and in the heating season it is about 2.2°C. On the other hand, the temperature of the return water in the network is higher by about 1.7°C throughout the year.

OUTLOOK

The project is still under implementation, hence the indicators adopted now will verified and corrected. At the moment various research work is being carried out both for the pre-insulated pipelines and those with fibrous insulation.

Over 500 field measurements of heat flux were carried out on the traditional district heating network in operation. Discrepancy between the measured and calculated values oscillates between -80% and 150%, and seemingly these discrepancies are considerable. However, in an overall analysis of all measurements the mean difference between the measurements and calculations is insignificant, amounting to about 15%, and additionally in about half of the cases the difference is below 25%. The results of a part of these surveys are presented in table 2. The problem still resides in the proper identification and classification of sections with undamaged insulations and with degraded insulation. Such classification should be carried out based on various data on the district heating network and its surroundings. Probably the parameters which would be helpful in such classification include the following: humidity in ducts, number of failures in the network, the water table map.

Table 2.

DN	No of measure ments	Difference between the measured values and those determined from indicators [%]
All	340	-14.60
400	10	35.85
500	66	-10.78
600	68	-20.41
700	75	-8.32
800	30	0.05
900	6	-19.54
1000	42	3.11
1100	43	-10.40

Graph 10 presents an example of a comparison of measured and calculated values. The graph shows an up trend in heat losses with the age of the network, and this trend is stronger in supply pipelines. Different levels of measured and calculated values for the same age result from taking the measurements at different temperatures of the network water.

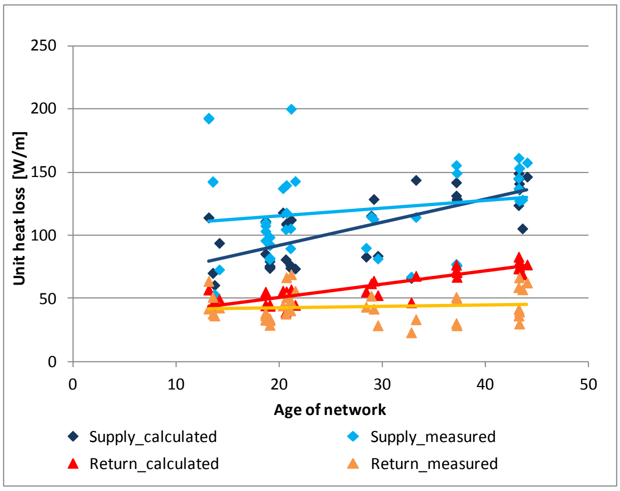

Fig. 10 Comparison of field measurements and calculations for DN 1000 diameter network.

Also local measurements were carried out for the network water flow and drops in its temperature. However, the results of these measurements have not yet been analysed and it is impossible to explicitly confirm the usability of this method for validation of the adopted heat loss indicators.

Running calculations in the Termis programme is planned as a consecutive stage of the works, to determine the difference in temperature between the source of heat and each section of the network. Such calculations will be carried out for several different levels of the demand for heat in the system. The final result of these calculations shall be used in a heat loss calculation algorithm.

In the case of pre-insulated pipelines laboratory tests should be carried out on sections after 20 to 30 years of operation. Such tests will check the currently adopted ageing indicators for this type of networks. Furthermore, more attention should be paid to the impact of excessively high temperature (above 120°C) on the rate of degradation of the PUR insulation.

In the case of fibrous insulation the insulation tests are planned after putting the pipes out of operation. The tests will be carried out both for the whole pipeline sections with insulation and for sections of the sole insulation. Most probably field surveys on the traditional network will be continued.

CONCLUSIONS

The presented method of acquisition, processing and use of available data is useful in calculation of heat losses from sections of the district heating network. The values obtained to-date confirm the correct approach to the problem. However, there is still a lot of data on pipelines (GIS) which are not reliable and which need supplementing or correction.

Further work is also necessary with respect to the adopted values of heat loss indicators in sections of the network in operation. The Heat-Tech Center has the necessary research tools which allow validation of these indicators.

This module will calculate the forecast (over several years) heat loss values for individual sections of the network in the case of application of different modernization variants. The calculated hest losses (and the associated maintenance costs) will not, probably, decide on selecting the section of the network for replacement, but they will be useful for determination of the modernization variant. The module will also help in forecasting the changes in the heat lost costs in consecutive years.

ACKNOWLEDGEMENT

The module used for calculating heat losses was constructed for the needs of a broader project related to the management of the district heating network assets. The past subject matter of the Heat-Tech Center activities with respect to the laboratory tests, determination of designing guidelines for district heating pipelines and numerous analyses of the district heating network operation, inclusive with those related to heat losses, allowed quick acquisition of the results close to the ultimate expectations. The final output of this research project is to support the optimum process of the network assets management not only at Dalkia Warszawa, but also at other Dalkia district heating enterprises in Poland and across the world.

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PROBABILITY OF FAILURE ASSESSMENT IN DISTRICT HEATING NETWORK

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ABSTRACT

The aim of this paper is to present works performed in Heat-Tech Center (HTC), Research & Development centre of Dalkia Group located in Warsaw regarding assessment of probability of failure in District Heating network (DHN). This work is a part of a project dedicated to develop an IT which objective is to increase reliability of DHN.

The research methods consisted of 3 approaches. First, using database of failures which happened in Warsaw DHN and repairing protocols from past ten years, a statistics approach was applied to perform first analysis. The result was that pipelines with nominal diameter DN≤150 had higher failure rate per km, than pipelines with DN>150.

The next step of research was to study influence of internal (corrosion caused by heat carrier, quality of materials) and external (stray currents) factor in order to assess its individual influence on failure rate of pipe and explain reasons of differences in failure rate.

To end a Failure Mode and Effects Analysis (FMEA) will aim to identify the main failures modes appearing on DHN, to estimate the main causes of these failures and to propose the best solutions regarding the causes, the costs, the means available.

INTRODUCTION/PURPOSE

DHN like any other industrial system ages and is more likely to fail due to worsening of mechanical properties of used materials. DHN issues are more complicated because most of pipelines are installed in duct channels and there are a few possibilities to monitor condition of assets. Better knowledge about condition of assets may allow to better plan investments in replacement of old part of network and reduce cost of repair and increase security of supply for customer. Therefore, Heat-Tech Center has started a Research & Development project dedicated to develop an IT tool which aims to increase reliability of DHN.

The main criteria which leads to positive decision of renovation of a segment of pipeline is risk of destabilizing operation of DHN if given segment has a malfunction. Such a risk criteria has two main components: a probability of occurrence of failure, and consequences caused by a failure. This paper will put more attention to part related to probability of failure, whereas, part related to consequences will be covered in narrower scope.

The subject of study is Warsaw DHN owned by Dalkia Warszawa, presented on Figure 1. The history of Warsaw's post-war DHN starts in 1952. Currently it is the biggest centralized DHN in Poland and one of the biggest in Europe. DHN has radial-ring structure, with 100 rings and length of about 1691 km. It supplies 19000 buildings, and covers 80% of city's demand for heat [1]. Annually 38 PJ of heat are delivered to customers. Heat losses of network are about 10% [2]. DHN is supplied from 2 base heat sources and 2 peak heat sources owned by company PGNiG TERMIKA which have installed capacity of 4635 MWt [3].

Figure 1 – Map of Warsaw DHN

The technology of construction of pipelines in Warsaw DHN can be divided into three main groups: pre-insulated, traditional (which consist of pipelines installed in duct channels, in buildings), and overhead. The corresponding lengths are given in

Table 1.

Table 1 – Length of pipelines per each technology

Technology	**Length**	**Share**
Pre-insulated	691 km	41%
Traditional – in building	152 km	9%
Traditional – duct channel	816 km	48%
Overhead	31 km	2%

STATE OF THE ART/ METHODS/METHODOLOGY

Modernization of Warsaw DHN

Until mid ‘80s technical condition of Warsaw DH system was unsatisfying. Corrosiveness of network water on internal surface of pipelines (shown on Figure 2 [4]), bad condition of devices (especially shut-off valves), poor quality of pipes, flawed workmanship, and difficult external conditions of duct channel pipelines are main shortcomings of Warsaw’s DH network from this period of time. All those factors had significant influence on increasing failure rate. In 1980’s failure rate was systematically growing [5].

Since 1989 failure rate in Warsaw’s DH network was slowly decreasing, what was caused by applying pipes with thicker steel wall since 1986. Nevertheless, annual number of failures was high, what was burdensome for customers. Modernization of Warsaw’s DH network started in 1992, when a loan from World Bank was given. In May 1995 a process of reverse osmosis and demineralization was applied in heat sources for water treatment. This lowered aggressiveness and corrosiveness of network water.

Change of water quality and pipe renovation for pipes with thicker walls, installation of pre-insulated pipes, and exchange of armature caused significant drop of failure rate in Warsaw’s DH network (from 5470 in 1988 to 380 in 2012). Figure 3 [6] presents the change of failure rate in years 1978-2012.

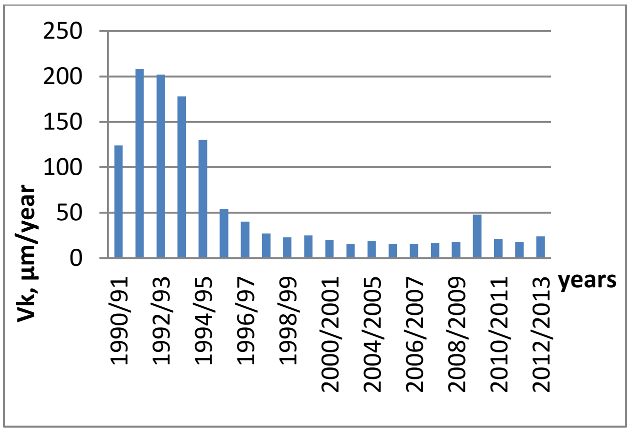

Figure 2 – Average surface corrosion rate of DH pipelines (supply + return) in years 1990-2002 and 2004-2013 determined with use of gravimetric method in µm/year [4]

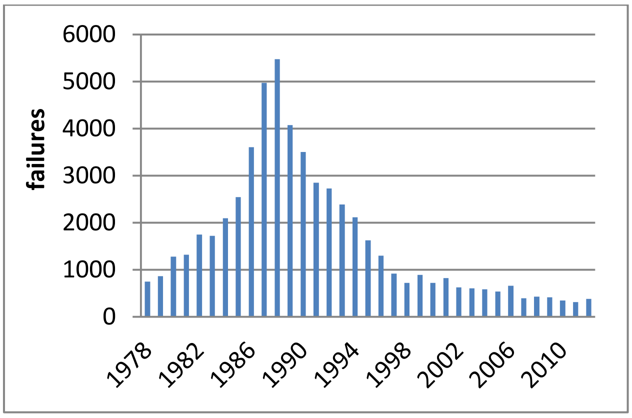

Figure 3 – Failures in Warsaw DHN in years 1978-2012 [6]

The part of data presented in Figure 3 was collected from paper failure protocols which have been filled in by workers after removing each failure starting from year 2003. Until year 2012, 4616 failure protocols have been recorded. Such a failure protocol included following data: address of failure, time of disconnection, time of start-up, type of damaged element, DN of element, type of damage, method of repair, cause of failure, etc. Therefore, the data about the failure were quite accurate, however, information about the damaged pipeline (ID of pipeline, type of pipeline, age of pipeline, etc.) were not sufficient.

The previous works in Dalkia Warszawa regarding failures consisted only of statistical analysis of number of failures per different categories (DN on which failure occurred, DHN administration zone, cause of failure, etc.). Moreover, failure rate [failures/km/year] was calculated for the whole DHN and administration zones.

In this paper the same set of data is used to assess probability of failure. Such an information can allow operator of DHN have greater knowledge about condition of assets and make better decisions regarding renovation of pipelines.

To be complementary with failure rate approach, we decide to also use Failure Mode and Effects Analysis

(FMEA) to make better decisions regarding renovation of assets on the DHN.

Failure rate methodology

In year 2013 a new process of data treatment started. Recorded failures were manually added to Warsaw's Geographical Information System (GIS) and linked with the ID number of pipeline on which given failure occurred. However, not all failures could be identified in GIS. Some of failures have happened on pipelines which were replaced before year 2013 and due to lack of historical data it is not possible to make such a link. Other failures had poor data in the failure protocol and it not sufficient to identify exactly where they happened. Therefore, the study concerns only the set of identified failures. Figure 4 shows shares of failures with poor data, which occurred on replaced pipelines, and linked failures.

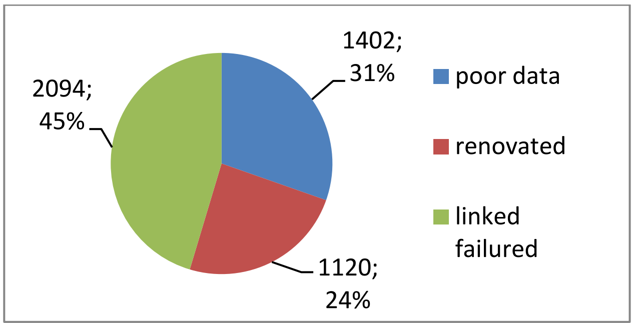

Figure 4 – Quality of data regarding 4616 recorded failures in years 2003-2012

This allowed to have accurate data about pipelines on which failures happened. Moreover, it was possible to quickly extract information how many failures occurred per one segment of pipeline (segment of pipeline in GIS is defined as part of network with homogenous characteristics) in any time period between 2003-2012.

The methodology of study consisted of analysis of occurrence of failures depending on different characteristic of pipeline and different characteristic of failure.

The first step (A) was to determine what was the change of failure rate [failure/km/year] in Warsaw DHN in order to investigate what is the trend. This was obtained by dividing the number of failures which happened during a given year by the total length of the DHN. Due to lack of consistent historical data about pipelines, the total length of DHN in given year is the same and assumed to be equal to 1691km, which is the current length. Such a assumption is valid because the size of Warsaw DHN is very big and changes of total length which occurred during last 10 years are relatively small and can be neglected.

The next step (B) was to study how often failures occur on one segment of pipeline. To obtain such an information the GIS data base of pipelines with unique ID numbers was linked with data base of failures which had ID numbers of pipelines on which failures happened. This way each segment of pipelines had assigned number of failure which occurred on it. This information allowed to make statistics how many segments had 1 or more failures.

The third step (C) was to determine which characteristic have greater influence on failure rate. With use of the same approach, the number of failures per each group of selected characteristic was determined and divided by the corresponding length and time in order to obtain failure rate [failure/km/year]

The first studied characteristic was technology of construction of pipeline (C1). As it was mentioned Warsaw DHN has used 3 technologies for construction of pipelines: pre-insulated, traditional (which consist of pipelines installed in duct channels, in buildings), and overhead. In total they give 4 different groups.

The next characteristic that was investigated was nominal diameter (DN) (C2). In Warsaw DHN DN can be between values from 15 on up to 1200. However, to make results easier to interpret, the 3 groups of DN were considered: connections – DN 15-150, distribution – DN 200-350, and main-line DN 400-1200.

The third studied characteristic was the year of construction of pipeline (C3). The oldest pipelines in Warsaw DHN are from 1950, however, there is a small share of such an old pipelines. Most of the pipelines were build in '70s and '80s. Sadly Warsaw GIS has quite many missing records regarding the year of construction. About 634km of pipelines (37% of length) have assigned date of construction as 01.01.1980 and 1995, what was by default set for pipelines with missing date. The reason why those dates were selected as default for missing record is that they correspond to average construction date of traditional pipelines (01.01.1980) and pre-insulated pipelines (01.01.1995). Therefore, there is some inaccuracy, however, it can be partially dealt with by analyzing this characteristic by setting some groups. The groups are as follows: before-1970, 1971-1980, 1981-1990, 1991-2000, 2001-2014. This way, even if a pipeline with unknown year of construction (with set default value, for example 1995) was build a few years earlier or later, it will still be classified in the same group.

The fourth investigated characteristic was stray current effect on pipelines (C4). On a basis of study conducted by Instytut Elektrotechniki [7] 42 zones in Warsaw were determined, in which there is a higher risk for underground infrastructure of being exposed to stray currents produced by trams. With use of the GIS the pipelines in those zones were assigned to them. That allowed to calculate how many failures occurred and what was the total length of pipelines in each zone. With this data failure rate was calculated. Moreover, Warsaw DHN is equipped with cathodic protection, which protects parts of network from electrochemical corrosion caused by stray currents. Therefore, failure rate was calculated for: zones equipped with cathodic protection, zones near cathodic protection, zones without cathodic protection, and the rest of pipelines outside zones.

The last part of the methodology consisted of investigation of cause of failure on failure rate (D). As it was mentioned the records of failure protocols have information about the most probably cause of failure: surface corrosion, pitting corrosion, corrosion around the circumferential weld, perforation at the seam of the pipe or nearby, other, and unspecified. By dividing the number of failures of each group of cause of failure by the total length and time, the failure rate was obtained.

RESULTS

Failure rate approach results

The step (A) of analysis allowed plotting the change of failure rate in time, what is shown on Figure 5. In 2006 there was a peak of failure rate, its value was 0,17 [failure/km/failure]. Such a peak in 2006 was also observed in other DHN networks in Poland. It can be explained by some external global factor like very cold winter [8] which caused extreme operational conditions and forced more failures. Therefore, the failure rate in Warsaw DHN in last 10 years is quite stable and is 0,12 [failure/km/year] on average. Moreover, failure rate for 2012 was also equal to 0,12 [failure/km/year]. If Warsaw DHN replaces old pipelines with new ones with the same place as it was in this period of time, and operational conditions will be kept on the same level, it can be expected that the failure rate will follow this trend.

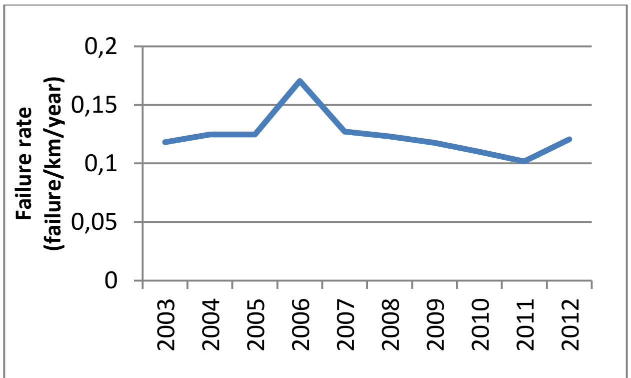

Figure 5 – Change of failure rate in time in years 2003-2012

The part (B) of the analysis showed that only 1665 (2%) of segment of DHN out of 82688 had failures between 2003 and 2012. The total length of damaged segments of pipelines was 67 km, what corresponds to about 4% of length of Warsaw DHN. The results of part (C1) are presented in Table . The lowest result which was obtained for overhead pipelines, however, this result should be neglected, because overhead pipelines consist of only 2% of total length of Warsaw DHN and this category is not representative for this network. Therefore, in fact the lowest result was for pre-insulated pipelines and it was equal to 0,02 [failure/km/year]. Traditional pipelines have 0,19 and 0,31 [failure/km/year] for pipelines installed in duct channels and in buildings respectively. This is 10 and 15 times higher than for pre-insulated pipelines, and 1.6 and 2.6 higher than average value for Warsaw DHN. Moreover, traditional pipelines have the highest share of length in Warsaw DHN.

Table 2 shows that the majority (81%) of pipelines which had failure had it only once. Moreover, if one failure have already happened on segment of pipeline there was 14% chance that this segment will have one more failure, and 5% that it will have 2 or more additional failures (there were only 3 extreme case which had 9,8, and 7 failures respectively). Therefore, the more attention should be put to determining the probability of such an incident.

The results of part (C1) are presented in Table . The lowest result which was obtained for overhead pipelines, however, this result should be neglected, because overhead pipelines consist of only 2% of total length of Warsaw DHN and this category is not representative for this network. Therefore, in fact the lowest result was for pre-insulated pipelines and it was equal to 0,02 [failure/km/year]. Traditional pipelines have 0,19 and 0,31 [failure/km/year] for pipelines installed in duct channels and in buildings respectively. This is 10 and 15 times higher than for pre-insulated pipelines, and 1.6 and 2.6 higher than average value for Warsaw DHN. Moreover, traditional pipelines have the highest share of length in Warsaw DHN.

Table 2 – Number and share of damaged segments of pipeline in years 2003-2012

Number of failures	Number of segments	Share of damaged segments
9	1	0%
8	1	0%
7	1	0%
6	0	0%
5	4	0%
4	11	1%
3	63	4%
2	234	14%

1	1350	81%
Total	1665	

Table 3 – Failure rate [failure/km/year] per different technology of construction

Technology	**Number of failures**	**Failure rate**
Pre-insulated	111	0,02
Traditional – in building	467	0,31
Traditional – duct channel	1513	0,19
Overhead	3	0,01

Table 2 contains the values of failure rate for different DN groups (C2). As we may observe the smallest rate was for the main-line and was equal to 0.04 [failure/km/year]. Twice higher result was obtained for distribution pipelines, and 4 times higher for the connection pipelines. What is more, the connection pipelines have the highest share of length. It means that the probability and number of failures for this group is the highest.

Table 2 – Failure rate [failure/km/year] per different group of DN

Group of DN	**Length [km]**	**Share of length**	**Number of failures**	**Failure rate**
Connection	1090	64%	1780	0,16
Distribution	307	18%	209	0,07
Main-line	294	17%	105	0,04

Results of part (C3) of analysis are shown in Table 3. Surprisingly, the oldest pipelines do not have the highest failure rate. The highest failure rate is for pipelines build in ‘70s due to poor quality of material and poor quality of workmanship, and the value is 0,26 [failure/km/year]. Pipelines built after 1990 have very low failure rate 0,05 and 0,01 [failure/km/year]. The rest of them is close to the average value for the whole DHN.

Table 3 – Failure rate [failure/km/year] per different group of year of construction

Year of construction		**Length [km]**	**Share of length**	**Number of failures**	**Failure rate**
from	to				
before	1970	78	5%	110	0,14
1971	1980	550	33%	1409	0,26
1981	1990	251	15%	296	0,12
1991	2000	486	29%	241	0,05
2001	2013	327	19%	38	0,01

Table 4 presents the values of failure rate depending on the influence of stray current (C4). The pipelines outside the zones have the failure on the same level as the average value for the whole Warsaw DHN – 0,12 [failure/km/year]. Whereas, pipelines in the zones without cathodic protection have slightly higher failure rate – 0,13 [failure/km/year]. Nevertheless, the pipelines in the zones with cathodic protection have value 0,08 [failure/km/year] and that is significantly lower the average value.

Table 4 – Failure rate [failure/km/year] for different stray current influence

Cathodic protection	**Number of failures**	**Length [km]**	**Failure rate**
No	290	217	0,13
Yes	26	32	0,08
Near	22	26	0,08
Outside zones	1756	1422	0,12

The Table 5 contains values of failure rate for different causes of failure (D). As we may observe, the surface corrosion has the highest result 0,07 [failure/km/year]. Whereas, pitting corrosion is about half of that value and is equal to 0,03 [failure/km/year], other causes of failure are rather marginal and are 0,01 [failure/km/year] or smaller.

Table 5 – Failure rate [failure/km/year] for different causes of failure

Cause of failure	**Number of failures**	**Failure rate**
Surface corrosion	1234	0,07
Pitting corrosion	534	0,03
Corrosion around the circumferential weld	75	0,00
Perforation at the seam of the pipe or nearby	27	0,00
Other	139	0,01

Unspecified	85	0,01

STATE OF THE ART/ METHODS/METHODOLOGY

Failure Mode and Effects Analysis State of the Art

To better assess failures on the DHN, the idea is to try to use Failure Mode and Effects Analysis (FMEA).

FMEA principle:

Failure Mode and Effects Analysis is an industry recognized tool to plan inspection activities based on relative risk. There are several methods for developing a risk analysis. Whatever method is chosen, it is based largely on feedback from the network operator and, if applicable, the specific characteristics of the assets and their environment.

The Failure Modes Effects and Analysis method includes:

- Analysis of the causes and effects of failure of the various components of a system. Each intervention is listed as a Failure Case (FC);
- Evaluation of the criticity of different failure modes according to their probability of occurrence and the severity of their effects in the absence of safety barriers;
- Identification and evaluation of the effectiveness of existing safety barriers or implementation such barriers which reduce the criticity of failure modes to a level considered as acceptable. There may be barriers to prevent the occurrence of the event generating the hazard and / or barriers to limit, reduce or avoid the consequences of this event.

Among the Fedene-SNCU [9], the occurrence and criticity scores are define as follow in Table 6 but can also describe using other more quantitative criterions as in Oil and Gas industry (see Table 7 & Table 8).

In France, a new policy implies to use FMEA methods with design rules from January 1st 2014 for District Heating Networks [9].

Table 6 – Probability and criticity scores [9]

Score	Occurrence	Criticity
1	Not known or low occurrences (relatively few failures) on similar assets	Low: No impact or low impact on the distribution of heat
2	Moderate (occasional failures)	Major: No distribution
3	High (repeated failures)	Critical: No distribution and degradation of surrounding facilities
4	Very high (failure is almost inevitable)	Catastrophic: No distribution and endangering workers or the public

A Risk Priority Number, RPN, can be define multiplying occurrence and criticity scores (1) and is estimated for each Failure Cases (FC).

RPN = Occurrence x Criticity (1).

Indeed, in this method, occurrence and criticity of failure are considered simultaneously as shown in Figure 6. Thus for each failure case, RPN is placed on a four by four matrix (see Figure 6) which visually represents on which assets focus effort and on which assets inspections can be reduced. Fedene-SNCU considers that the risk is acceptable if RPN ≤ 4 [9].

We propose to add another acceptance criterion in order to be less critical. Thus, as shown in Figure 6:

- If RPN ≤ 4, the risk is acceptable;
- If 4 < RPN ≤ 8, the risk is high but can be acceptable depending if the failure mode only led to an economical loss and don't include human injuries or death;
- If RPN ≥ 9, the risk is very high and not acceptable.

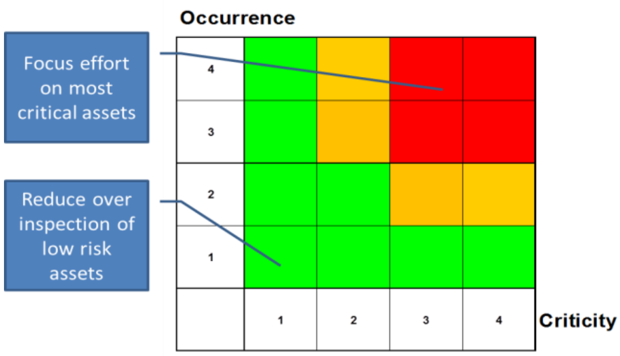

Figure 6 – Occurrence and criticity of failure's matrix

FMEA methodology

Before to start to develop FMEA, occurrence and consequences seen in Table 6 should be refined by project team (see Table 7 & Table 8) according to Mean Time Between Failure, Probability, Economic Loss, Health and Safety, Environment. Each parameter depends on network size.

Table 7 – Example of occurrence scores regarding number of failures [11]

	Occurrence	
Score	Mean Time Between Failures	Probability
1	> 50 years	Unlikely: <1%
2	10-30 years	Possible: 1-5%

3	3-10 years	Probable: 5-10%
4	<3 years	Expected: >10%

Table 8 – Example of criticity scores regarding impact of failures [11]

	Criticity		
Score	**Economic Loss**	**Health & Safety**	**Environment**
1	< 0,5 k€	First aid	Neglecting impact
2	0,5-1 k€	Lost time accident	Spill contained
3	1-10 k€	Permanent disability	Inside fence damage
4	>10 k€	One or several fatalities, Life-threat illness	Off-site damage, Long time effect

Then, the main different steps in a FMEA study are listed below:

- Standardize database: first of all, technical team needs to standardize database with same vocabulary for assets, failure modes, causes, solutions and numerical datas.
- Identify and quantify failure cases: engineers identify and quantify main failure cases using failure modes, causes and solutions.
- Identify and benchmark solutions applied: engineers and managers identify best solutions to fix failures and evaluate long term impact of the solutions applied.

RESULTS

FMEA results

First of all, the engineer identifies with his team all the scenarios which happened during the operating period and assign a Failure Case number, FC, for each one. But the more failure cases are listed the more accurate and the better interpretation of FMEA results will be.

Here only FC on valve family from 2009 to 2012 coming from a failure case database are represented. Using the database, FMEA is established on a first year before to evaluate the solutions impacts on the following years (see Table 9). Then, we put the RPN in different FMEA grids which show risk for all valves and the evolution along the years (see Figure 7).

In this case, solution applied is replacement for all assets but seems to not have such a positive impact on RPN. Indeed, in 2010, the RPN for FC1 does not decrease furthermore the RPN for FC2 increase and a third Failure Case appears. It is interesting because it means that solutions applied were not efficient. In 2011 and in 2012, even if some new Failure Cases appear (FC4, FC5 and FC6), the solutions decrease the RPN for previous Failure Cases (FC1 and 2).

It could be interesting to investigate deeper causes and solutions according seasons on this case study.

Comparing different risk matrix for several years shows the impact of solutions applied on assets which failed in the past and helps engineers and DHN manager to choose actions that will be apply in the following years.

Table 9 – FMEA results on valve family

Failure Case Nb	Date	Asset	Criticity	Occurrence	Criticity rate	Occurrence rate	Risk Priority Number
FC1	2009	Ball valves	Major	High	2	3	6
FC2	2009	Valve	Catastrophic	Moderate	4	2	8
FC1	2010	Ball valves	Major	High	2	3	6
FC2	2010	Valve	Critical	Very high	3	4	12
FC3	2010	Valve vents	Low	Low	1	1	1
FC1	2011	Ball valves	Catastrophic	Moderate	4	2	8
FC4	2011	Valve flange	Major	Moderate	2	2	4
FC3	2011	Valve vents	Major	Moderate	2	2	4
FC5	2012	Drain valve	Major	High	2	3	6
FC2	2012	Valve	Catastrophic	Low	4	1	4
FC6	2013	Stop valve	Catastrophic	Moderate	4	2	8

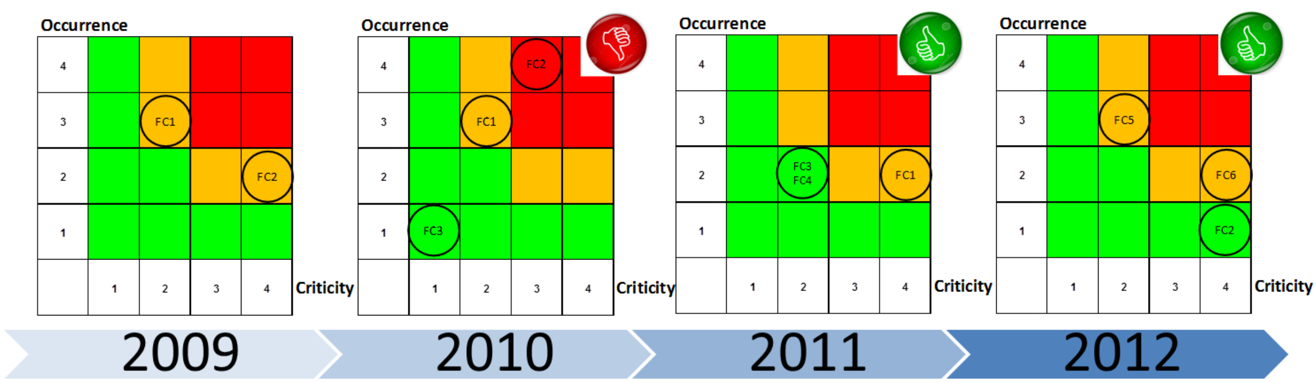

Figure 7 – RPN evolution on valve family

OUTLOOK

We present some methodologies and first results on how to assess District Heating Network. This is only the first part of a bigger study in which we will use these tools to try to make more reliable District Heating Networks.

CONCLUSIONS

District Heating Network is constituted of both pipes and assets which age and need to be repaired or replaced during their operating life.

In order to invest time and money as wise as possible, it is very important to choose were and how plan interventions on the DHN.

Failure rate give quantitative information about network evaluation along the years whereas FMEA leads to make some priority between asset families.

The key to better manage DHN is to find the best criteria to evaluate efficiency of solutions applied to fix asset for each DHN regarding their own parameters.

Thus, FMEA dynamic approach is very interesting to see impact of solutions applied to fix asset all along the years. As seen in this study, FMEA is clearly adapted to District Heating Networks because it aims to focus on risker equipments and to benchmark solutions in the past to find the best solutions for the next interventions according:

- Cost;
- Water and energy loss;
- Others Key Performance Indicators.

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AN ONLINE MACHINE LEARNING ALGORITHM FOR HEAT LOAD FORECASTING IN DISTRICT HEATING SYSTEMS

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ABSTRACT

Optimization of heat production in district heating systems is important both from a financial and an environmental standpoint. In particular, energy companies aim at minimizing peak boiler usage, optimizing combined heat and power generation and planning base production. To achieve resource efficiency, the energy companies need to estimate how much energy is required to satisfy the market demand. Heat load forecasting enables effective planning and decision-making. In this paper, we suggest an online machine learning algorithm for heat load forecasting. Online algorithms update the prediction or regression model when new information becomes available. These algorithms are increasingly used due to their computational efficiency and their ability to handle changes of the predictive target variable over time. The proposed algorithm was evaluated on operational data from a district heating system. The results of the study show that the algorithm has a solid predicting ability with a mean absolute percentage error of 4.77%. Robust heat load forecasting is an important part of increased system efficiency within district heating, and the presented algorithm provides a concrete foundation for operational usage of online machine learning algorithms within the domain.

INTRODUCTION

Over the last few decades, District Heating (DH) has been increasingly used for space heating, domestic hot water and industrial processes [1]. The reason lies in the fact that DH is an energy-efficient and environmentally sound way to supply heating [2], [3]. Combined Heat and Power (CHP) plants can be used to generate heat in DH systems [4]. In CHP plants, electricity and heat are produced simultaneously [4], [5]. This results in efficiency that ranges between 80-90%, since CHP plants require less resources to produce the same amount of energy as separate heat and power systems [4],[5],[6]. Regarding environmental benefits, CHP plants can use environmentally friendly resources such as biomass and renewable energy.

An important issue that exists in DH systems is the long delivery time of heat to the customers. When a production unit is activated, it might take hours to carry out all the processes that are required to generate heat. In addition, customers are usually geographically dispersed and many kilometres away from the production units. As a result, it can take several hours to produce and distribute the heat to the customers. This can lead to a situation where the heat is no longer needed at the moment of delivery, e.g. due to a raise in outdoor temperature. Consequently, heat suppliers aim at producing the amount of heat that is required to satisfy the customers' demand at any given time, including heat losses in the distribution network. To achieve this, a reliable prediction of the heat load would be beneficial.

Heat load forecasting enables effective planning and management [7], [8]. By estimating the heat demand, heat suppliers can avoid producing superfluous heat. At the same time, heat suppliers can schedule which production units to activate. Normally, heat suppliers want to initially activate production units with lower operational costs [1], [9]. Moreover, heat load forecasting enhances the effectiveness of techniques such as demand side management and load control [9], [10], [11]. These techniques are used to coordinate the heat consumption at the customers' side. That way, heat suppliers can avoid the use of peak load boilers, which mostly use expensive and environmentally unfriendly fossil fuels. In addition, demand side management enables load shifting. Load shifting can be used in relation to CHP plants in order to synchronize peak demands in electricity and district heating. This technique is profitable for heat suppliers, since they can match their production with high spot-prices on the power market [4],[5].

The heat load is used for space heating and heating tap water. The demand for space heating mostly depends on the outdoor temperature. The demand for hot tap water is influenced by the social behaviour of the consumers, e.g. there is a difference in the need for hot tap water between weekdays and weekends [1]. The overall heat load exhibits a nonlinear, stochastic and non-stationary behaviour [12], which limits the predictive capabilities of current approaches. To achieve an accurate prediction of the heat load, there is a need for models that can be incrementally updated in order to capture changes in the heat load over time. At the same time, modern systems for supervision collect massive amounts of data during the operation of heating grids. Consequently, there is a need for robust, memory-efficient, high-speed models that will be able to process real-time data.

Heat Load Forecasting

The heat load in a DH system is defined as the amount of energy that is required for space-heating and heating tap water at any given moment in time together with the distribution losses. Space heating is highly dependent on outdoor temperature [1]. When the outdoor temperature is lower than the desired indoor temperature, heat is transmitted from the inside of the building to the external environment through walls and windows. To cancel out this heat loss and maintain a desired indoor climate, it is necessary to supply heat to the building. The amount of heat that has to be supplied is proportional to the difference between the indoor and outdoor temperature. Sometimes space heating also includes heating the cold air that is used in ventilation systems. On the other hand, the demand for hot tap water is affected by the social behavior of the consumers. For example, the tap water demand is lower during the night since most people are asleep.

The input for heat load forecasting includes factors that affect both space heating and heating tap water. The most important factors that are usually used are outdoor temperature, time of the day and day of the week.

Machine Learning

Machine Learning (ML) is a branch of Artificial Intelligence, which aims at building models that learn from data [13]. The most common task in ML is supervised learning [13, 14]. In supervised learning, we build a model using training data that consist of N data records (x_1, y_1), (x_2, y_1), . . . ,(x_N , y_N), called instances. Each instance is described by an input vector x_i - which consists of a set of attributes $A = \{A_1,A_2,\ldots,A_m\}$- and a label y_i of the target attribute that denotes the desired output .The goal is to train a model that can predict the label of new instances. Supervised learning tasks mainly include classification and regression. In classification problems, the label y_i takes discrete values, whereas in regression problems it takes continuous values. Table 1 shows the first five instances of three attributes from the Electric Bill dataset, which represents a regression problem [15]. The outdoor temperature and the Heating Degree Days (HDD) are used to predict the monthly household electric bill charges.

One of the most popular classification and regression models is the decision tree. Decision trees are easy for humans to interpret and can achieve high levels of predictive accuracy. They consist of internal nodes, branches and terminal nodes [16], [17]. Each internal node corresponds to a particular attribute that splits the instance space into two or more subspaces, according to the possible values that the attribute can take. Each possible value represents a branch. The terminal nodes are the endpoints of the tree and represent the final output of the algorithm. In order to predict the label of an instance, the algorithm navigates the instance from the root node to a terminal node, according to the instance's attribute values along the path. Fig 1 illustrates a decision tree that is constructed from the Electricity Bill dataset

Table 1 First five instances of the Electric Bill dataset

Temperature (F^o)	HDD	Amount of bill (dollars)
29.1	1229	162.10
31.5	999	256.90
41.9	734	151.15
53.4	373	118.76
63.7	162	100.71

Decision trees are also widely used in ensemble learning. The main idea behind ensemble learning is to combine the output of multiple predictive models using voting mechanisms [18]. One of the most popular techniques for constructing an ensemble is bagging. Bagging uses a sampling technique called Bootstrap Aggregating to generate multiple training datasets. Each dataset trains one model in the ensemble. The output of bagging is either the majority vote (in classification problems) or the average (regression problems) of all the models in the ensemble. Generating multiple predictive models with bagging provides diversity that often leads to more reliable and accurate predictions. An example of ensemble algorithms that use bagging is Random Forests. Random Forests creates an ensemble of decision trees and it is considered a state-of-the-art ML algorithm. In this study, we apply bagging to construct an ensemble of regression trees, in order to increase the predictive accuracy of the proposed algorithm.

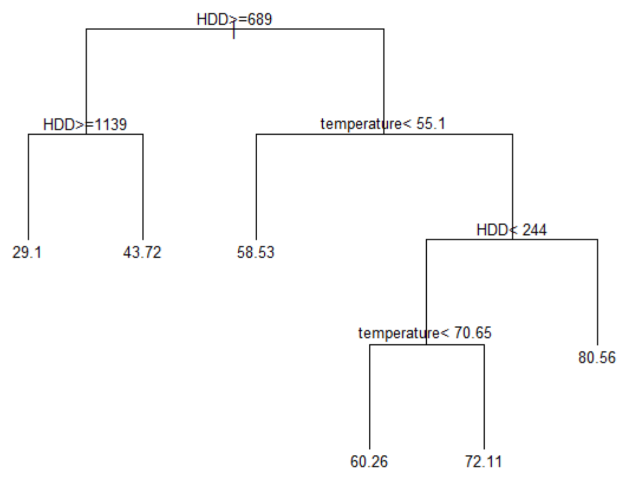

Fig. 1 Structure of a decision tree for the Electric Bill Dataset

Traditional ML algorithms are trained only once on a particular set of data, called the training set. The main drawback of this approach is that the algorithms cannot adjust to potential changes in the distribution of the target attribute. This behaviour is called concept drift [19] and it is very common in real-world settings. Incremental learning is an effective way to handle concept drift. The idea behind incremental learning is that the model can be updated whenever new information becomes available. Previously acquired knowledge can be either discarded or maintained [20], [21].

Incremental learning can be done offline or online. In online learning, each instance is processed only once to update the model, and then it is discarded without the need to store it in the memory [13]. Incremental online algorithms have been successfully implemented in several domains such as robotics [22], autonomic wireless networks [23], handwritten character recognition [24], web page classification [25] and semiconductor manufacturing [26].

STATE OF THE ART

Heat load forecasting in DH systems has received a lot of attention in the last 15 years. There are several proposed approaches, which mainly include statistical and ML models.

Most statistical models comprise a temperature-dependent component and a social component, which is related to the social behaviour of the consumers. Erik Dotzauer proposed a simple model, in which the temperature-dependent component is represented as a piecewise linear function, and the social component is equal to a constant value for each day of the week [27]. Henrik Aalborg Nielsen and Henrik Madsen used a grey-box approach that combines physical knowledge with statistical modelling [28]. The physical knowledge provides a general structure of the model, considering heat transfer through walls, heat transfer through windows, ventilation as well as the social behaviour of the consumers. A statistical modelling process is then used to calculate the actual coefficients of the model. Bronislav Chramcov used a polynomial function for the temperature-dependent component, and a Box-Jenkings methodology for the social component [29]. The Box-Jenkins methodology applies an autoregressive moving average (ARMA) model. In [30], the non-stationary behaviour of the heat load is captured with a Seasonal Autoregressive Integrated Moving Average (SARIMA) that is embedded in a state space framework. The forecasting values are calculated using classical Kalman Recursion. The influence of outdoor temperature is described as a piecewise linear function.

ML algorithms are capable of dealing with the nonlinear and non-stationary behaviour of the heat load. The most widely used ML approach to forecast the heat load in DH systems is Neural Networks [31], [32], [33].

To our knowledge, neither online ML algorithms nor decision tree-based ML algorithms have been applied to heat load forecasting. We address this identified research gap by investigating an ML method that mixes both techniques. This method efficiently processes streaming data and it generates and calibrates comprehensible models that can perform heat load forecasting in DH systems. Decision trees have been used in a plethora of real-world applications such as power systems [34], medicine [35], object recognition [36], smart homes [37].

METHOD

Algorithm

Online bagging creates an ensemble of decision trees [17]. The base model of the ensemble is the Fast Incremental Model Trees with Drift Detection (FIMT-DD) algorithm [38], which was introduced by Ikonomovska et al. in 2006. FIMT-DD is a state-of-the-art online decision tree that is used for regression. The tree is constructed as follows: when a new instance arrives, FIMT-DD traverses the instance to a terminal node and updates the necessary statistics for this node. Then the algorithm checks if the splitting criterion is satisfied, in order to decide on whether this node should be further expanded. To predict the target value of an instance, FIMT-DD calculates a weighted average of the instance’s attributes. FIMT-DD has also the ability to detect concept drift and adjust to non-stationary environments. When concept drift is detected, FIMT-DD grows subtrees in order to replace parts of the tree that are not relevant for the new concept.

Due to measurement or communication errors, the data from a DH system can often contain missing values and outliers. The proposed algorithm handles missing values and outliers in an online fashion. Missing values for the temperature and the heat load are filled in by the average value of measurements from the previous 6 hours, since the most recent values are more relevant and can approximate the missing values to a sufficient extent. Outlier detection is carried out through a statistical approach. The algorithm computes the mean (μ) and standard deviation (σ) of the 50 most recent values for the heat load, and then a threshold is used in order to determine whether a value for the heat load is an outlier. A value x is considered an outlier if it satisfies one of the following conditions

$$x < \mu - 3\sigma \qquad (1)$$

$$x > \mu + 6\sigma \qquad (2)$$

These thresholds were decided after parameter tuning. Outliers are not discarded. Instead, the algorithm removes the outlier value and imputes a new value with the same technique that is used for imputing missing values.

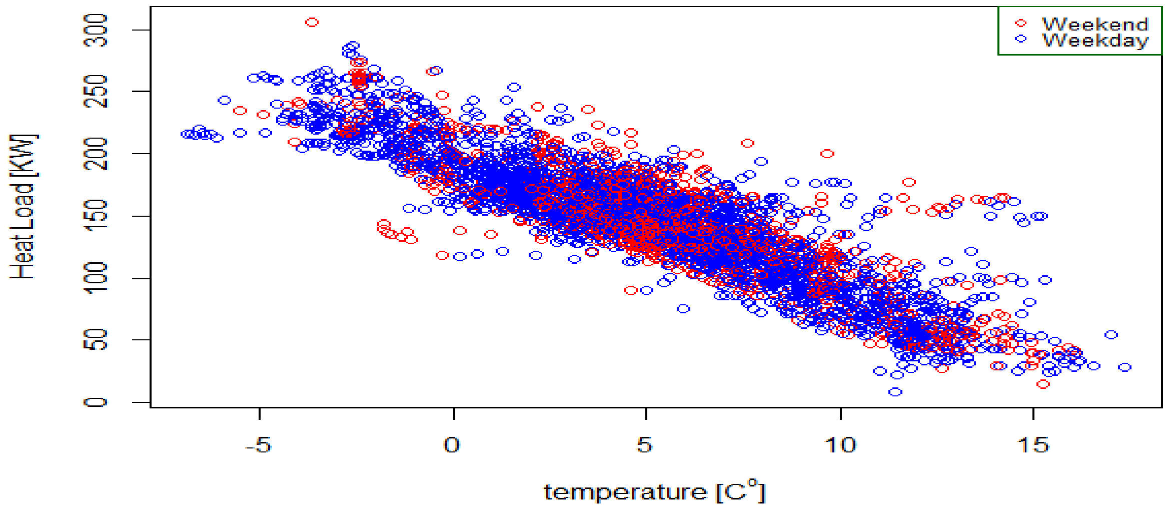

Fig. 2 Hourly heat load measurements with respect to outdoor temperature for a residential building

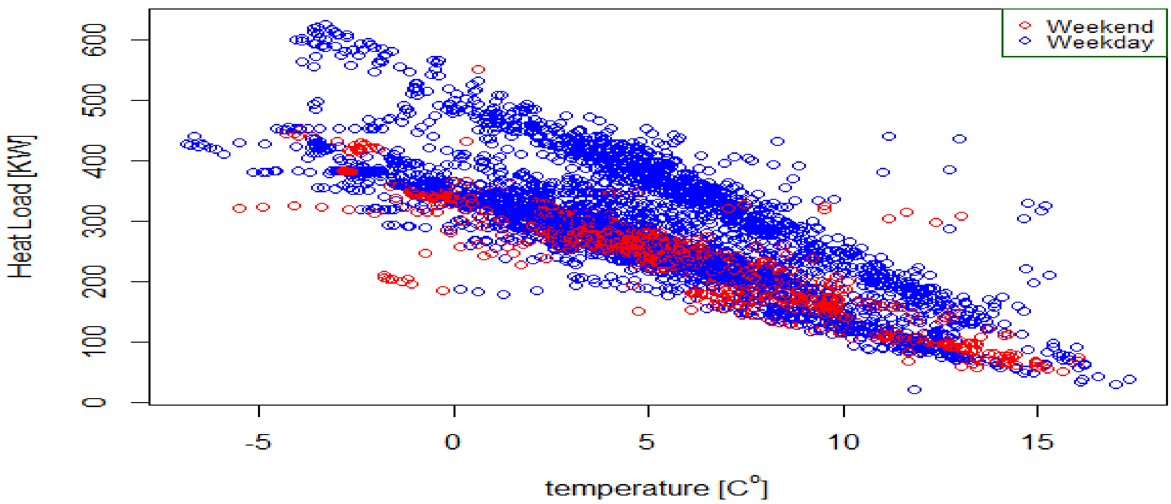

Fig. 3 Hourly heat load measurements with respect to outdoor temperature for a commercial building

Data collection

The data consist of hourly measurements from 26 building substations in a part of Karlshamn DH network in the south of Sweden. The data was collected from 01-10-2013 to 31-03-2014. The nodes comprise residential buildings, commercial buildings and a school. Figure 2 shows the heat load for a residential building with respect to the outdoor temperature. For a given temperature, the higher values of the heat load occur during the day due to the increased consumption of hot tap water. For a commercial building (Figure 3) there is a higher variation since during the night and weekends there is a limited number of people inside the building as well as the ventilation system does not operate at full capacity [1].

Software Platform

We conduct experiments using two software applications, namely Waikato Environment for Knowledge Analysis (WEKA) [39] and Massive Online Analysis (MOA) [40]. WEKA and MOA are open-source, written in Java and compatible with each other. They are widely used for ML tasks such as classification, regression and clustering. WEKA mainly contains batch algorithms, whereas MOA is a framework for online learning from data streams. Both applications can be used for data preprocessing and running experiments either through a Graphical User Interface or an API. The API is also used for developing new algorithms.

Experimental design

The customer heat load in a DH network is calculated by aggregating the heat load of all the nodes in the network. This study investigates the impact of two different approaches for heat load aggregation. Approach 1 is to create one model for each node and aggregate the predictions of the 26 nodes. Approach 2 is to aggregate first the heat load of the 26 nodes and then create one model to predict the aggregated heat load.

The primary aim of the experiments is to evaluate the performance of the proposed algorithm in terms of accuracy in predicting the heat load. For this purpose, we use two of the most common evaluation metrics for regression, namely Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE), which are defined as follows

$$\text{MAE} = \frac{\sum_{i=1}^{N}|p_i - y_i|}{N} \quad (3)$$

$$\text{MAPE} = \frac{\sum_{i=1}^{N}\left|\frac{p_i - y_i}{p_i}\right|}{N} * 100 \quad (4)$$

where p_i is the actual value , y_i is the predicted value and N is the number of data points.

With respect to heat load forecasting, the MAE represents the average magnitude of the difference between the actual and predicted heat load in terms of kW. The MAPE is a relative metric, i.e. it does not depend on the scale of the values, and is used to express the average accuracy of a predictive model as a percentage.

The prediction values are calculated by taking the average of 100 runs of each experiment. A prequential evaluation is used, i.e. each instance in the stream is used to test the algorithm, and then the same instance is used to update its model. All predictions are made 36 hours ahead. The attributes that are used for training and evaluating the model are time, weekday (true or false) and outdoor temperature.

RESULTS

The predictive ability of the proposed algorithm is evaluated by conducting experiments for the two approaches of data aggregation. Figures 4 and 5 illustrate the average of the 100 runs for predicted values, difference (actual - predicted), and evaluation metrics for Approaches 1 and 2 respectively. Table 2 shows the mean and standard deviation of the MAE and MAPE for the two approaches for the 100 runs of the experiments. In addition, Table 2 shows the results of the Student T-Test which is performed to determine whether there is a significant difference in the prediction error between the two approaches. The p-value is considerably lower than the significance level (0.05), which means that Approach 2 has a significantly lower prediction error than Approach 1.

Table 2 Mean, Standard Deviation and statistical analysis of 100 runs for Approaches 1 and 2

	Approach 1	Approach 2	t-statistic	p-value
MAE	85.063	78.714	3005	22e-18
	(0.019)	(0.007)		
MAPE	5.135	4.770	1597	22e-18
	(0.002)	(0.001)		

Note. Standard Deviations appear in parentheses below Means

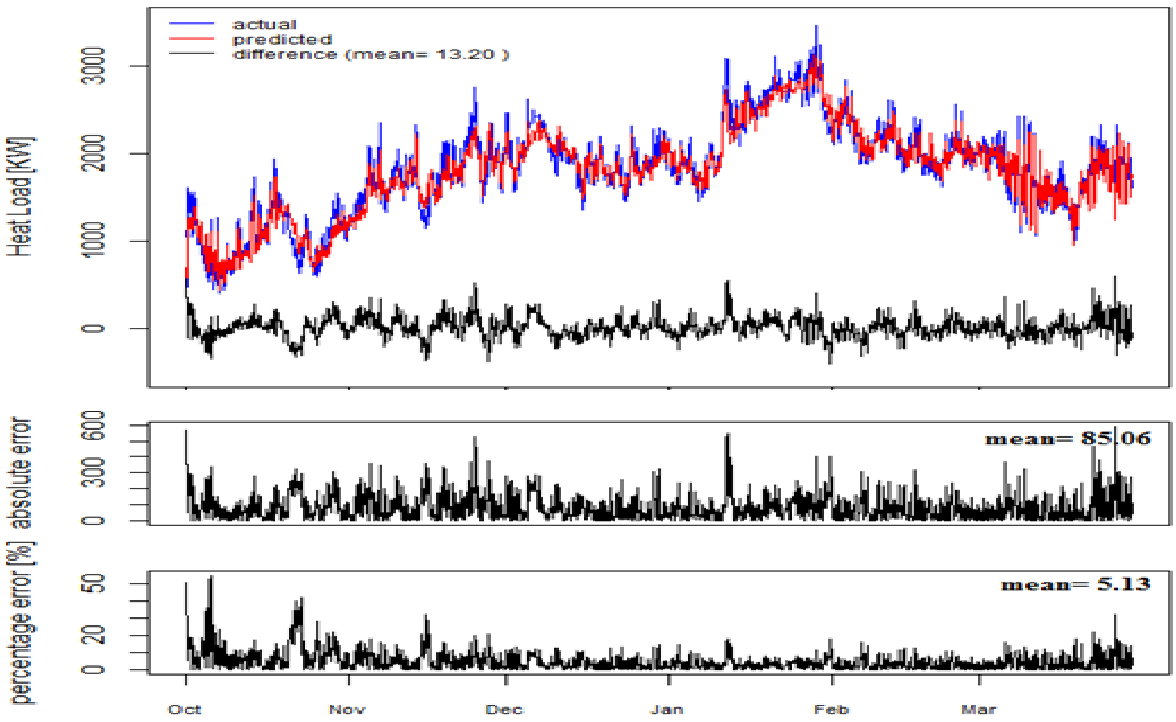

Fig. 4 Predictions and evaluation metrics for Approach 1

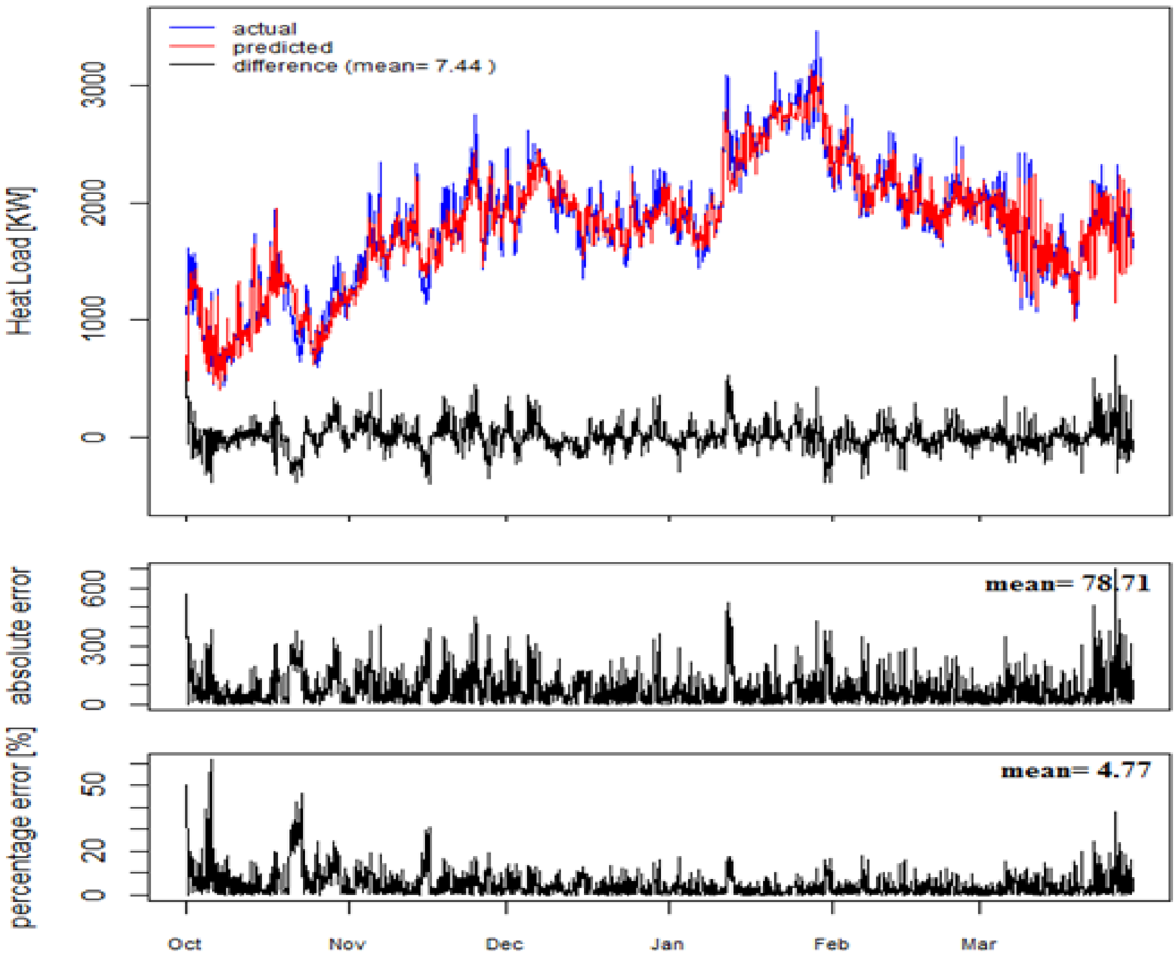

Fig. 5 Predictions and evaluation metrics for Approach 2

DISCUSSION

The experimental results show that the proposed online algorithm possesses a solid predictive ability. The mean absolute percentage error of 4.77% is lower than or at least equal to the mean percentage error of state-of-the-art approaches that have been proposed for heat load forecasting in DH systems. However, a direct comparison is not possible due to different operational data, configurations, and experimental design. The results are even more important if we take into account that online learning has an inherent disadvantage in comparison to traditional algorithms. This disadvantage pertains to the fact that traditional algorithms are fully trained with all the available data before the evaluation, whereas in online algorithms the training and the evaluation evolve simultaneously as new instances arrive from the data stream.

Another aspect of the experiments is related to the propagation of the error with regard to different ways of data aggregation. The results show that the error is significantly lower when we aggregate first the heat load of the 26 nodes and then build one model to make the predictions. The use of individual models for each node leads to higher error.

A key feature of the model is its ability to handle missing values and outliers, which increases the robustness of the model to noise and measurement errors.

OUTLOOK

One possible direction to extend this work is the implementation of a more sophisticated technique to handle missing data and outliers. Measurement errors occur frequently in real-world applications and therefore there is a need for a robust technique that will handle missing data and outliers more effectively. This technique has to take into account the different type of buildings that exist in a DH network. The behavior of the heat load varies according to the type of building and therefore an optimal solution cannot be achieved when the same approach is used for all types of buildings. A possible solution to this problem is the implementation of an automated parameter tuning technique that will tune parameters and thresholds according to the behavior of the heat load for each building.

CONCLUSIONS

Heat load forecasting is an area that attracts a lot of interest within the research community, since it can assist in effective planning and management of DH systems. This leads to environmental benefits as well as cost reduction for heat suppliers.

This work investigates the potential benefits of the application of online learning to the DH domain. We present an ensemble of decision trees that is able to capture the nonlinear, stochastic, non-stationary behaviour of the heat load. Experimental results on operational data show that the model possesses a strong predictive ability.

The model is memory-efficient, since it does not require the storage of data in the memory. Each instance is discarded after it updates the model. Another important feature of the algorithm is the ability to learn incrementally and process massive amounts of data in real time.

Due to all the aforementioned advantages, online learning is increasingly used in real-world applications in order to process and analyse high volumes of data in real time. This work provides a foundation for further use of related ML algorithms in the domain of DH systems.

ACKNOWLEDGEMENT

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METHOD FOR THE QUANTIFICATION OF A LEAKAGE IN A DISTRICT HEATING NETWORK

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ABSTRACT

A2A Calore & Servizi (ACS) is one of the main district heating companies in Italy. It manages the district heating network of Brescia, Bergamo and Milan.

ACS carries tests on the networks in the summer to find leaks. In these tests a part of the network is sealed off and the pressure trend over the time is plotted in a curve.

These tests are useful to find leaks, but they do not provide an estimation of the volume of water lost. The proposed method allows an estimation of the loss of water using the data collected during the tests. The knowledge of the lost water is crucial to assess the leaks seriousness and to define the repairs priority.

The method considers the network as a compressible system with its own bulk modulus estimated with the data registered in tests. The leak orifice area is calculated through the bulk modulus and then it is used in the orifice flow equation to calculate the loss of water.

The results of the model were validated using a portable make-up water facility, in order to actually measure the leakage. The method estimates the loss of water with a precision of around ± 15%.

INTRODUCTION

Leak detection is one of the major tasks that a district heating company has to face. The leak detection methods currently used (thermography, acoustic correlation, gas tracer, etc.) allow to find a leak and, in some cases, even to pinpoint it but, although the constant use of the aforementioned methods can lead the operator to a qualitative evaluation of a leak seriousness, these methods are not able to estimate the actual loss of water.

Being able to estimate correctly the loss of water due to leaks is a crucial issue to improve the leak detection process and to make it more effective and more efficient, because with the knowledge of the amount of lost water it is possible to concentrate the attention on the areas with the higher level of lost water. The advantages of this are remarkable especially for very big network with high number of leaks.

BRESCIA DISTRICT HEATING NETWORK

The district heating network of Brescia is one of the biggest and oldest in Italy. Its development began in the 1972 and, today, it has reached the total length of 660 km (trench length), with a total volume of around 26,000 m³ (supply line + return line). Table 1 shows some of the main data about the network.

Table1. Main network data

Network length	660 km
Network volume	26,000.00 m³
Number of customers	20,500.00
Max supply temperature (winter)	130 °C
Max supply temperature (summer)	90 °C
Return temperature (constant all over the year)	60°C
Max. operative pressure	16 bar
Minimum ground level	107 m (above the sea level)
Maximum ground level	214 m (above the sea level)

The heat is produced in a WtE and in a CHP plant, both located in the south part of the network. Peak load boilers are located in the middle of the network and also close to the CHP plant. The network works as a single system and cannot be divided in smaller hydraulically separated sub-networks.

In the network there are three main different types of pipes. The 22% of the network length is made by concrete duct pipe laid in the years 1972 – 1979. The steel pipes are installed in concrete duct and they are sustained by rollers or metallic saddles. They are free to slide on the supports and the displacements at the bends are allowed through angular compensators installed in underground structures. The insulation is made by rock wool protected with tarry slated sheath.

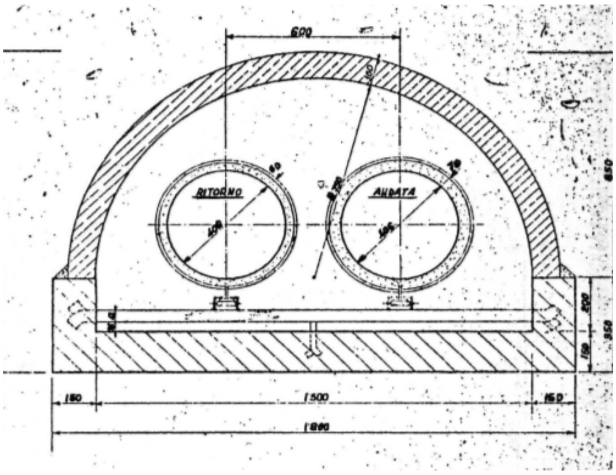

Fig. 1 Concrete duct pipe. [1]:

Over the years from 1979 to 1985, the pipes were laid in preinsulated sheathes named Wanit, composed by two concentric fibrocement pipes with a layer of polyurethane in the middle. The steel pipes can slide into the inner sheathe. This type of pipe covers 2% of the whole network length.

Fig. 2 Wanit pipe.

Finally, since 1985 preinsulated pipes has been used

Fig. 3 Preinsulated pipes.

THE PRESSURE TESTS

Since many years, pressure tests are conducted on the Brescia DH network during the summer in order to find leaks. This method generally allows to detect leaks in parts of the network but rarely lead to pinpoint them. Generally, about 80% - 90% of the whole network is checked with pressure tests every summer (from April to October). The pressure tests are conducted on small parts of the network (*test areas)* which are sealed off and separated from the rest of the network. In these areas the pressure drop is checked. In some cases, the pressure reduction speed is a qualitative index about the size of the leaks in the area. Over the years the operators have been developing their own experience and sensitivity, but that is not enough to actually assess the seriousness of the leaks and, consequently, give them the correct importance in terms of repair priority.

So, in 2012 a method based on the data available from pressure tests was implemented to assess the seriousness of the leaks. Furthermore the pressure tests procedure was slightly improved. The complete new test procedure is here summed up:

1. The part of the network that has to be tested (*test area)* is sealed off from the rest of the network closing the line valves except one valve on the supply line. The supply and the return lines are connected via the customers substation and so, the pressure in the return line (p_r) is increased, reaching the pressure of the supply pipe (p_s).

2. As soon as the pressure in the return pipe is equal to the pressure in the supply pipe, the last valve in the supply pipe is closed. The *test area* now is completely separated from the rest of the network.

3. The initial pressure in the *test area* ($p_0 = p_s$) is lowered up to 1 bar opening a draining valve and the discharged volume (ΔV) is measured.

4. The pressure is checked for at least ten minutes. If there pressure does not rise, the valves tightness is verified and the test can continue.

5. The pressure in the *test area* is then increased to the initial value p_0 opening one valve on the supply line. Then the network is sealed off again.

6. In case of a leak the pressure starts to decrease and the pressure p_i at the instant t_i is registered till the pressure drops to 0 bar or till thirty minutes. The pressure trend over the time is plotted (fig.4).

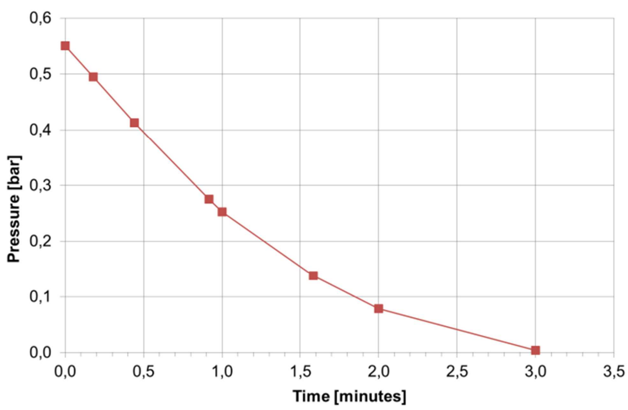

Fig. 4 Example of a pressure trend over the time registered during a pressure test.

The pressure is measured by means of two digital manometers connected to the supply pipe and to the return pipe (fig.5). The discharged volume is measured weighing the water, temporarily stored in buckets, with a dynamometer (fig.6).

Fig. 5 Digital manometer used in the pressure tests.

Fig. 6 Dynamometer and bucket used to measure the discharged volume in the pressure tests.

So, the following data are collected at the end of the test: initial pressure (p_0), volume discharged (ΔV) and the pressure p_i at the instant t_i (pressure vs. time curve). This data are used to estimate the loss of water in the area.

METHODOLOGY

The proposed method considers the pipes in the *test area* like a pressurized vessel full with water and with an unknown volume of air entrapped into the pipes. This system is also considered compressible, with his own bulk modulus [2] [3]:

$$\beta_e = -V_T \frac{\Delta p}{\Delta V} \tag{1}$$

where: β_e = system bulk modulus, V_T = total volume of the pipes in the test area, Δp = pressure variation, ΔV = volume variation. The bulk modulus can be estimated through the data registered during the pressure test (see point 3 of the pressure test procedure). In fact, the pressure variation Δp is the difference between the initial pressure p_0 and the final pressure (1 bar), whereas the volume variation ΔV is the volume discharged to reduce the pressure.

This is a rough estimation of the system bulk modulus because the volume variation ΔV is actually given by two contributes: the volume discharged to reduce network pressure, which is measured, and the loss of water due to the leaks in the area, which is unknown.

As consequence, the greater is the loss of water due to leaks, compared to the discharged volume, the higher is the overestimation of the system bulk modulus. However, the system bulk modulus β_e cannot be greater than the water bulk modulus (2,000.00 MPa) [2] [3].

A leak can be roughly approximated as a flow that comes out from an orifice, so the flow rate is given by the orifice flow equation:

$$Q = Av = A\sqrt{2\frac{p}{\rho}} \tag{2}$$

where Q = flow rate, A = orifice area, p = pressure in the pipeline and ρ = water density.

The flow rate is also the volume variation over the time:

$$Q = \frac{\Delta V}{\Delta t} \tag{3}$$

where Q = flow rate, ΔV = volume variation, Δt = time variation.

Combining (1), (2) and (3) it is possible to obtain the equation that describes the pressure drop over the time:

$$p_i = \left(\sqrt{p_0} - t_i \frac{\beta_e A \sqrt{\frac{2}{\rho}}}{2V_T} \right)^2 \tag{4}$$

where p_i = pressure at the instant *i*, p_0 = initial pressure, t_i = time at the instant *i*, β_e = system bulk modulus, A = orifice area, ρ = water density, V_T = total volume of the pipes in the test area.

Knowing the pressure p_i at the time t, with (4) is possible to calculate the orifice area *A:*

$$A = -\frac{2V_T}{\beta_e t_i \sqrt{\frac{2}{\rho}}}\left(\sqrt{p_i} - \sqrt{p_0}\right) \qquad (5)$$

The values p_i and t_i are collected in the last step of the pressure test procedure (See point 6 of the procedure).

Finally, the flow rate due to a leak, or due to a sum of leaks, can be calculated setting a pressure value p and using (2).

It should be noted that this method allows to estimate the total amount of water lost in the *test area*. Depending on the area dimension the loss of water could be due to more than one leak. In this case the orifice area is the area of a fictive orifice which represents the sum of all the leaks in the area.

At this stage the cooling of the pipes is not take into account because the maximum pressure tests duration is thirty minutes, so the effect of the pipes cooling on the estimated loss of water is negligible.

Anyway, taking into account the cooling effect, especially for very small test areas with small diameter pipes, could even lead to a more precise evaluation of the loss of water.

METHOD CALIBRATION

The results of the method were validated through a portable make-up water facility.

The loss of water due to leaks in a sealed off parts of the network was measured evaluating the necessary flow rate to maintain the pressure in the area at a constant value.

These measures were conducted quickly as much as possible so that the pipe cooling effect on the pressure was negligible.

The portable make up water facility was composed by the following sections:

- a 1 m³ tank to store demineralized water. The tank was installed on a van;
- a pump to inject the water into the *test area.* For leaks with a supposed size smaller than 2,5 m³/day a volumetric pump was used. For leaks with a supposed size greater than 2,5 m³/day a variable speed centrifuge pump was used*;*
- a power generator, installed on a van, to provide electric energy to the pumps;
- a flow meter to measure the flow injected in the network.

The following picture shows the portable make up water facility for leak size greater than 2,5 m³/day.

Fig. 7 The portable make up water facility

A total number of 23 *calibration tests* were conducted on 23 *test area*. For each of these *test areas* the loss of water was assessed both using the described methodology and measuring it with the portable make-up water facility and the results were compared.

Information about the dimension of the test areas are summarized in the following graphs. A total of 12 classes of *network length* and *network volume* were defined. Fig.8 shows the number of tests carried for each volume class: 13 out of 23 tests were conducted on test areas with a network volume smaller than 100 m³

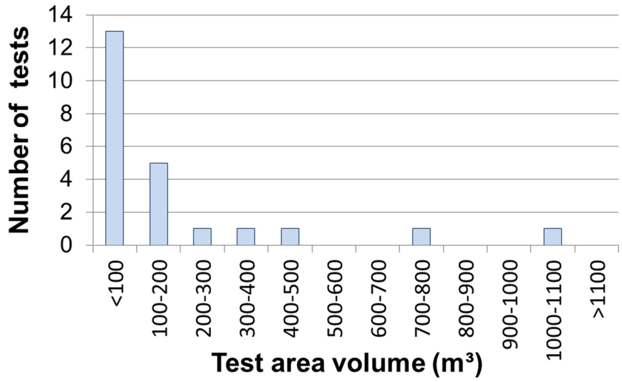

Fig. 8 Number of tests per network volume classes.

Fig.9 shows the number of tests carried for each length class: 15 out of 23 tests were conducted on test areas with a network length smaller than 5 km.

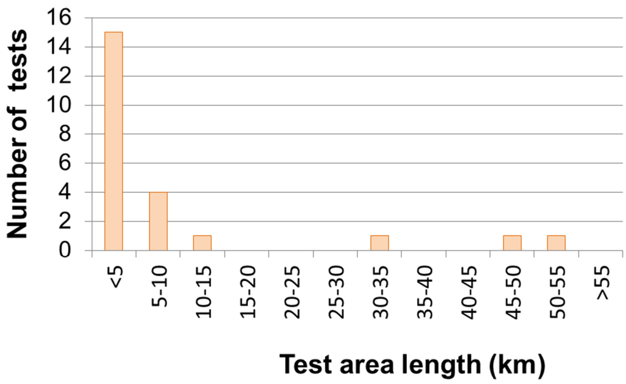

Fig. 9 Number of tests per network length classes.

RESULTS AND DISCUSSION

The system bulk modulus was calculated for each calibration test and its value was compared with the water bulk modulus. Then the estimated pressure drop and the estimated loss of water were compared with the on-site measured values and plotted into graphs as shown in fig.10.

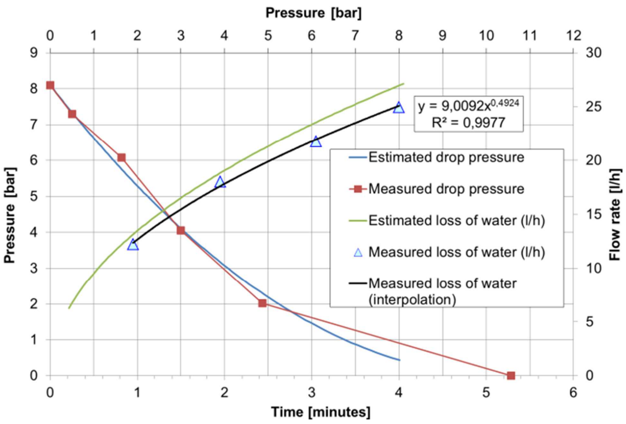

Fig. 10 Comparison between method results and calibration tests

In order to get an easy and immediate comparison between the method results and the values measured on-site with the portable make-up water facility a performance index, called *Test Index*, was calculated:

$$Test\_Index = 1 - \frac{A_e}{A_c} \qquad (6)$$

Where: A_e = average orifice area estimated with the method described, A_c = average orifice area calculated with (2) on the basis of the measures carried with the portable make up water facility. The *test index* represents, in terms of percentage, how much the measured values are different from the estimated values. In Fig.11 and Fig.12 the calibration tests results were sorted by decreasing *Test Index* and the *average orifice area estimated* (A_e) and *the average orifice area calculated* (A_c) were plotted. The analysis of the data shows that 3 out 23 tests have a Text index value greater than 100% (fig.11).

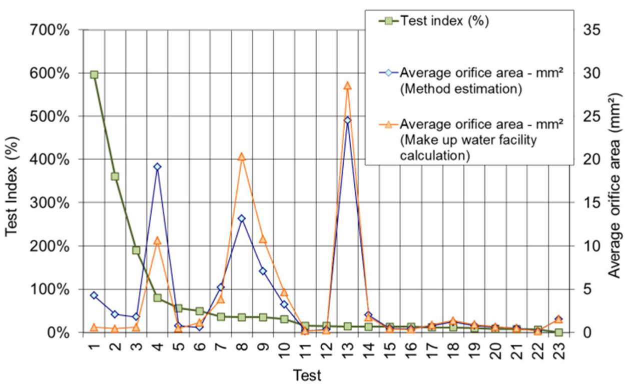

Fig. 11 Number of tests per network volume classes

Leaving aside the 3 tests with a *Test index* greater than 100%, and focusing on the remaining 20 calibration tests (fig.12), the results show that in 13 tests the values of A_e match the values of A_c with a maximum *test index* of 15 %.

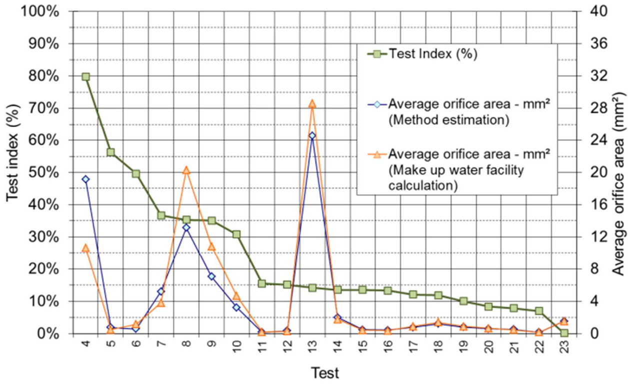

Fig. 12 Number of tests per network volume classes

Fig.13 shows the results distribution shared in class of *test index*. The 65% of the tests shows a *test index* smaller than 20%. The 20% of the test shows a *test index* smaller than 40%, which can give anyway a rough idea about the size of the leaks.

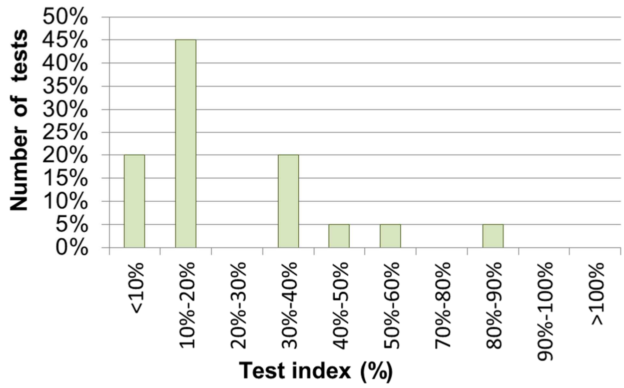

Fig. 13 Number of tests per network volume classes

The difference between estimated and measure values is smaller than 20% in the 65% of the tests.

CONCLUSIONS

- The knowledge of the amount of water lost is essential in order to know where could be more effective to concentrate the leaks localization and the repair efforts.
- The method proposed is used to detect leaks and to estimate the amount of water lost. With this method is generally difficult to pinpoint leaks.
- The estimation of the water lost is made using the information available from the pressure tests. These tests are carried on the Brescia DH network since many years and they are well known by the operators. The teams that perform the tests need just a couple of digital manometers, few fittings to connect them to the network and devices to measure the volume of water discharged (a

dynamometer and few buckets can be enough or, alternatively, a volume meter).

- The reliability of the method depends on the possibility to perform valid pressure tests. The valves tightness is a crucial factor to seal off effectively the test area and to perform correctly the pressure tests.
- It is important to pay attention to the ground level during the pressure tests. The point where the pressure is measured should be placed at the highest level in order to avoid the water column effect on the measures.
- Customer with hot tap water heat exchangers or customers located in blocks of flats with primary circuit that reaches the floors could affect the measures during the pressure tests.
- The 65% of the calibration tests shows that the method estimates the average orifice area, and consequently the leaks flow rate, with a *test index* smaller than 20%.
- The 20% of the calibration tests shows a *test index* smaller than 40%. These tests gave anyway an idea about the leaks size.
- The precision of the estimation of the water lost is influenced by the calculation of the bulk modulus. When the leaks size is high the system bulk modulus is overestimated and the leaks size is underestimated. Anyway this can give an idea about the leaks size.
- The method can be further improved taking into account the cooling effect, especially for area with small pipes. A2A is currently working on this.

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SESSION 5

Low temperature district heating and key developments for future energy systems

PERFORMANCE SPECIFICATIONS FOR HEAT EXCHANGERS FOR DH SUBSTATIONS OF THE FUTURE

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ABSTRACT

The performance specifications for heat exchangers in district heating (DH) substations have traditionally been made at summer conditions for the domestic hot water (DHW) part and at winter conditions for the heating (HE) part. In future, the DH supply temperature will be reduced to achieve higher efficiency. However, to realize this future trend for performance specifications for the heat exchangers applied, it need to be specified regarding to energy efficiency and system cost optimisation.

The suggested performance specifications take temperatures applied today and for future into account. Hence, the applicable temperature sets are considered for primary and secondary side of the heat exchanger.

To find the optimal thermal length regarding cost impact for the heat exchanger, the specified temperature sets are considered in relation to energy price for the DH source and the DH distribution heat losses.

The results are presented for symmetric heat exchangers, while for HE also asymmetric heat exchangers are considered and discussed. Specific suggestions for the needed heat exchanger area and the thermal length are made for the temperature sets. The available pressure drop is assumed to be similar to what is applied today.

The main finding is a tougher performance specification for heat exchangers. Especially the future lower DH supply temperatures require a longer thermal length for DHW and HE heat exchangers as well as a larger heat transfer area compared to what is typically specified today.

Key Words: Low Temperature District Heating (LTDH), Heat Exchanger Performance, Thermal Length, Heating, Domestic hot water

INTRODUCTION/PURPOSE

The concept of DH has been continuously developing during the last 135 years. Today many systems are on the level of what is referred to as 3rd generation. This is typically represented by “Scandinavian DH technology”, e.g. represented by pre-insulated pipes and industrialised compact sub stations. The next generation of DH is characterised by smart energy systems including optimal interaction between supply and consumption across the entire energy system, supply to low energy buildings and low temperature DH systems, [1].

The current dimensioning temperatures applied for the heat exchangers are adequate for the 3rd generation DH system demands. Here primary supply temperatures normally do not go below 65°C. But next generation demand lower supply temperature, typically in the range down to 55°C, or the secondary flow temperature + 5°C. The analysis of the impact of lower temperatures in DH systems is presented in [2]. In case of lower temperatures special attention must be paid to the dimensioning criteria for heat exchangers. Over specification leads to high costs, and thus, lower competiveness of the DH concept to other technologies. On the other hand higher specifications lead to lower DH return temperatures and thus lower distribution heat losses. Different analysis and field experience regarding LTDH are presented in [3-5].

The technology of compact heat exchangers have developed, thus higher demands can be specified. Danfoss has developed the “dimple pattern” heat exchanger technology making new technical performances reachable, [6-7].

The main contribution of this paper is to specify a suggestion of the performance criteria’s for heat exchangers supplied with low DH temperatures corresponding to the needs of the future 4th generation LTDH systems.

STATE OF ART

The relevant temperatures for specifying the performance of a heat exchanger is shown in figure 1.

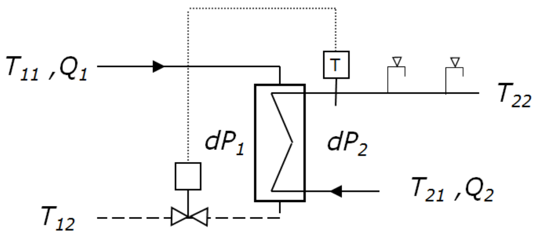

Fig. 1 The characteristic parameters/variables

The heat exchanger can be applied for DHW and HE as well. The variables shown are:

T_{11}: DH inlet temperature
T_{12}: DH return temperature
T_{22}: HE or DHW flow temperature
T_{21}: HE return or cold water temperature
Q_1: DH flow through primary side of heat exch.
Q_2: HE or DHW flow through sec. side if heat exch.
dP_1: Prim. side pressure drop trough heat exch.
dP_2: Sec. side pressure drop trough heat exch.

The main performance indicator selected is the well-known pinch temperature or "grädichkeit", defined by:

$\theta_1=T_{12}-T_{21}$

An expression for the temperature drive:

$\theta_2=T_{11}-T_{22}$

And finally the secondary dT expressed by:

$dT_2=T_{22}-T_{21}$

Based on θ_1, θ_2 and dT2 the performance of the heat exchanger can be defined. Media property changes due to temperatures are neglected.

Typical examples of current performance demands for HE and DHW are shown in figures 2 and 3. Both figures include a base line. This line represents the current performance reference level applied in the analysis.

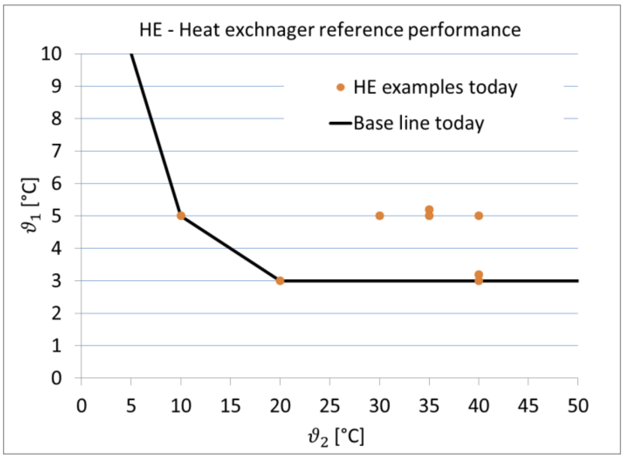

Fig. 2 Reference performance level for HE, including some performance examples applied today

For HE performance specification, a θ_1 value of 3°C is normally specified. In some cases also a θ_1 value of 5°C is seen. The demand of 3°C is reachable with the typical heat exchangers on the market today, and as long as θ_2 is sufficient large there is no problem. In case θ_2 decreases below 15°C challenges regarding needed thermal length of 1 path heat exchangers become visible. For θ_2 values below 10°C the curve is based on extrapolation of the performance at θ_2=10°C, and thus the result is a higher θ_1 value. This area of specification is relevant to focus on for the future LTDH systems.

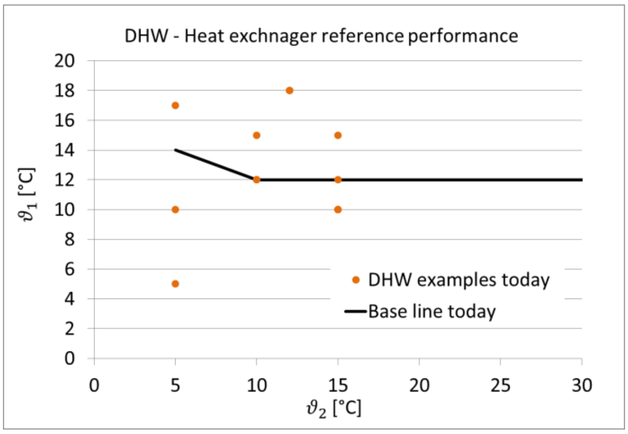

Fig. 3 Reference performance level for DHW including some examples applied today

When looking at fig. 3, it can be seen that the specification examples are a bit more spread. Due to the fact that DHW is specified at low θ_2 values, no performance specification examples are seen at θ_2 values above 15°C. In case of θ_2=5°C, there is one θ_1 example values that is specified quite tough, with a θ_1 value of 5°C. This represents a demand to LTDH systems demonstrated in Denmark.

Parameters of Q_1 and Q_2 are disregarded in this analysis. These relate to the capacity of the heat exchanger, which is indifferent to the specified performance demands. Regarding pressure drop, dP_1 and dP_2, these values are assumed to be maximum 20 kPa for all cases.

METHODOLOGY

Specifying tougher conditions for the heat exchanger implies more heat transfer area and thus higher costs. On the other hand tougher specification also leads to lower return temperatures, lower flow temperatures or a combination hereof. The basic question is therefore how much heat transfer can be added for a certain reduction of DH network design temperatures. This depends on the energy price and the level of DH distribution losses. Typically 1°C reduced DH network temperature for flow or return pipe leads to 1% distribution loss reduction.

Table 1:

DH net loss	Energy costs	Area increase HE pr. °C	Area increase DHW pr. °C
[%]	[EUR/MWh]	[%]	[%]
10	40	17	7
10	**60**	**25**	**10**
20	40	33	13
20	60	50	20

The area increase pr. °C reduced flow or return temperature stated in the table is related to design temperatures.

Due to simplicity, the applied analysis focuses mostly on the situation in table 1 marked in bold.

Assumptions behind the "area increase" values are:

DH network temperatures are based on the HE heat exchanger 7 months/year, while the DH network temperatures are based on DHW heat exchanger 5 months/year. For DHW it is assumed that the heat exchanger is "idling" or running in by-pass mode corresponding to 50% of the energy. Based on this, the area increase pr. °C reduced flow or return network temperature is significant lower for the DHW heat exchanger compared to HE heat exchanger. Further the values are corrected by the effect that at part load the return temperature reduction is reduced compared to the design situation. Therefore, a factor of 0,7 is applied between the design temperature differences and the operational temperature difference regarding the yearly distribution heat loss impact.

RESULTS

Based on well-known principles of calculating heat transfer, pressure drop and needed area, it is possible to calculate the heat exchanger performance. Assuming a certain allowable heat exchanger area increase pr. degree reduced design return temperature, e.g. like stated in table 1, the optimal design temperature can be calculated, where the additional heat exchanger costs is to be balanced by the reduced network return temperature. The reference is the base lines shown in fig. 2 and 3.

Examples of results for the HE heat exchanger are shown in the next two figures.

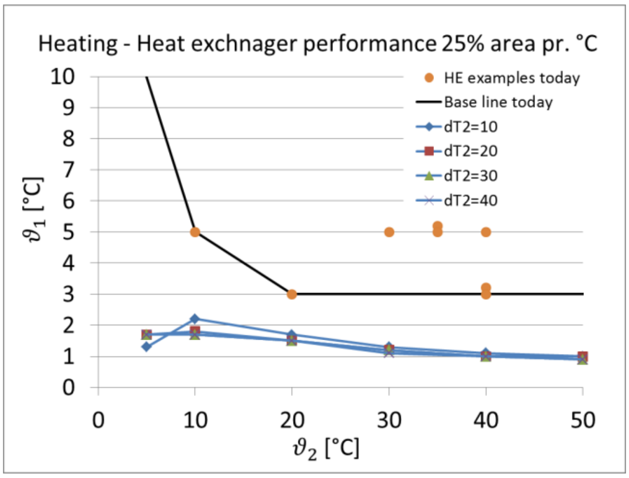

Fig. 4 HE heat exchanger performance based on 25% area increase pr. reduced °C design return temperature

First important result is that lines for different dT_2 values are on the same level. The reason is that the base line and the suggested future lines are both based on the same dT_2 value.

The area increase can indirectly be seen from the figure as well. For each degree temperature difference on the θ_1 axis, 25% area has to be added to the area corresponding to the base line area. E.g. for θ_2=10°C; θ_1 difference is approx. 3°C, this results in a heat exchanger with 75% increased area compared to the needed base line area.

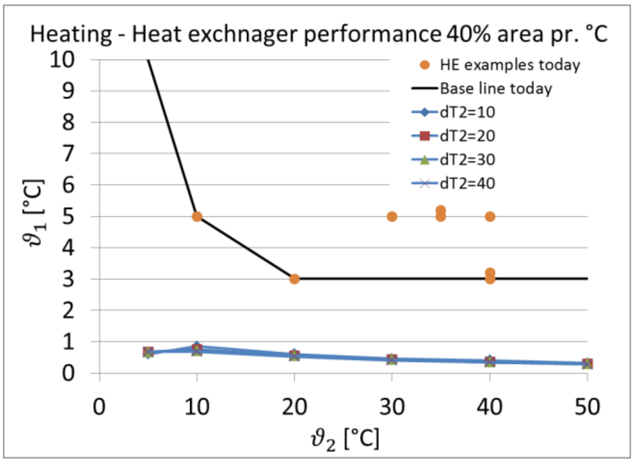

Fig. 5 HE heat exchanger performance based on 40% area increase pr. reduced °C design return temperature

In this case the performance lines end lower compared to the results in fig. 4. This is because the value in terms of added plate area pr. °C reduced return temperature is higher. Also in this case the result is independent on the dT_2 value.

Examples of results for the DHW heat exchanger are shown in the next two figures.

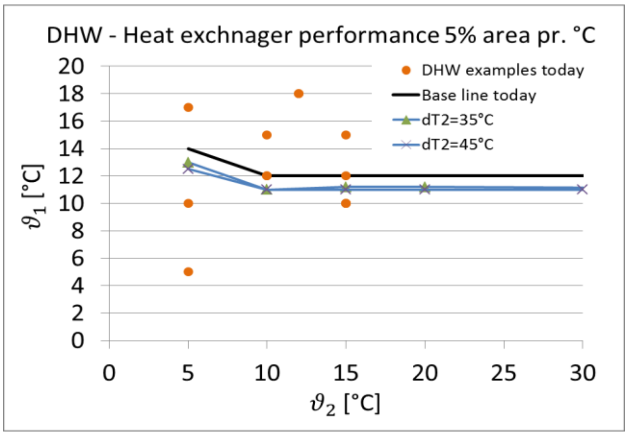

Fig. 6 DHW heat exchanger performance based on 5% area increase pr. reduced °C design return temperature

In case of 5% area increase pr. °C reduced return temperature, the results show that the suggested return temperature should be reduced approx. 1°C corresponding to 5% heat exchanger area increase compared to base line.

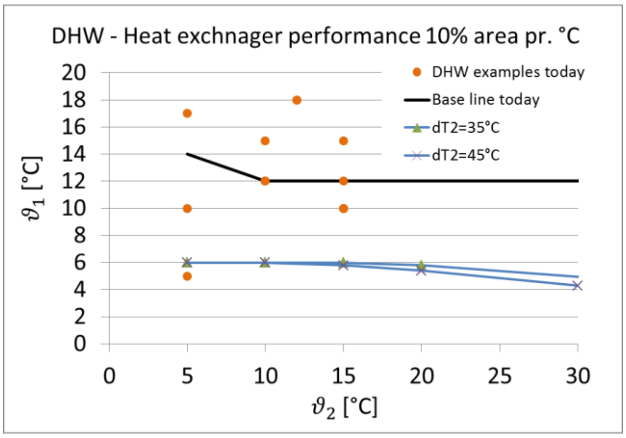

Fig. 7 DHW heat exchanger performance based on 10% area increase pr. reduced °C design return temperature

In case of 10% area increase pr. °C reduced return temperature, the results show that the suggested return temperature should be reduced approx. 6-8°C corresponding to 60-80% heat exchanger area increase compared to base line area.

Reducing the θ_1 value implies a longer thermal length for the heat exchanger. Especially for the low end of θ_2 values this becomes visible.

In this analysis the thermal length is based on a typical H pattern with a reference thermal length of 1. In case the physical length of the plate in doubled, also the thermal length is doubled. For an H plate, the thermal length can be doubled by realizing it as a 2-path heat exchanger. Alternatively the plate length can be doubled or the pattern itself can be changed. Important is to stress that the physical length of the heat exchanger normally is not the same as the thermal length.

In fig. 8 the thermal length is shown as well as the area ratio for HE heat exchangers for the case of 25% area increase pr. °C reduced return temperature.

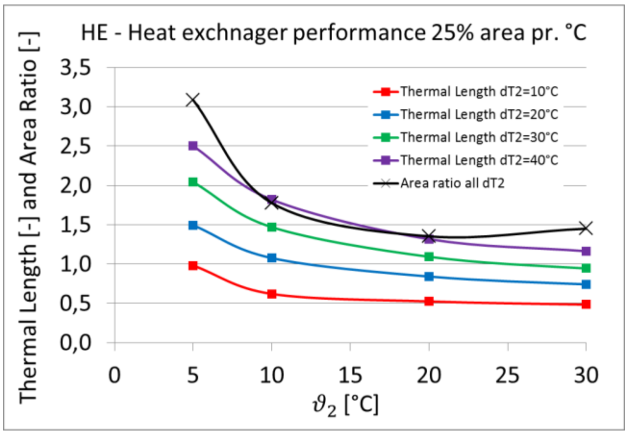

Fig. 8 Thermal length and area ratio for suggested heat exchanger performance (HE)

Baseline thermal length for HE heat exchanger in range of 0,25 to 1,25. This is not shown in fig. 8 due to simplicity reasons. For the suggested heat exchanger performance, a thermal length up to 2,5 will be needed for dT_2=40°C. It can be seen that the thermal length is quite dependent on dT_2. The higher the dT_2 the longer thermal length is required.

Further it can be seen that the area ratio, meaning the relation between suggested performance heat exchanger area and baseline area, varies between approx. 1,5 to 3,0. The highest area ratio for the lowest θ_2 value.

In case asymmetric heat exchangers are applied for HE, the needed heat transfer area can be reduced. The benefit of an asymmetric heat exchanger is that the allowed maximum pressure drop is utilised on the primary side and on the secondary side as well. In case a symmetric heat exchanger is applied for HE, then typically the allowed pressure drop on secondary side is not utilised, due to the lower flow through the secondary side. Pressure drop results in convective heat transfer, and thus the overall heat transfer coefficient is increased, allowing the area to be reduced. In case a symmetric heat exchanger with thermal length of 1 is replaced by an asymmetric heat exchanger, the thermal length on primary side could be 2 and it could be 0,7 on the secondary side. In general area reductions in the range of 20-35% can be expected for typical HE temperature specifications when applying asymmetric heat exchangers instead of symmetric heat exchangers. For DHW asymmetric heat exchangers are not relevant, due to the symmetric performance specification, or basically same flow through primary and secondary side of the heat exchanger.

Fig. 9 shows the thermal length as well as the area ration for DHW heat exchangers in case of 10% area increase pr. °C reduced return temperature.

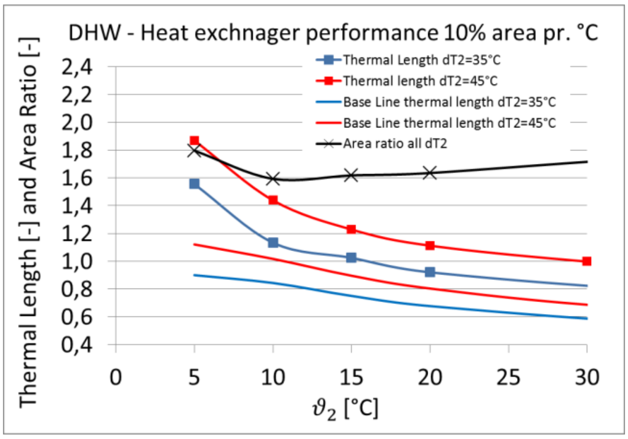

Fig. 9 Thermal length and area ratio for suggested heat exchanger performance (DHW)

In case of DHW, a thermal length of approx. 2 is needed and requiring an area ratio of up to approx. 1,8.

DISCUSSION

This analysis applies one selected set of parameters for DH distribution loss and energy costs. Still the assumptions applied represent a typical DH network situation, and, therefore, the suggested performance levels can be a good starting point. The optimal heat exchanger performance specification is in principle case dependent. This is rarely done, because the cost of additional heat transfer area is rather low. Based on this, the performance of the heat exchanger should not be underspecified.

When looking at fig. 4-7 it is evident that the optimal suggested heat exchanger performance is rather sensitive. Small changes in e.g. area increase pr. °C have considerable impact on the outcome of suggested performance.

The difference between design specification return temperatures and yearly operative return temperatures involves many parameters and assumptions. In this analysis it is simplified by applying a factor 0,7. This factor is based on relevant heat load duration curves for typical Danish conditions.

An example of a substation type for one family housing sold in Sweden is the Danfoss Gemina Termix VVX-ID 22-22. This substation is tested at SP in Borås and the test results are publically available in [8]. For HE the realized performance values are θ_1=0,4°C at θ_2=20°C for 50% and 100% design load. For DHW the values are θ_1=8°C at θ_2=15C for 100% design load. Comparing this realized performance results of year 2012 to the suggested performance in fig. 8 and 7, it can be seen that for HE the suggested performance is already met. For DHW the suggested performance is almost met, only missing 2°C.

OUTLOOK

Today´s suggested heat exchangers are realised as to thermal length. This applies two step heat exchangers. Still this does not apply for one step heat exchangers. Here more R&D work is needed. But there should not be any major obstacle preventing this development. For the smaller capacity range the challenge of longer thermal length is most evident, because the physical length of the heat exchanger is shorter.

When it comes to asymmetric heat exchangers this technology is not yet applied within DH. It is applied in the field of refrigeration and air-conditioning, and could be applied in the DH sector as well. The value of the asymmetric heat exchanger will be eliminated in case the performance specifications go towards symmetric conditions. LTDH is a step in this direction, but will probably not end up in symmetric specifications for the HE part of it.

Next step regarding this analysis would be to make a case specific analysis, based on simulations where the entire system is included from source to distribution, to substation and to the radiators and DHW taps. Also a parameter sensitivity analysis would be relevant. Hereby additional knowledge of the applied factor 0,7 will be obtained.

In any case it is clear that the performance specifications must meet LTDH demands. If not, the concept of LTDH and thus the future of DH is at risk.

CONCLUSION

DH is developing; the sector is approaching the 4th generation of DH technology. This implies technology development. Otherwise it will hardly find its place in the future energy system. One central element of this development is the performance of the heat exchangers. This paper presents some adjusted performance specifications for HE and DHW as well. The specifications address the needs when it comes to future LTDH systems. Based on a cost benefit analysis it is concluded that the area of the heat exchangers and the thermal length should be increased. Today products are available for the mid to high end capacities, whereas for the low end capacities it must be developed in case 1-path heat exchangers are to be applied.

For HE the area should be increased by a factor of approx. 3 and the thermal length should be increased by a factor of approx. 2,5. For DHW the area and thermal length should be increased approx. by a factor of approx. 2, based on the baseline of today.

The suggested area increase factor should be understood as a “maximum” value. This because today´s heat exchangers can be oversized. Hereby the missing area up to the suggested needed is reduced.

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DECENTRALISED HEAT SUPPLY IN DISTRICT HEATING SYSTEMS – IMPLICATIONS OF VARYING DIFFERENTIAL PRESSURE

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ABSTRACT

There is a rising interest for the integration of decentralised heat supply in district heating (DH) systems in the form of so-called prosumers, i.e., customers that both can withdraw and supply heat to the grid. The interest comes from a growing interest in local energy supply among owners of property as well as a growing awareness among DH companies about the need to view their customers more like partners rather than just consumers of heat.

In a previous study, decentralised solar heat plants in Sweden were mapped out and their performance were evaluated. In general, the performance in terms of delivered heat was at least 20% lower than expected. The main reason for this is deficiencies regarding the feed-in of the heat to the grid, caused by an inability of the control system to handle the variation of the differential pressure between the supply and the return pipe in the DH network. These variations, caused mainly by the rapid load fluctuations caused by consumption of domestic hot water, has so far been overlooked when designing the control system. This paper describes and pins down this problem with support from measurements and simulations of differential pressure.

There are different ways to connect decentralised heat supply, where a primary return/supply connection is the most common, implying the heat being added to the DH water before the customer's substation or directly to the DH supply pipe. Although the field study-objects utilise solar energy, it must be emphasised that the results from the project will be of general interest for any type of decentralised heat supply, e.g. surplus heat from local cooling machines or industrial processes. Suggestions for improved control strategies is given in the paper and future work will aim to support them.

Keywords: Prosumers, decentralised heat supply, differential pressure, return/supply connection

INTRODUCTION/PURPOSE

District heating (DH) has traditionally been characterised by a central heat supply and a one-way distribution. Lately, this situation has slowly started to change. In Sweden, a statutory third party access to DH systems has been investigated, suggested and turned down. However, it appears as the awareness and interest for this matter is rising. In Sweden, Fortum has opened up the DH network to anyone who wants to deliver heat [1]. A couple of papers have been published lately dealing with the integration of solar heating into DH – both centrally [2], [3] and locally [4], [5], [6] and [7]. One likely scenario is that the increased focus on distributed power generation and smart grids is about to spill over to the DH industry.

Prosumer is a term originally referring to a "professional consumer", typically focusing on electronic goods, or a very engaged customer. Today, the term is becoming more common as a term used for energy customers who are also selling energy, i.e. as a combination of the words "producer" and "consumer". One can for instance find many hits on "prosumers" and "distributed power generation" in recent scientific publications.

In order to stay competitive, future DH systems likely need to better integrate small sources of heat supply. The progress for grid-connected micro production is much slower in the DH sector than in the power sector, even if things have started to change. There is today, for instance in Sweden and in Germany, some DH prosumers. These mainly includes solar collectors, even if other heat sources such as for instance surplus heat from chillers can be used. Operational data from 22 Swedish solar prosumer installations [8] indicates a need for improved control systems and guidelines regarding the DH connection as well as operation and maintenance. Typical production data was generally lower than expected. It is mainly the nature of the differential pressure in the DH network that cause problem for the feed-in control.

In places were DH was introduced some time ago, it involved substitution of several decentralised boilers which entailed benefits in terms of economy of scale. These benefits does not exist today to the same extent, and the DH sector has gone through a transition towards exploiting economy of synergies instead, such as waste incineration, bio-based combined heat and power and industrial surplus heat. Some areas of further plausible development is an increased customer-orientation with the possibility to offer different sources of heat, and better utilisation of other heat resources within the DH system's area.

If a building sometime has a surplus of heat, the DH system can act as an accumulator and possibly benefit from the heat supply. One important condition is that all heat from the prosumer can be delivered into the DH network and the central heat supply must produce less heat. In small DH systems is it important that it is possible to reduce the central heat supply. In such cases there will be a limit for how large a decentralised heat source may be.

Objective

In this paper, some results from a recent mapping of DH-connected solar heating in Sweden and the initial stage of a new two-year project on decentralised heat sources is reported. The objective with the new project is to compile a technical description of how prosumers can supply heat (solar or other) to a DH system in a way that benefit both prosumer and DH utility. The initial stage, reported here, is to identify the most common existing connection principles employed for prosumers solar installations in Sweden and to describe why they are not working as well as expected.

STATE OF THE ART

The purchase of DH via a substation is well described, not least in technical guidelines. The delivery of heat into a DH network is more complicated and less developed. There are however some basic principles, for instance documented in Swedish technical guidelines [9]. There is no scientific literature, or other literature, that in detail describes the connection of decentralised heat sources.

In order for a decentralised heat source to be integrated with the DH grid to be able to deliver surplus heat, exclusively primary connections are considered in this study.

A further distinction concerns whether the DH water, after being heated, should be fed into the return pipe or into the supply pipe. Both so called R/R connection, meaning that water is taken from the return pipe and fed back into the return pipe after being heated, as well as R/S connection, where water is fed into the supply pipe, exists. The R/R connection can be suitable if the heat source has a temperature that is lower than the temperature of the supply pipe [4]. However, an increased return temperature is often not beneficial for the DH system. Moreover, supply of surplus heat with a lower temperature than the supply temperature does not always has to be a problem, especially if the heat supply is small in relation to the total network load or if it occurs in peripheral or “weak” (i.e. low differential pressure) parts of the network.

One very important difference between R/R and R/S is that R/S can produce its own flow in the DH piping system while R/R cannot. The R/R system is dependent on the flow characteristic where it is located. The implication of this is that the R/R system must be connected to the main DH piping and the heat output cannot be larger than what the actual flow can take care of. Fore solar installations, this can be a problem in situations with a high production.

This project will focus on R/S connection because it has become the most common alternative in Sweden and definitely has the largest potential. More on the overall system perspectives with R/S connected solar prosumers installations can be found in [6].

When solar heating is used, the set point for which temperature that must be achieved in order to allow feed-in has an impact on the solar collectors’ efficiency. The lower the temperature, the higher the obtained heat rate. At the same time, as already mentioned, the temperature cannot be too low in order to meet the requirements from the DH system.

What the recently performed mapping on the performance of R/S-connected solar collectors showed, was that all substations basically have the same deficiency. The control of the feed-in pump, together with one or more valves, is not fully capable to handle the variation in flow resistance in the connection point.

There is to our knowledge no study on the existence of other types of decentralised R/S-connected heat supply. We know of at least one case where there is problem to achieve a well-functioning feed-in control of a small peripheral peak load boiler.

METHODS/METHODOLOGY

The results presented in this paper is based on production data gathered from existing R/S-connected solar plants. The main author of this paper has been involved as a consultant, more or less, in all installations in Sweden.

RESULTS

We here choose to divide the R/S feed-in connection into four categories. In each category, more variants can be found depending on control principles, i.e. how control valves and pumps interact.

1. The most common alternative, shown in Figure 1, is that the feed-in pump works in combination with a two-way valve.
2. Another variant, shown in Figure 2, uses a three-way valve which controls the temperature and a pump which maintains the appropriate flow.
3. The category shown in Figure 3 contains hybrids between category 1 and 2 with 2 two-way valves instead of a three-way valve.
4. In the last category, shown in Figure 4, we can find connections from all previous categories, instead the main difference is that the heat source is connected to the main DH pipes and not to a service pipe.

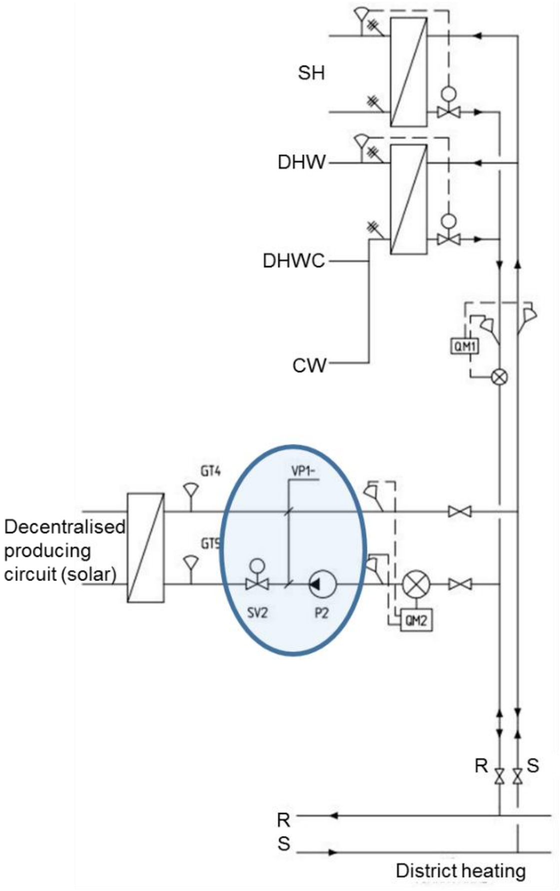

Fig. 1 Category 1 scheme.

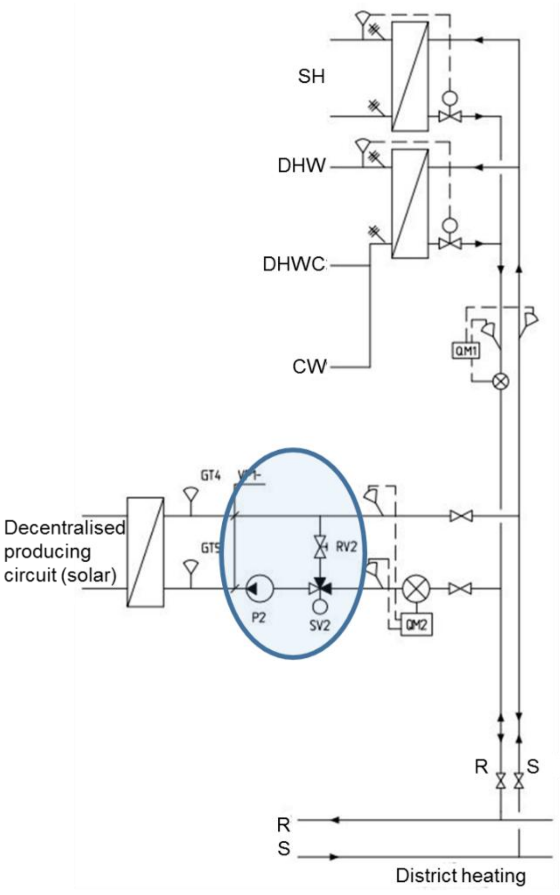

Fig. 2 Category 2 scheme.

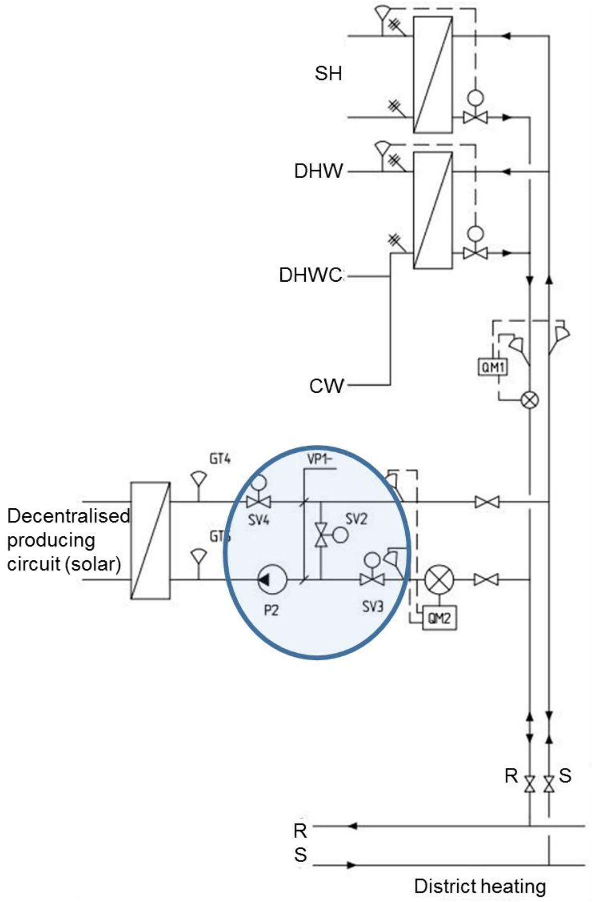

Fig. 3 Category 3 scheme.

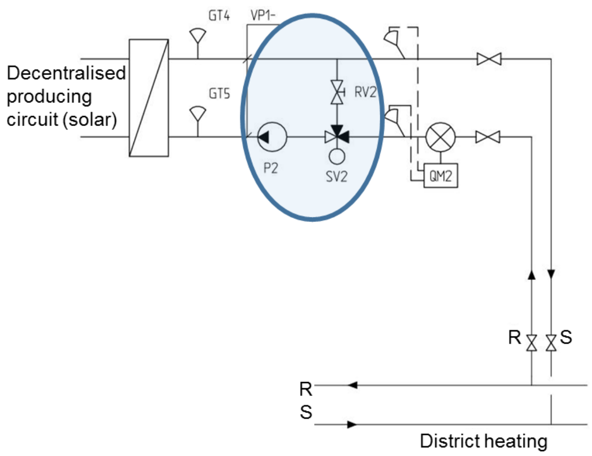

Fig. 4 Category 4 scheme.

The main author of this paper has participated in the planning of installations in all these categories. The control deficiency described in this paper has, however, been found for all categories, even if schemes involving a three-way valve perform better than others. What can be observed is that the rate of feed-in varies in a cyclic manner. This happens because the feed-in pump, denoted P2 in the connection schemes, is not correctly controlled.

The pump P2 must overcome the flow resistance in the feed-in circuit and the differential pressure between the return and supply pipe in the DH network. The pressure loss in the feed-in circuit can be divided into two levels for category 1-3:

- If the flow resulting from consumption of DH is larger than the production of the local heat source.
- If the flow resulting from local heat supply is larger than the consumption of DH.

In the first alternative, the feed-in circuit can be defined as the added part of the system that connects the local producing heat exchanger from the shut-off valves close to the DH service pipe. The minor losses in the feed-in circuit consists mainly of losses in the heat meter, one or two motorised control valves and a non-return valve. The heat exchanger makes up a larger part of the total loss, whereas the pipe friction losses are very small.

In the second alternative, the length of the pipes and number of minor losses is increased because the actual point of feed-in is relocated, from a position by the service pipe to a position by the main pipe. The minor losses might increase slightly, depending on the placement of the heat meter. The pipe friction losses will however increase, although still remain small.

If the local heat supply is larger than the local consumption, the pressure losses should be examined closely in order to establish how these affect the control of P2. The large challenge is to control P2 in order for it to overcome the feed-in circuit pressure losses and the DH differential pressure. The difference between these two is that the DH differential pressure is independent of the feed-in flow, whereas the feed-in losses are not. At low feed-in rates and a relatively large difference between DH return and supply pipes, the feed-in flow can be very small. In such a case, the pump more or less only has to overcome the differential pressure. Once that is achieved, the feed-in flow increases rapidly. Too high a feed-in flow will empty the local production circuit from heat which is automatically brought to a standstill.

For category 1, a high loss can be created by the two-way valve, which thereby creates controllability of the feed-in circuit. The pressure loss in the valve must be dominant over the differential pressure. The problem is however that the pump's electricity consumption will increase.

The idea with schemes according to category 2 is that P2 is to produce a sufficiently high pressure and the three-way valve will then control the feed-in supply temperature by controlling the flow in the inner circuit. This implies that the feed-in flow varies depending on the rate of local heat supply.

The mapping of solar prosumers installations shows that they are not producing as much heat as could be expected. As mentioned before, the specific production rate is dependent on the working temperature of the solar collector. If there are fluctuations in the system, the temperature in the collectors becomes higher and the efficiency is reduced.

Figures 5-7 illustrates the control problem which causes fluctuating feed-in. The figures show production data from a substation fitting into category 2 during a day in mid-July. Figure 5 displays the heat rate fed into the DH network. It should be mentioned that this day was sunny and the average production (of about 50 kW) was high.

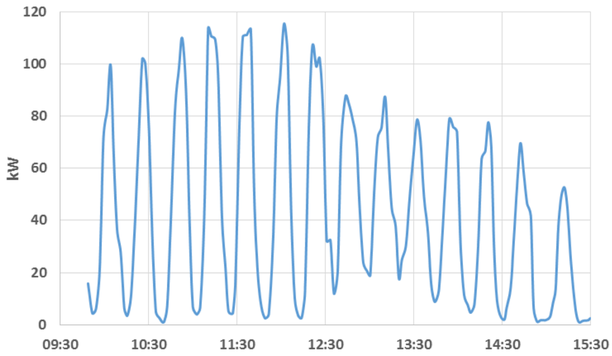

Fig. 5 Rate of heat feed-in from a solar prosumers during a day in mid-July.

As can be seen, the feed-in varies between virtually 0 to 100% in cycles of around 20 minutes. Figure 6 displays the solar collector circuit temperatures – the "warm", entering the heat exchanger, and the "cold" leaving the heat exchanger – and the feed-in circuit temperatures – the "warm", leaving the heat exchanger and going into the DH supply pipe, and the "cold", coming from the DH return pipe and entering the heat exchanger. In dotted lines the temperature difference on each side is displayed, which is inversely proportional to the flow rate.

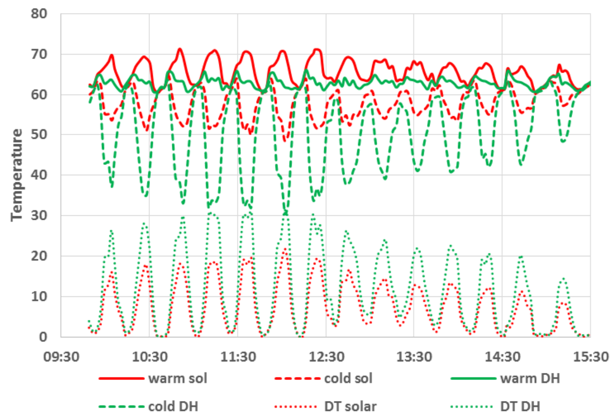

Fig. 6 Solar circuit and feed-in circuit temperatures entering and leaving the heat exchanger.

Figure 7 displays a combination of Figures 5 and 6, but zoomed in to illustrate the course of events during two cycles.

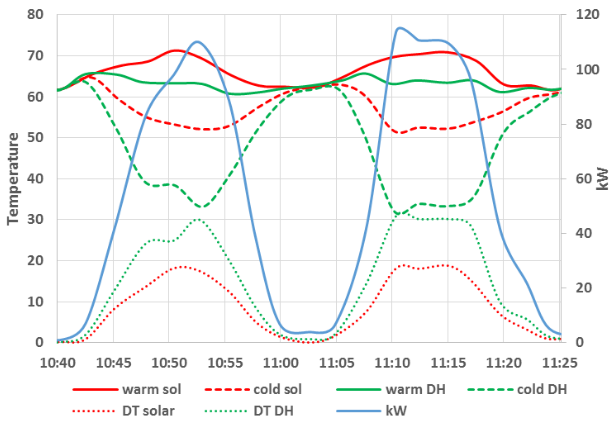

Fig. 7 The data displayed in Figure 5 and 6 zoomed in to show two cycles.

The fluctuations are caused by the control system, regardless of type of system being used. The course of events can be explained as follows:

The sun shines and the pump in the solar circuit starts and transports the heat to the substation. When the temperature on the DH side of the heat exchanger is sufficiently high, the feed-in starts. There is now a certain amount of fluid in the solar circuit containing a certain amount of heat energy. If the control system cannot control the pump and/or control valve properly, the feed-in flow will be too large and rapidly transfer all heat in the solar circuit into the DH network. If the transferred heat rate is larger than what is produced by the solar collectors, the temperature in the solar circuit will decrease, and subsequently the heat output. Then, the temperature will increase again and the circle is closed.

There is a connection between the duration of the sequence just described and the transport time for a unit of flow to travel one lap in the circuit. The latter can be described as:

“Lap time” [minutes] = “The circuit volume” [Litre] / “Solar circuit flow” [Litre/minute]. Typical for a solar installation with a primary DH-connection is around 10 minutes. The duration of the sequence is often 1.5 to 2 times the circuit lap time. In category 2 schemes, where heat is more easily transported to the DH side, the sequence time is shorter. In category 1 schemes, where feed-in of too cold water into the DH network must be avoided, it is harder to transfer the temperature from the solar circuit to the DH side, resulting in longer sequences.

Figure 8 illustrates further the varying characteristic of the DH network differential pressure. It was measured at another substation which fits into category 4, i.e. connected directly to the main DH pipes.

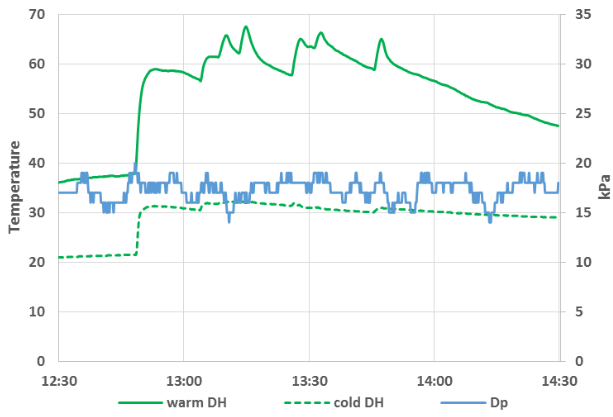

Fig. 8 DH temperatures and differential pressure in a prosumer substation.

At the time, there was no production of solar heat. The increase in DH temperatures was the result of an experiment aiming to test the controllability of the feed-in pump. The pump speed was manually altered in steps of 5%. The feed-in went from 0 to 100% during one such 5%-step. It is worth noting that the differential pressure varies rapidly with an amplitude of 16-19%. In just a few minutes, the variation can be substantially larger than what the pump speed control id designed for.

The result of the initial mapping of decentralised R/S-connected systems is that it is of large importance to achieve a well-adjusted feed-in flow. The feed-in heat rate must match the heat rate produced by the solar (or other) circuit. One of the conditions for this is that the decentralised heat supply always is prioritised and that the heat supply balance is maintained by the DH utility. Network calculations concerning the impact of prosumers have been performed in [5] and [10]. This is the same principle applied for e.g. solar photovoltaic; all power is guaranteed access to the grid and the frequency is maintained by another part.

DISCUSSION

At this stage of the project, it is hard to say exactly what needs to be done in order to improve the controllability and function of these prosumer installations. There is no literature or previous work dealing with this, which perhaps is understandable considering that distributed generation is far less common in DH systems than in the power system. In order for this development to continue and gain a wider interest, it is of uttermost importance to get the feed-in connections to work properly. Hopefully, the continued work, of ours and others, will reach that goal.

OUTLOOK

Considering the large interest for distributed power generation in many countries, a similar development within the DH sector, in countries where this sector is fairly large, is likely to follow. As for power, solar energy will probably, at least initially, be the most common source of decentralised heat supply. However, since the DH sector has a long tradition of utilising industrial surplus heat, we might see a quite large diversity of types of decentralised heat supply in the future. At least two trends speak in favour for this: with lower network temperatures, it will be easier to utilise surplus heat of low temperature, and with more liberalised heat markets, more DH customers and owners of property might want to make use of surplus heat. Such surplus heat might comprise for instance rejected heat from cooling machines.

CONCLUSIONS

The connection scheme involving a three-way valve appears to be a more suitable solution in order to achieve a proper flow and pressure than schemes using a two-way valve. In order to fully control the feed-in flow, it is important to know the differential pressure in the connection point and to take it under consideration. The control system must be able to follow and adapt to any changes. Existing control methods are generally not capable of handling such changes.

ACKNOWLEDGEMENT

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STUDY OF A DISTRICT HEATING SUBSTATION USING THE RETURN WATER OF THE MAIN SYSTEM TO SERVICE A LOW-TEMPERATURE SECONDARY NETWORK

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ABSTRACT

The development of district heating (DH) systems is facing the challenge of servicing areas with lower energy demands whose connection might not be either effective or profitable if the conventional DH technology is used. The purpose of this paper is to propose a complementary approach on how to effectively service low-energy building (LEB) areas using the existing DH networks. The proposed solution consists in supplying a secondary low-temperature (LT) network by means of a 'low temperature' substation that uses the return water from the main DH network as a substitute for the primary energy source, together with a minor portion of the main DH supply. Two types of LT substations are proposed and compared to a reference substation: First, a one-stage heat exchanger that uses a mixture of the main DH network return and supply flows as thermal energy source. Second, a two-stage heat exchanger that is fed by both the main DH return and supply flows. The system subject to this study consists on the LT substation with supply/return temperatures at 55/25 °C average. The system energetic performance is analysed though thermodynamic simulation. Outdoor ambient temperatures variations throughout the year are considered for two specific locations, assuming full and partial load operation. The results show that it is possible to supply 20-50% of the total annual heat demand of a LTDH network using the return flow from the main DH network. The solution presented in this paper is seen as being of potential interest to deliver thermal energy services to LEB areas.

INTRODUCTION

The current European climate goals on greenhouse gas (GHG) emissions reduction, increased share of renewable energy sources, and improved energy efficiency have had a marked impact on recent policies for the development of the built environment. New directives on the construction and refurbishment of buildings define the expected pathways. These directives encourage the use and development of preferred primary energy sources and technologies for servicing the building stock. They also define how building structures are to be built or renovated in order to achieve high energy efficiency.

The expansion of District Heating (DH) systems is considered as an opportunity to reduce GHG emissions, increase the security of supply, and improve the overall energy system efficiency while providing the required heating services to the building stock [1]. The existing DH production and distribution networks have been appropriately designed for the current level of heat demands. Nevertheless, to incorporate a wider variety of thermal energy sources and to match lower heating demands, the standard DH technology is not suitable technically and economically.

As a consequence, the development of DH systems is facing the challenge of servicing low-energy building (LEB) areas [2]. Moreover, with the desired increase in the share of renewable energy sources operating at lower temperatures than the conventional DH system, the system requires an enhancement to effectively accommodate these developments and maximize their benefits [3].

Supplying thermal energy services to LEB areas by the conventional DH technology implies a mismatch between the quality and quantity of the heat supply and the demand. As customers, LEB areas are highly energy efficient; they have low annual thermal energy demands for space heating (SH); and therefore, lower line heat densities than the existing building stock [2]. As a consequence, from the supply and distribution perspectives, relative heat losses are higher; investment costs increase relative to total heat consumption or sales; and thus, the DH technology loses competitiveness becoming uneconomical. The distribution losses in areas with low heat densities can account up to 40%. Especially during summertime when low heat demands reduce the network flow rates to a minimum, losses due to flow stagnation may exceed the actual heat consumption [4].

At present, the development of the 4th generation DH systems operating at lower temperatures is considered as a sufficiently flexible solution able to provide the link among the building stock with low energy demands, suppliers of heat with primary energy content at lower temperature levels, and the DH distribution network in an efficient and environmental friendly way [5].

It is expected that the DH sector will experience a transition period during which both the already existing networks and the 'new' low-temperature (LT) networks will be operating simultaneously, competing and complementing each other to satisfy the urban thermal energy demand. This situation will become increasingly prevalent over the next 20 years. In the longer term, as the share of existing buildings being refurbished to become energy efficient increases, they will be supplied at the lower operating temperatures, and then a total penetration of the 4th generation DH technology will be achieved [1]. In the short term, for the development of the LT networks near the existing DH infrastructure, LT networks can be, at first, connected to the return pipes of the existing networks. This concept of network cascading offers the possibility to expand the distribution network by efficiently connecting new LEB developments without mayor modifications to the existing network and with low initial investments [6]. It represents an advantage for DH companies, because the DH network coverage can be expanded, servicing more customers with lower operation costs.

Traditionally, the DH networks guidelines account for design margins to connect future additional consumers. These recommendations usually result in over-dimensioned systems mostly operating at partial loads even during peak periods [7]. Therefore, it could be possible to connect a LEB area without the need to increase the capacity of the existing DH system and without causing major disturbances.

LTDH systems can be established in new and existing DH areas by sectioning/dividing the network into subnets. Subnets operating at lower temperatures and using as primary energy supply the energy from the conventional DH return pipes have been designed and successfully tested in Denmark [8],[9]. There, LTDH networks distribute heat to LEB areas, both to new and refurbished networks. In these particular experiences, the coupling of the LTDH network to the existing distribution network has been made via a direct connection. Nevertheless, depending on local conditions and design requirements, a heat exchanger can also be installed.

The aim of this paper is to propose a complementary approach on how to effectively service low-energy building (LEB) areas using the existing DH networks. This solution consists of a ‘low temperature’ DH substation supplying a secondary low-temperature (LT) network suitable for LEB. This LT substation uses the return water from the main DH network as the main substitute for the primary energy source, together with a minor portion of the main DH supply only to be used when the return water temperature is not sufficiently high, or to boost the temperature at the LTDH supply, for instance, during peak load periods. This can be achieved without additional thermal energy sources.

This proposed solution has the potential to increase the overall system efficiency by allowing a more efficient extraction of a larger portion of the thermal energy already carried by the main DH system.

STATE OF THE ART

Low-Temperature District Heating (LTDH)

The low-temperature district heating concept is a promising solution for supplying thermal energy services to LEB areas. LTDH systems are a strategic technology for reaching the energy and climate targets and have the potential to be widely implemented due to their cost effectiveness, environmentally friendliness and reliability. Low-energy or low-temperature DH is part of 4th Generation DH technologies characterized by lower and more flexible temperatures in the distribution networks. By complying with two main requirements for future energy use: high energy efficiency and high share of renewable energy, LTDH becomes highly attractive for the energy commodities sector [2].

On the matter of energy efficiency, LTDH can help reduce network distribution losses by lowering the network operating temperatures and making the connection of low heat density areas economically feasible. Also, lower temperatures induce less pipeline thermal stresses. Therefore, the risk of pipe leakage due to thermal stress and related maintenance costs are reduced. Furthermore, this reduction also extends the lifetime of the distribution network components [8].

Concerning a higher share of renewables of low grade and intermittent nature, these sources can be used directly in LTDH due to a better match of the operating temperatures, besides, when combined with thermal energy storages (TES) a more stable supply can be obtained. The same applies for surplus heat from industry or urban processes usually rejected to the atmosphere due to its lower temperature. Another advantage of lower return temperatures is that they allow the extraction of a larger portion of thermal energy via condensation heat recovery at the heat production unit. For instance, in the case of biomass boilers it can be beneficial due to the high water content of the fuel. In this aspect, the overall advantage of LTDH lies on the possibility to efficiently exploit the locally available low-temperature or low-grade thermal energy resources [3].

Previous studies on LTDH have shown the importance of the effects of lowering the operating temperatures. One study [4] confirmed that lower heat losses lead to lower temperature drops along the network, and accordingly a lower flow rate at a specific heating power, thus a lower demand for pumping energy. This study also established that ‘*the effect of the temperature on the heat loss is more significant than the effect of the media pipe diameter*.’ Finally, this study concludes that even though the energy used for pumping purposes may increase about 3 times, its share in primary energy demand only reaches about 2% of the total.

The key limitation on the efficiency of a DH system is linked to the minimum possible supply temperature, usually driven by the minimum desired DHW temperature rather than the space heating (SH) requirements. Nevertheless, the LTDH supply temperature can be further lowered by separating SH from DHW preparation and adding a temperature booster system in order to heat up DHW to the desired temperature level while also avoiding bacterial growth issues [5].

It is possible that with the existing DH substation technology by lowering the operating temperatures the investments costs of the end-users side can increase. The lower operating temperature makes the current heat exchangers less efficient [1]. Nevertheless, by using new customer substation designs and with the development of highly efficient heat exchangers, the costs for the customer can be reduced. On the distribution network side, this can be easily avoided by keeping a similar temperature difference between the design supply and return temperatures. Additionally, financial benefits/savings can be achieved on the DH production unit by reducing supply temperatures, which lead to lower production costs and a larger share of low-cost thermal energy sources.

Full Scale Applications of LTDH

In the Danish governmentally founded project "*EUDP 2010-II: Full-Scale Demonstration of Low-Temperature District Heating in Existing Buildings*" the low temperature DH concept has been investigated, designed and tested. The latest deliverable consisted of a set of guidelines for Low-Temperature District Heating in [8] that includes recommendations, lessons learned and expertise obtained from the ongoing experiences.

The set of demonstration projects in Denmark have showed the way for LTDH technology application in the case of renovated buildings and network refurbishment. Detailed discussions about technical and practical aspects are given regarding: *a)* pipe dimensions, insulation thickness, and maximum pressure levels, that lead to reduced capital costs; *b)* adequate customer units/substations for domestic hot water preparation and space heating; *c)* effects on electric consumption for pumping and pressure losses; and *d)* the thermostatic bypass, required to ensure a sufficient temperature level, but that increases the return temperature during summertime.

These projects also showed that human behaviour is a crucial factor for the pattern of overall consumption in LEB areas and should be included in every analysis. There are a few LTDH systems already in operation and have moved beyond the demonstration phase, three of them are briefly described in **Table 1**.

Table 1. Examples of successful low-temperature district heating systems already in operation

Location [Reference]	*Lystrup, Denmark [5]*	*Kırşehir, Turkey [10]*	*Okotoks, Canada [11]*
Operating Year	2011	1994	2007
Supply/Return Temperatures (Average)	55/30 °C	57/48 to 54/42 °C	55/32 °C
Heat Sources	Mix from main DH return and supply flow	Geo-thermal heat	Solar thermal
Dwellings	40 low-energy houses	1800 existing buildings	52 energy efficient houses
Heat Demand Covered	SH and DHW (150 kW)	SH and DHW (5,6 MW)	90% of SH (since 2012)
Additional Characteristics	Direct connection to existing DH system using a mixing shunt	Auxiliary peak boiler	Separate solar DHW systems, Short-term and seasonal storage

These previous studies and demonstration project have proved the feasibility of the concept. They have confirmed that the LTDH networks have the expected low heat losses. They have also shown that, even though more pumping power is required, it is less than expected, and it only accounts for a minimal share in the total primary energy demand. Besides, its magnitude is comparable to the well-established conventional DH systems.

Network Cascading and Subnets for LTDH

The concept of network cascading consists in creating subnets operating at lower temperatures connected to the return line of an existing network and further decreasing the return temperature [6]. In this way, the quality of the thermal energy demanded by low-energy customers is appropriately matched leading to an increase in energy use efficiency. The coupling of LTDH network to a larger DH network can be done by means of a direct connection or an indirect connection (substation).

In case of the direct connection of a LTDH subnet, two arrangements have already been tested successfully in Denmark as shown in [8]: 1) *mixing shunt*, and 2) *3-pipe connection shunt*. However, only a limited analysis on the performance of these arrangements has been conducted. On the other hand, the use of an indirect connection (a heat exchanger substation) has neither been analysed nor tested. The indirect connection could better match the low energy customers' demands, giving the benefits of flexibility and control over those of a direct connection.

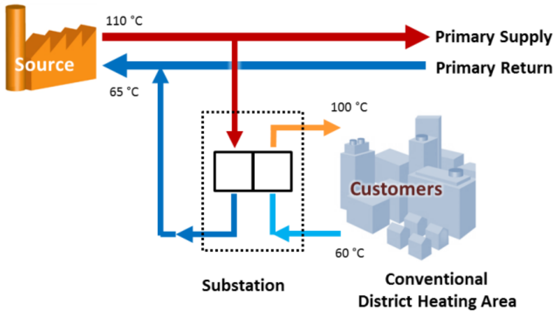

Figure 1a. Conventional DH substation

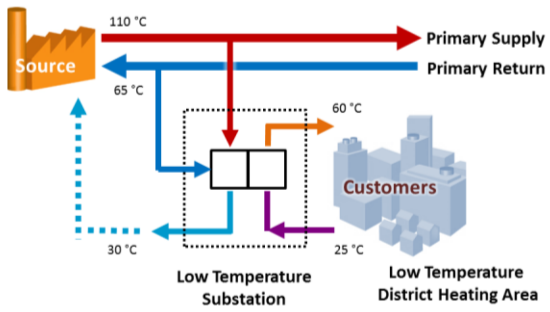

Figure 1b. Proposed LTDH substation

The 3-pipe connection shunt arrangement has been successfully operating since 2012 [8],[9]. It comprises 75 existing single-family houses in *Høje Taastrup* near Copenhagen, DK. The existing DH system was renovated; including new piping, and new customer substations, but the existing floor heating system in the houses was still used. The maximum (instantaneous) heat load is about 500 kW during winter and 90-200 kW during the summer period. Average supply/return temperatures for the network are 55/40 °C, the return temperature being higher than the design due to faulty settings or defective components at the customers. The distribution network heat loss has been reduced to 13-14% of the total heat supply from an original 41%.

Design Challenges in LTDH

LTDH is considered as one of the most promising concepts to tackle the issue of supplying thermal energy services to LEB areas in the most efficient way. In order to stimulate a fast expansion, this technology must be: a) *cost-effective*, by reducing distribution losses and total costs; b) *competitive* with the existing heat pump solutions (either centralized or decentralized); c) *replicable*, showing modularity and standardization; and d) *flexible*, being able to manage variations in the network's operation to properly match the demand, and to integrate alternative sources that optimize the energy use.

METHODOLOGY

'Low Temperature' Substation Concept

The concept of a 'low temperature' DH substation supplying a secondary low-temperature (LT) network is proposed as a complementary approach on how to effectively service low-energy building (LEB) areas using the existing DH networks. A high-level schematic of the concept is depicted in **Fig. 1b.** The LT substation takes the return water from the main DH network as the main substitute for the primary energy source, together with a minor portion of the main DH supply only to be used when the return water temperature is not sufficiently high so to boost the temperature at the LTDH supply, for instance during peak load periods.

A DH substation supplying a LT network by using the return temperature from the conventional DH network allows a better match of the quality and quantity energy supplied and the requirements of a LEB area. This substation acts as an interface that allows the separation of the network's operation parameters, giving the benefits of flexibility and control over those of a direct connection. With the substation, the LTDH network becomes an extension of the existing DH network, with a single connection point where a cluster of customers with low energy demands are serviced.

The water coming from the 'low temperature' substation return at the primary side outlet is cooled at a lower temperature than the main DH return. This flow could be used for other purposes such as condensation heat recovery, or the extraction of energy from cheaper low temperature thermal energy sources. This would improve the performance and efficiency of heat extraction of the DH network, leading to cost reductions and savings for both the supplier and end customer.

Scope of the Analysis

An energy performance analysis of the 'low temperature' substation proposed is presented in this paper. The objective is to investigate the total share of the energy demand that can be covered by the main DH return pipe flow during a typical year for two specific locations. Therefore, the simulations are performed for the usual operating range of outdoor ambient temperature in steady state conditions for full load and partial load operation. The systems boundaries of this study are limited to the substation itself, with incoming and outgoing flows, thus the issue of thermal losses in the LTDH network is not addressed. The same applies for consumer demand dynamics. The thermal energy demand is then assumed to be a linear relation for space heating (SH) as a function of outdoor ambient temperature, plus a constant demand for domestic hot water (DHW) preparation. Hence, the effects of consumer behaviour on variations in the return temperature are not considered at this point. In the following paragraphs a more detailed description of the assumptions, input parameters, data sources and the reasons for the choices used in this study are further explained.

DH Network Operational Strategy

The conventional operation of the forward/supply water temperature usually follows an ambient temperature compensation strategy. This strategy is widely used because of its benefits: by reducing the water temperature when the heating demand decreases, lower return temperatures are also obtained, and consequently energy losses in the distribution network are reduced. The lower operating temperatures also reduce the effects of pressure fluctuations, and thus the life of the hardware can increase considerably [14]. These benefits clearly apply to LTDH as well.

For this analysis, it is assumed that the DH supply follows the aforementioned operational strategy as shown in **Fig. 2a.** In addition, an average return temperature curve is used for simplicity, since the overall fluctuations in this parameter are a combination of the behaviour of all consumers, the outdoor ambient temperature, and the actual condition of all substations, and the network itself [12]. Only the ideal return temperature is used for the design (sizing) of the substation heat exchangers and as a for a conservative simulation approach to be compared in the analysis. Nominal load (100%) occurs at -20°C of outdoor ambient temperature when the forward temperature is supplied at the maximum of 110°C and it decreases linearly to a minimum of 65°C [13], when the outdoor ambient temperature is +5°C (break point).

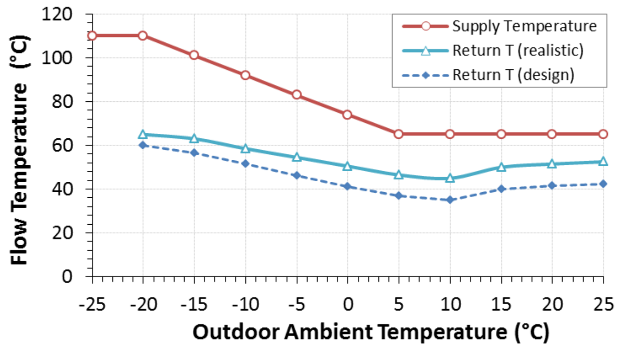

Figure 2a. Traditional DH network control operation based on outdoor temperature compensation

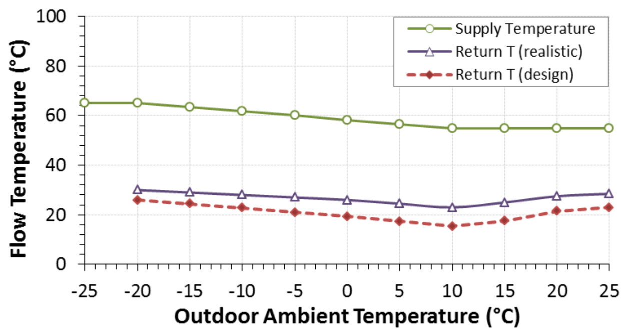

Figure 2b. Network control operation strategy for the low temperature substation

The low temperature substation operational strategy is defined following the same principles. In the case of the forward flow, a similar average return temperature 'hypothetical' curve is used, as shown in **Fig. 2b**. The minimum supply temperature of 55°C is defined as the lowest forward temperature to supply the required 50-45°C DHW at the tapping points of the end users, plus 10°C to compensate for losses. It is expected that the substation will be able to boost the temperature levels up if required, for instance during extremely low ambient temperatures or peak load periods.

Thus, a maximum supply temperature of 65°C is fed when the outdoor ambient temperature is -20°C (100% of design load), although higher temperature levels could be occasionally reached.

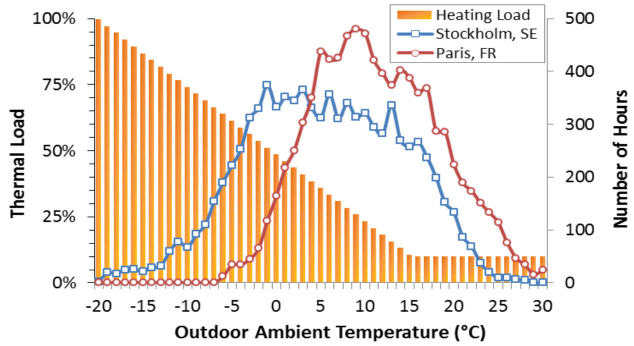

Figure 3. Heat load and annual temperature distribution at outdoor ambient temperature

Heat Demand Profile

The load at the substation coming from the secondary LT network is assumed as inversely proportional to the outdoor ambient temperature. As can be seen in **Fig. 3** an average linear heating load is chosen for the simplicity of the analysis at this stage [12]. This figure also shows the corresponding duration hours for two selected locations. It is assumed that for temperatures from 16°C and above, the heat demand is only due to DHW preparation that is about 10% of the maximum load. Space heating is required anytime the temperature is below 15°C, and the full load (100%) occurs at -20°C.

The selected locations correspond to two European cities with different heating demands. The temperature distribution data are obtained from a uniform meteorological data basis, *Meteonorm* [15], which exemplifies a hypothetical year that statistically represents a typical year at each location.

System Modelling

With the purpose of analysing the energy performance of the substation, two possible configurations of the substation are modelled chosen with the aim to compare their performance; plus a third configuration that solely uses the DH supply is defined as baseline. The system description and the configuration of each substation type are the following:

Substation Type A – **Figure 4a** depicts the first configuration analysed. It shows how first the flows from the DH supply and return pipes are mixed in a 3-pipe shunt arrangement, where a 3-way valve is used to regulate the ratio between these two flows to obtain the required temperature. Next, the mixed stream passes through a heat exchanger, properly designed for lower operating temperatures, whose energy is then transferred to the return flow in the secondary network rising the temperature to the desired level. The mixed stream from the primary side finally exits the substation at a temperature close to the secondary LT return temperature level.

Substation Type B – In this configuration, as shown in **Fig. 4b**, the substation consists of two heat exchangers: a booster and a preheater. A small portion of flow from the DH supply firstly goes through the booster where it rejects part of its thermal energy content to the preheated return flow from the secondary network to reach the desired supply temperature. Then the flow from the outlet of the booster in the primary side is mixed with the flow form the main DH return via a 3-way valve that regulates the ratio between these two flows. Next the mixed stream passes through the preheater where its energy is transferred to the return flow from the secondary network, and heating it to an intermediate temperature. Similarly to the previous substation type, the mixed stream from the primary side finally exits the substation at a temperature close to the secondary LT return temperature level.

Baseline Substation – In this configuration, the flow only from the DH supply goes through a heat exchanger to transfer the heat to the secondary network as in a typical substation. It is assumed a larger than usual temperature difference between the supply and the return from this substation since the flow exits the substation at a temperature close to temperature level of the secondary LT return. In this way the flow is kept relatively small. The diagram for the baseline configuration is not detailed but a similar high-level depiction was shown in **Figure 1a**.

The sizing of the substations is done at the nominal load operating point at -20°C of outdoor ambient temperature. The input parameters are taken from the operational strategies shown in **Figs. 2a** and **2b**, and the lower (ideal) return temperature set is used.

Table 2. Parameters for substation design (nominal load)

Nominal Load	100% (at -20°C)	1 MW
Primary Side	DH Supply (t_s)	110°C
	DH Return (t_r)	60°C
Secondary Side	LT supply (t_s^{LT})	65°C
	LT return (t_r^{LT})	25°C
Maximum ΔT	$\Delta T = t_r' - t_r^{LT}$	3°C

Table 2 shows the sizing parameters at nominal load. The system sizing and thermodynamic models are done using *Thermoptim* [16] software. Operating pressures are assumed 16 bar for the main DH network and 6 bar for the secondary LT network [13]. For the simulation, any operating temperature that is not at the design condition is a partial load operating point.

Simulation

Once the heat exchangers are sized at the design condition, the UA values, NTU and effectiveness are fixed. The simulations at different outdoor ambient temperatures and partial load conditions are then performed. For each outdoor ambient temperature, the inputs are the corresponding load and temperatures from the curves in Figs. 2a, 2b and 3. The outputs are the flow rate at the LT substation, the steady state flow rates required from the main DH supply and return, and the substation primary outlet return temperature. With the flow rates and temperatures (enthalpies) it is then possible to calculate the energy coming from each the DH supply and DH return flows as a function of outdoor ambient temperature.

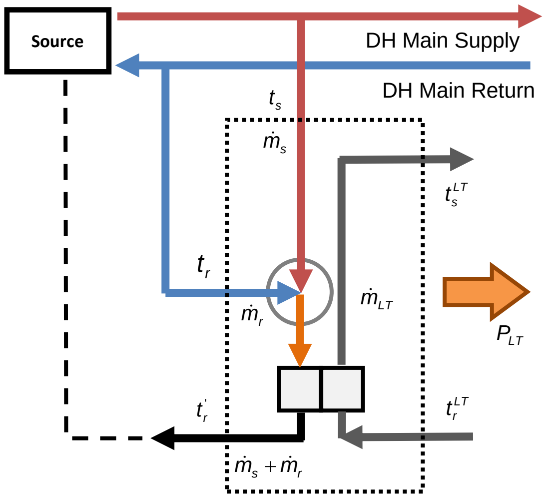

Figure 4a. Substation Type A schematic

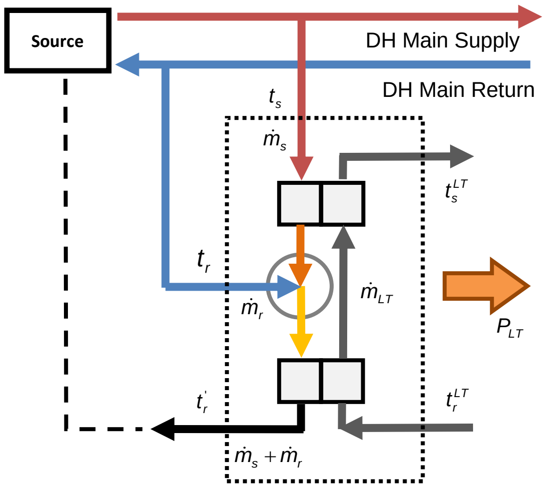

Figure 4b. Substation Type B schematic

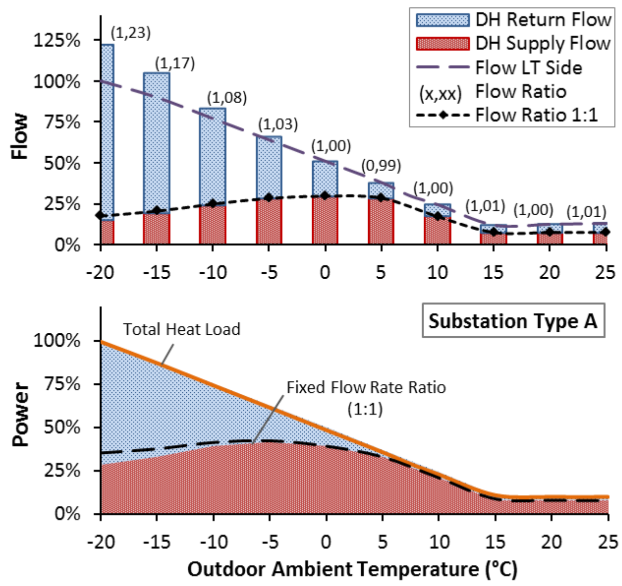

Figure 5a. Flow rates and power supplied for substation Type A

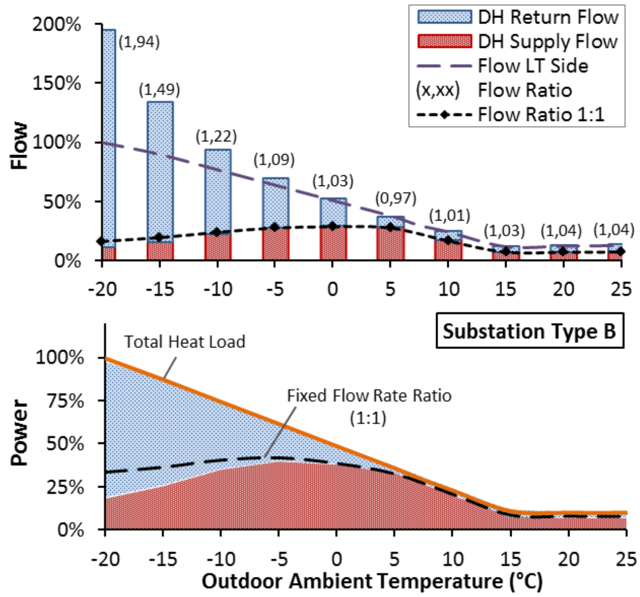

Figure 5b. Flow rates and power supplied for substation Type B

Two operating modes of the substation are simulated with respect to the flow rates in the primary side. The first one uses an equal flow rate ratio from the primary and secondary sides of the substation. In this case, the objective is to find the ratio of main DH supply and return flows that, when added, the total flow rate is equal in magnitude to the secondary side flow rate, while the desired forward temperature at the LT network is reached, ($\dot{m}_s + \dot{m}_r = \dot{m}_{LT}$). In the second mode, there is no restriction in the flow rate ratio but instead, the objective is to use the minimum amount of flow from the DH supply at each outdoor temperature to obtain the desired supply temperature in the LT network, $min(\dot{m}_s)$.

Finally, the annual energy performance is evaluated depending on the selected locations. The inputs used are the annual temperature distributions, and the load as a function of outdoor ambient temperature (**Fig. 3**). The cumulative load curves are plotted for each location, and using the resulting curves from the thermodynamic simulation (Figs. 5 a and 5b) the load duration curves are calculated in terms of main supply and return flows, which conclude this analysis.

RESULTS

This section presents a summary of the outcomes from the thermodynamic simulation. In the first part, the described results are the proportion of power and flows from the DH supply/return as a function of the outdoor ambient temperature for both substation types, and the two operating modes: fixed flow rate ratio, and variable flow rate ratio. The next part presents the results regarding return temperatures for the two substation types and operating modes as a function of outdoor ambient temperature as well. In the last part of this section, the performance of the two types of substation is tested by using two selected locations with different yearly outdoor ambient temperature distributions and different heat demands.

Figures 5a and **5b** show the two first parameters of interest: power and flow rates from DH supply/return required to meet the load as well as the target supply temperature in the LT side as a function of the outdoor ambient temperature. The figures show the curves for each substation type A and B correspondingly, for the case of variable flow operating mode. An additional curve is also shown in to these plots to compare with the performance using a fixed flow rate ratio operation mode.

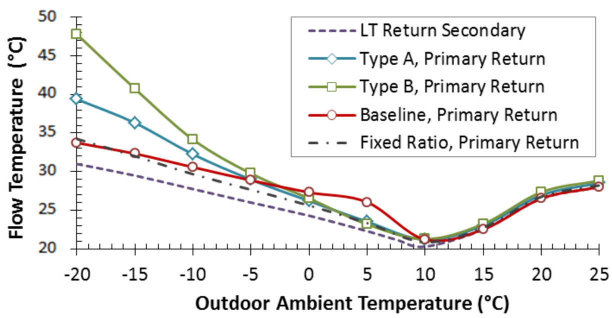

Figure 6. Comparison of return temperatures depending on outdoor temperatures

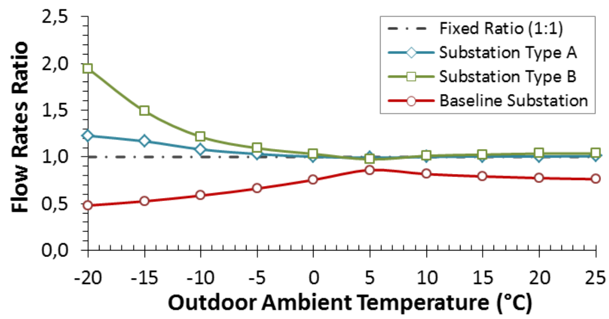

Figure 7. Minimum flow rate ratios required as a function of outdoor temperatures

A key parameter to study is the outlet temperature (t_r') at the primary side of the substation. This flow could be potentially used for heat recovery in low temperature sources applications, and having lower return temperatures increase the efficiency of heat production units. **Figure 6** shows the variations of the return temperature as a function of outdoor ambient temperature are shown in. In this figure, the assumed return temperature from the secondary network is plotted to serve as a reference. Then, the resulting return temperatures using a fixed flow rate ratio, and using a variable flow rate for each substation are compared. **Figure 7**, shows the flow rate ratios $(\dot{m}_s + \dot{m}_r)/\dot{m}_{LT}$, that minimise the use of the DH supply and that lead to the outlet temperature curves shown in the previous figure.

As seen from **Figs. 6** and **7**, for outdoor ambient temperatures above 10°C, the outlet temperature at the primary side is very close to the return temperature of the secondary network. This is explained by all the cases having a flow rate ratio close to 1. At lower temperatures, the tendency is to an increase of the return temperature, and the effect of higher flow rate ratios is evident in the higher outlet temperatures in the primary side of the substation.

Annual Energy Figures

The total annual energy delivered to the two selected locations was calculated assuming that 100% load equals 1MW$_{th}$, which could be, for instance, the case for a set of low-energy multi-dwelling buildings. Using the hourly temperature distributions and the heat load function from **Fig. 3**, the estimated annual heat supply for each location are: for a substation supplying a load in Stockholm: 3,20 GWh (11,5 TJ); and for one in Paris: 2,08 GWh (7,5 TJ).

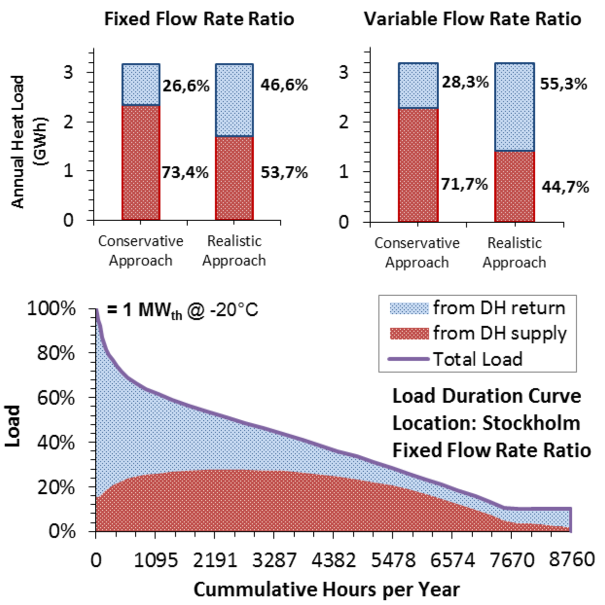

Figure 8a. Annual energy totals and load duration curve for substation type B in location 1

Table 3a. Annual energy totals for location 1

Location		Substation Type			
Stockholm (Capacity factor 0.36)		**Design A**		**Design B**	
Return Temperatures	**Flow Ratio**	DH return	(DH supply)	DH return	(DH supply)
Realistic (High)	*Fixed (1:1)*	**45,3%**	(54,7%)	**46,3%**	(53,7%)
	Variable	**50,3%**	(49,7%)	**55,3%**	(44,7%)
Conservative (Low)	*Fixed (1:1)*	25,6%	(74,4%)	26,6%	(73,4%)
	Variable	26,1%	(73,9%)	28,3%	(71,7%)

Table 3b. Annual energy totals for location 2

Location		Substation Type			
Paris (Capacity factor 0.24)		**Design A**		**Design B**	
Return Temperatures	**Flow Ratio**	DH return	(DH supply)	DH return	(DH supply)
Realistic (High)	*Fixed (1:1)*	**36,3%**	(63,7%)	**37,0%**	(63,0%)
	Variable	**39,9%**	(60,1%)	**43,2%**	(56,8%)
Conservative (Low)	*Fixed (1:1)*	17,3%	(82,7%)	18,2%	(81,8%)
	Variable	17,4%	(82,6%)	18,3%	(81,7%)

A summary of the annual energy totals is shown in **Tables 3a, 3b**. Each table compares the substation's performance according to: location, realistic and conservative approaches (depending on the assumed return temperature curves), and operation regarding fixed and variable flow rate ratios.

Figures 8a and **8b** show the annual energy totals and load duration curves (LDC) for the two locations using the substation Type B, assuming the low return temperatures (conservative approach). Overall, the results show that from ⅓ to ½ of the total annual heat consumption in the proposed LT network can be

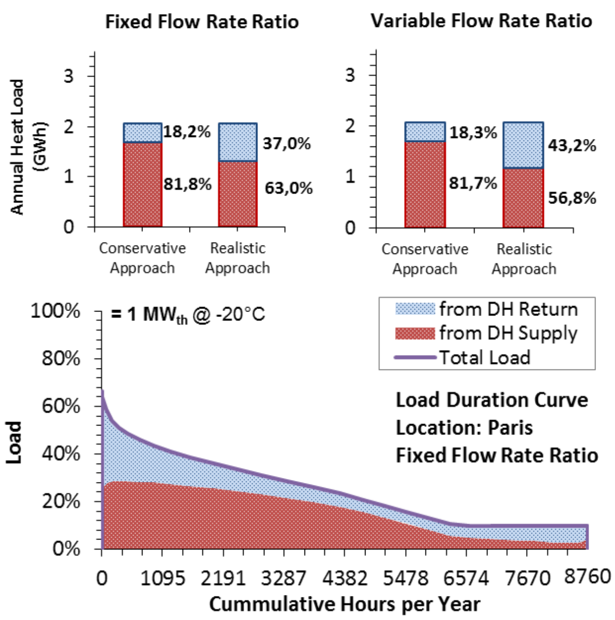

Figure 8b. Annual energy totals and load duration curve for substation type B in location 2

covered taking the heat from the main DH return flow. In a more conservative approach, although unlikely, with lower return temperatures, only 20-30% of the heat load can be supplied in this manner.

DISCUSSION

The results from the thermodynamic analysis show that with the LT substation it is possible to supply a significant portion (**20-50%**) of the total annual heat demand of a LTDH network using the return flow from the main DH network. Both substation configurations proposed deliver similar results. Except that type B gives more flexibility on operation for the variation of flows at lower ambient temperatures.

An observation drawn from **Figs. 5a** and **5b** is the difference between power and flow rate proportion as a function of outdoor ambient temperature when comparing the operation modes of fixed flow rate ratio and variable flow rate. While the flow rates from the DH supply are very similar, only slightly lower for the case of variable flow rate operation, for the same operating point the difference in power extracted from the supply is larger. This result is related to the return temperatures (Figs. 6 and 7) where it is shown that at lower temperatures, when it is possible to increase freely the flow rate in the primary side, the substation primary side outlet temperature also increases. These results show how the higher flow rates in the primary side allow the extraction of minimum energy from the DH supply, but rising the substation primary side outlet temperature, as well as the flows and the required hydraulic power (pumping power).

Regarding the fixed flow rate ratio operation mode, the results indicate that the performance of the substation is almost equal, just slightly better for substation type B (Figs. 5a, 5b and Tables 3a, 3b). The advantage of the operation near an equal flow rate ratio (1:1) is that the outlet temperature at the primary side follows closely the return temperature at the secondary side (**Fig. 6**), and thus the least hydraulic power is demanded.

One of the parameters whose variations showed to have a greater effect in the results is the return temperature from the main DH network. Since this is one of the parameters with the most complex dynamics (because it involves the dynamics of the aggregation of customers and the network itself), it is necessary to further perform a detailed analysis of the impact of variations of this parameter on the substation's performance. From the results it is also clear that more energy can be extracted from the DH return flow in a network with higher return temperatures, which is tied to the location with lower outdoor ambient temperatures and thus higher heat demands.

When comparing the annual energy totals of the substation types A and B (**Tables 3a, 3b**) for the fixed flow rate ratio operating mode, there is no significant difference in the amount of heat covered by the return flow (~1%). For the variable flow rate operating mode, this difference may increase (to ~5%) when the return temperatures from the primary DH network are high. It can be said then, that Substation Type B is preferred to be used networks with higher return temperatures.

OUTLOOK

The next generation of DH networks will require flexibility to ensure a smooth integration to the existing infrastructure [17],[18]. In order to reach an acceptable level of flexibility, it will be necessary to integrate smart networks and controls [6],[19], coupled to responsive thermal energy storages, so that the system can efficiently cope with the demand matching to the total heat supply.

With the purpose of fully exploiting the substation's capabilities regarding its operational flexibility, a study of the relations among the operating parameters is required. This study will be conducted to identify the control schemes, modes and strategies that are able to optimize its operation with the aim to minimize the system's costs.

It will be of special interest to analyse extending the 'low temperature' substation concept to that of a supporting interface for the coupling of low-temperature thermal energy resources. Its function can be analogous to power electronics converters in electric grid-supported systems that connect intermittent renewable energy sources and electricity storage to the local loads and the grid.

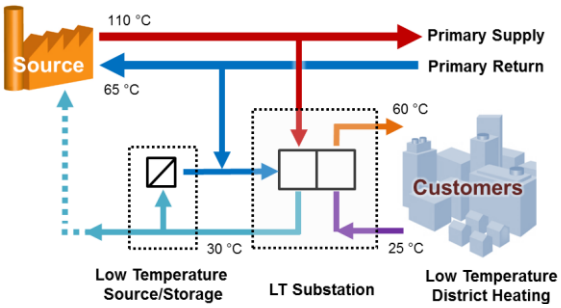

Figure 9. Low temperature substation coupled with low grade heat source/storage

The LT substation is a potential key link between low-temperature systems, renewable thermal energy sources, industrial surplus heat, thermal energy storage, and the heat demands of LEB areas. With this concept all agents can be effectively coupled despite differences in energy quality and quantity, enhancing the network compatibility of supply and demand quality. Therefore, it becomes increasingly relevant to conduct studies of the interaction and integration of LT substations with thermal storage capacity, multiple types of surplus heat, and/or renewable thermal energy sources within the district energy systems.

CONCLUSIONS

The findings discussed in this study show the feasibility of the LTDH substation concept to supply a LT secondary network with low energy demands. The results regarding the performance of the substation were obtained under the assumption that space heating demand is a linear function of ambient temperature. This assumption was made to simplify the analysis at this stage; still, a more precise evaluation of the overall performance will include a more complex demand pattern that more accurately reflects the consumers' dynamics. In a more thorough study, hourly demand fluctuations showing daily variations such as peak load periods and weekly and seasonal tendencies, will result in a more robust outcome.

Moreover, the simulations performed assumed that the temperature inputs and heat load are a function of the outdoor ambient temperature. Consequently, the flow rates ratios presented are also a function of this temperature. In reality, flow rates ratios are a function of the inlet supply and return temperatures, and the instantaneous load in the secondary network, which depend on several other factors. Hence, using hourly measurements of these inputs can improve the consistency of the results.

It was discussed that, as consequence of narrower temperature differences between the inlet and outlet points at the substation primary side, less heat is extracted from the flow, even though the total flow rate may be larger. The lowest reachable temperature at the primary outlet is limited by the heat exchanger dynamics and is equivalent to the return temperature form the secondary network. Nonetheless, to lower the primary side outlet temperature below this threshold, adding a heat pump at the primary side is an option. Yet, the need for an additional energy source to operate the heat pump. However, a lower return temperature (e.g. <15°C), could possibly be beneficial and cost-effective.

One drawback of the substation concept, when compared with a direct connection, is the need for the substation itself. This implies the operational and investment costs of a heat exchanger, as well as a more sophisticated control system. Nevertheless, by optimizing the substation's operation, including variables such as heat costs, hydraulic power demand and return temperature –unlike using a direct connection– the benefits and savings could justify the investment. A further study on the optimization of the costs and operation will be needed to support this concept, by performing a more detailed techno-economic assessment comparing the different alternatives.

An clear recommendation given from the results is that it is necessary to design (size) the substation for the specific location, in order to have an appropriate and efficient system performance. If the system is going to operate mostly with a fixed flow rate ratio, substation Type A is the preferred choice, since it is less complex. On the other hand, if the DH network return temperatures are high, and a variable flow rate ratio operation is used, then substation type B might be more appropriate.

This study reveals that the 'low temperature' substation concept can be an effective link to deliver thermal energy services to LEB areas, and has the potential to incorporate low-grade heat resources to the existing thermal energy networks, contributing to achieve a low-carbon, energy efficient and renewable energy supply.

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SIMULATION-BASED ANALYSIS AND EVALUATION OF DOMESTIC HOT WATER PREPARATION PRINCIPLES FOR LOW-TEMPERATURE DISTRICT HEATING NETWORKS

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ABSTRACT

District heating (DH) networks have been considered one key measure to support global CO_2 emissions reduction targets, replacing carbon intensive individual heating systems in the urban environment and enabling the integration of renewable sources. The challenges are to distribute and convert the thermal energy from various sources in the most efficient way, thus leading to the concept of low temperature district heating networks.

The present study supports the overcoming of technical barriers in implementing low temperature DH networks with the focus on the domestic hot water preparation on the consumer side, which is selecting optimal solutions of substation units (e.g. direct heating, additional heating, micro booster heat pump). In the simulation environment Dymola/Modelica models of different substations were developed being able to simulate in a realistic way the energetic, hydraulic and controls characteristics of substations. Ad hoc indicators were developed and simulations assessment provides advantages/disadvantages of substation types under specific conditions. As main result a decision support methodology was elaborated which, in dependency of different boundary conditions such as supply temperatures (varying between 35°C and 65°C), buildings characteristics, user behaviour, local weather conditions and with the help of the indicators, provides decision makers a valuable tool for choosing appropriate substation solutions.

INTRODUCTION/PURPOSE

Since space heating in traditional residential buildings has generally been ensured by radiation heat transfer from radiators at about 70°C, district heating networks have traditionally been designed for minimum supply temperatures of 90°C (considering gradients of the heat exchanger and to ensure a certain transport capacity). As a result, the distribution losses in district heating systems are usually in the range of 10-30%. Current building energy performance improvement trends contribute to a decreasing district heat demand, which leads to an increase of the relative distribution losses and a decrease of the cost effectiveness of district heating networks [1].

One important possibility to counteract this trend consists in reducing heat supply temperatures to e.g. to 35-65°C in order to lower distribution heat losses [2]. This temperature level is sufficient to gain comfortable room temperatures in buildings with suitable heating systems (e.g. floor heating, concrete core activation) [3], [4], [5], [6]

Based on the Austrian standards and in Austria applied regulations, this paper identifies and evaluates different solutions for the preparation of DHW for varying supply temperatures and building types. They are based on the following two principles: direct heating without storage of DHW or additional heating with different heat sources (e.g. heat pump, electric heating).

STATE OF THE ART

Low temperature district heating network

Low supply temperatures between 35 °C and 65 °C lead to several advantages. Due to a reduced temperature difference between the supply line of the network and the surrounding area of the pipes, the heat losses of the network can be decreased significantly. Furthermore the investment costs for a low temperature district heating network can be reduced through the possible usage of cost efficient installation of plastic pipes with less insulation compared to traditional networks. In addition, low supply temperatures of heat network facilitate the integration of renewable energy sources like solar thermal. Considering lower network temperatures, also heat pumps can be used and run with a high efficiency which enables the efficient usage of alternative energy sources (air, soil, water, communal waste water, low temperature waste heat, etc.) for district heating systems.

Besides these advantages, low temperature district heating has to cope with some challenges. Low temperature substations generally have smaller temperature difference between supply and return temperature, caused by a lower supply temperature resulting in higher mass flow required to transport the same amount of energy as a traditional heat network resulting in increased pumping costs and investment costs (larger pipe diameter).

Another challenge is the risk of legionella propagation when storing DHW at low temperatures. When storing DHW, normally a minimum temperature level (depending on national regulations e.g. [7]) has to be kept to avoid legionella. Different rather cost-intensive options for removing legionella are available, including ultraviolet sterilisation, membrane filtration (reverse osmosis), applying electric potential, electrochemical membrane processes, membrane distillation, selective ion conducting materials, or crystallisation of clathrates.

Low temperature substations

Standard substations for district heating networks are designed for supply temperatures of about 60°C and higher to avoid legionella.

In Austria, for DHW pipes with more than 3 liter volume (DVGW W551 [8]) a circulation pipe is needed and at least 60°C (ÖN B5019 [7]) DHW supply temperature to prevent legionella. An exception of the rule: for single-to two-family houses and DHW pipes with less than 3 liter volume (e.g. in flats) ÖN B5019 prescribes minimum DHW temperatures enough to feed showers (approx. 40°C) or bath tubes (approx. 45°C). Suitable DH substations with instantaneous DHW production (plate heat exchanger) and decentralized substations at each flat are commercially available.

Low temperature DH substation selection

Different evaluation methods for appropriate DHW preparation in a LTDH network have been applied in the past. In [9] two different types of substations were investigated concerning their ability to optimize the dimensioning of pipes. Therefore a system with a storage tank on the primary side was compared to a system without storage tank. Using a storage tank can lead to a reduction in the pipe dimensions due to reduced flow requirements. In [10] DHW preparation in a LTDH network using substations with an integrated micro booster heat pump and storage tanks were analysed. Three different types of substations with micro heat pumps were compared to DHW preparation with direct electric heating. The advantages of substations with booster heat pumps are lower electrical consumption and CO_2 emissions.

METHODOLOGY

In this paper, different LTDH substations are compared and a decision support methodology is developed. The methodology used for the evaluation of the substations is based on the simulations comparison of the demand connections on the basis of performance indicators. For the scope of comparing and assessing advantages/disadvantages and range of conditions where a substation type is preferably to another one, the substation types are evaluated with the assumption of simulating them as “stand-alone” objects. In other words, the connections are evaluated without considering the impact from and to other substations, which is excluding the network topology where they are installed. This assumption ensures that the results are valid in any type of network topology and the results can be applied to any operational conditions. Moreover the effect of return temperature increase or decrease on the PEF and on the CO_2 emissions of the DH network is neglected.

Based on this evaluation, a decision support methodology is derived for supporting the designer of low temperature district heating networks in selecting the appropriate substation in relation to the objective function. As an example for the return temperature as objective function, the decision support methodology will define, based on the specific characteristic of the connected buildings and the district heating operational conditions, the appropriate substation type. The following sections summarises the substation models developed, the simulation set-up being used and the indicators considered.

Variants of low temperature substations

Six different variants of low temperature substations were developed differing in the DHW production principle, the supply temperatures and the sizes of the building, shown in table 1.

The simplified hydraulic schemes are reported in Figure 2, Figure 3, Figure 4 and in the Annex I. Variant 1 and variant 3 are taken directly from [10].

Table 1: 6 developed types of substations for LTDH usage

ID	Building type	LTDH supply temp.	Description
1	Small customers e.g. flats to two-family houses	35-49°C	A microbooster heat pump heats the LTDH water to ~53°C,stored at a ~130 liter buffer. The DHW is produced by an instantaneous heat exchanger unit.
2	Small to medium customers	35-65°C	DHW is preheated by the LTDH and reheated by an auxiliary heater to >60°C and stored in a DHW tank.
3	Medium to big customers	35-49°C	DHW is preheated by the LTDH and reheated by a heat pump (LTDH is the heat source) to >60°C and stored in a DHW tank.
4	Small customers	50-65°C	LTDH heating water is stored in a buffer. The DHW is produced by an instantaneous heat exchanger.
5	Decentralize d customers, e.g. several flats	55-65°C	Decentralized units at each flat. The DHW is produced by an instantaneous heat exchanger.
6	Small customers	50-65°C	The DHW is directly produced by a central instantaneous heat exchanger.

The space heating loop of the radiators of the substations (which are identical for each substation type) could be connected direct or indirect (heat exchanger) to the LTDH grid, while e.g. floor heating loop is considered to be connected only indirect (limitations due to the existing commercial distribution valves and oxygen sensitiveness of the floor heating pipes).

Simulation set-up

The simulation of the substation is carried out with the numerical model of a simplified district heating network. In Figure 1 the model used for performing the parametric variations is presented. The detailed model of the district heating network computing the dynamic response was developed in Modelica/Dymola [11], [12] based on models of the Modelica Fluid library [13] and on the DisHeatLib [14] developed at the Austrian Institute of Technology. This includes models of producer units, hydraulic schemes of substations and preconfigured pipe models.

Due to computational time from one side and focusing on the substation configuration from the other side, a simplified building model developed in Modelica has been used (based on the “one node model” described in VDI 6020 [15]).

The following table, Table 2, summarises the variances for each demand connection respectively: network supply temperature, space heating system and building type, heated area and weather conditions.

Table 2: Summary of the variables considered in the parametric study for the demand connections evaluation

Variable	Range / Combinations	Notes
Network supply temperature	35°-65°C	Range depending on the variant
Space heating system	- Radiator - Floor heating	Different reaction time
Building type	- Standard -Low-energy	Different load profile
Heated area	- Single-family house (150m²) - Multi-family house (1500m²) - Multi-family house (7000m²)	Effect of the coincidence factor
Weather conditions	- 7 days winter - 7 days transitional period - 7 days summer	Representing the characteristic DH operational points

The choice of those variables and the range/number of combinations are based on considering the widest spectrum of DH operational conditions and buildings characteristics connected to a district heating network. It gives as well a reasonable computational time for performing such a parametric study. Combinations of floor heating and radiator heating were excluded from the study since the results could be aggregated from the two single assessments.

Considering Table 2 and the 6 variants including direct and indirect connections, the number of total combinations/simulations is 3024. Nevertheless based on the technical constrains and assumptions a reduction to 759 simulations has to be considered, including also:

- Variant 5-6: because of the single node building model and performing simplified hydraulic effects, variant 5 and variant 6 have the same hydraulic circuit
- Only indirect connections are considered for floor heating systems (limitations in terms of available distribution valves exceeding 8 bar)

The 759 simulations represent the database which is the cornerstone of the decision support methodology.

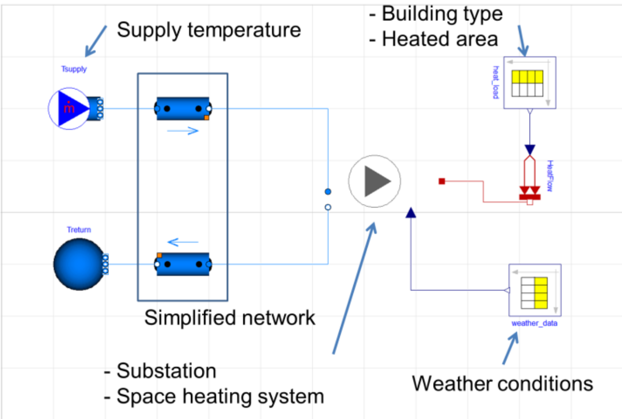

Figure 1: Modelica/Dymola model of the simulation set-up

Indicators

Table 3 summarised the indicators considered for simulations assessment in order to provide advantages/disadvantages of substation types under specific conditions. Economic indicators have not been considered.

Table 3: Indicators developed for the demand connection assessment

Indicator	Method	Unit	Effects
Network return temperature	Average	[°C]	Cooling effect
Volume flow rate	Cumulated	[m³/h]	Pumping costs
Booster heat load	Max	[MW]	Peak boiler costs
DH heat load	Max	[MW]	DH network costs
Booster primary energy	Cumulated	[MWh]	Additional costs/CO_2 emissions

The choice of those indicators is driven by the effects that they have on the network performances as reported in the last column of Table 3.

RESULTS

Two test scenarios evaluating a parametric variation of three selected substation variants have been setup exemplary to demonstrate the practicality and feasibility of the developed decision support method:

- supply temperature variation (35-65°C) with substation variant 2
- Comparison of substation variant 1, 2 and 3 at fixed supply temperature (40°C)

Those scenarios consider following assumptions:

- Consumer: single family house with 150m² heated area
- Simulation timeframe: summer period with only DHW preparation
- Ecologic indicators considered the primary energy factors and CO_2 emissions based on the Austrian guidelines (district heating plants from renewable sources) [16].

- Only direct connections for the radiator are considered

Simplified hydraulic schemes of variant 1, 2 and 3 are shown in figure 2, 3 and 4. The schemes of the other variants are shown in the annex.

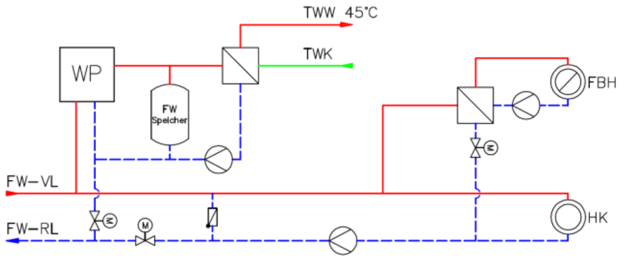

Figure 2: Simplified hydraulic scheme of **variant 1** (FW-VL = supply line, FW-RL = return line, TWW = DHW, TWK = cold water, WP = heat pump, FBH = floor heating, FW Speicher = DH storage, HK = radiator)

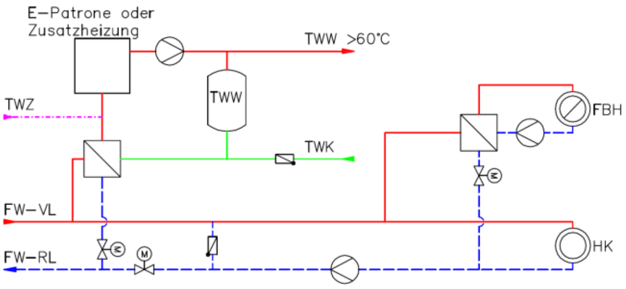

Figure 3: Simplified hydraulic scheme of **variant 2** (FW-VL = supply line, FW-RL = return line, TWW = DHW, TWK = cold water, Zusatzheizung = additional heating, FBH = floor heating, HK = radiator)

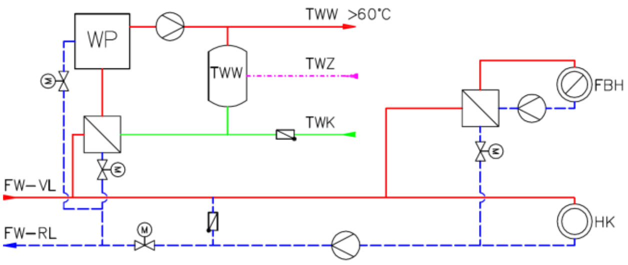

Figure 4: Simplified hydraulic scheme of **variant 3** (FW-VL = supply line, FW-RL = return line, TWW = DHW, TWK = cold water, WP = heat pump, TWZ = circulation line, FBH = floor heating, HK = radiator)

DH supply temperature variation scenario

The first scenario presented considers supply temperature with the substation variant 2, including 3 different possibilities as booster heater:

- gas condensing boiler (GCB)
- direct electric heating (el.H)
- heat pump with air as external source (HPA)

The effect on the supply temperature on the return temperature is reported in Figure 5. It shows an increase of around 5K if supply temperature is increased from 35°C to 65°C.

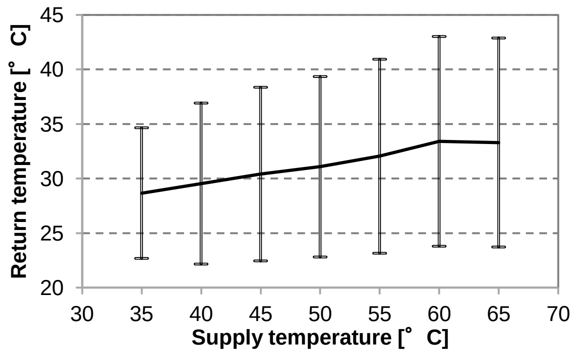

Figure 5: Return temperature dependency on the supply temperature for variant 2 GCB

The more the supply temperature increases, the less is the heat load from booster needed to lift the DHW cold water to the required temperature, see Figure 6.

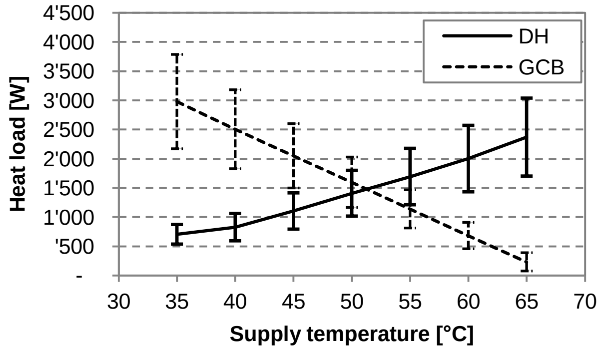

Figure 6: Peak heat load dependency on the supply temperature for variant 2 GCB (DH = District heating and GCB = gas condensing boiler as booster heater)

To evaluate the optimal supply temperature in terms of ecological impact the total primary energy consumption (from district heating and booster heater for el.H and HPA) and CO_2 emissions (GCB) are reported, Figure 7, Figure 8 and Figure 9.

In the case of usage of an el.H as booster heater the decrease of the supply temperature requires the higher utilisation of the booster, which as consequence increases the total primary energy Figure 7. The opposite is occurring in the case of the HPA, since the primary energy factor of the HPA is advantageous compared to the DH. A similar trend is as well for the GCB.

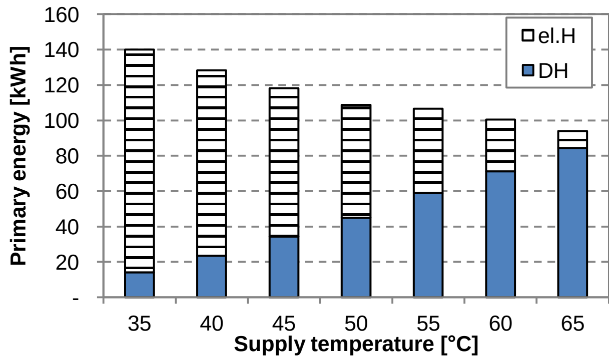

Figure 7: Primary energy - variant 2 el.H

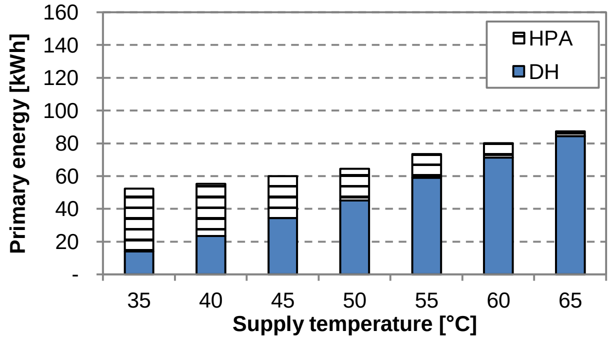

Figure 8: Primary energy - variant 2 HPA

Based on the CO_2 emission factors as reported in [16] the CO_2 emissions dependency of the variant 2 GCB on the supply temperature is presented in Figure 9. As a result of high CO_2 emission factors from the booster heater GCB compared to the DH network, the decrease of supply temperature causes an increase of CO_2 emissions too. Both for el.H and HPA the trend is similar to the GCB.

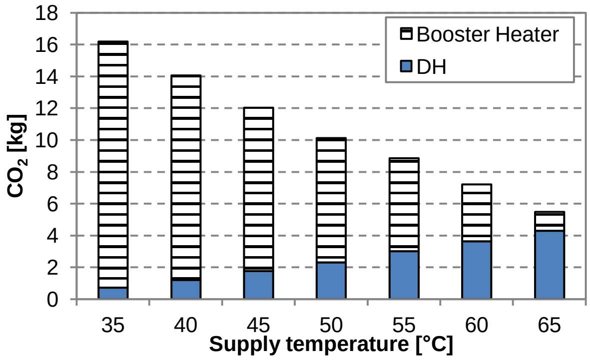

Figure 9: CO_2 Emission - variant 2 GCB

Variant 1-2-3 comparison

The second scenario considers fixed boundary conditions (supply temperature is set at 40°C) and three different demand connections. Figure 10 shows the return temperature of the three solutions, where variant 1 represents the best solution with an average return temperature around 27°C.

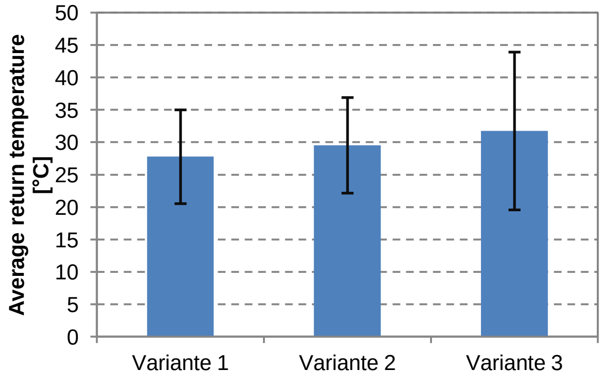

Figure 10: Average return temperature - variants 1-3

Primary energy consumption for all variants is shown in Figure 11, for which the best solution is represented by the variant 2 HPA for the same reason as explained in the previous section.

On the other hand, if CO_2 emissions are considered as decisional factor, variant 1 has the best performance, see Figure 12.

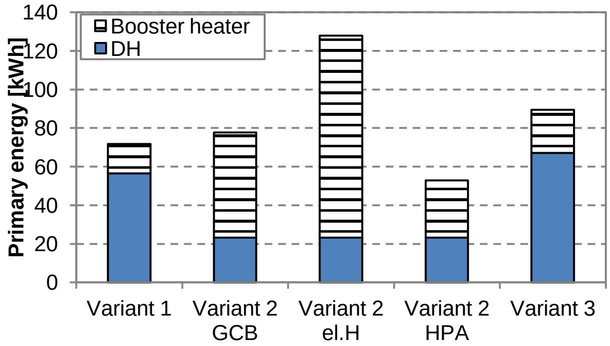

Figure 11: Primary energy for variants 1-2-3

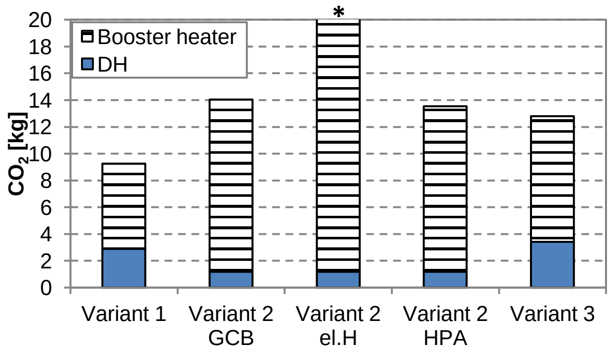

Figure 12: CO_2 emission – variants 1-2-3 (***** >>20 kg)

Decision support methodology

The decision support methodology, as explained in the previous sections, represents the link between indicators calculated for each simulated demand connection configurations and the network/consumer settings (e.g. supply temperature or building type). The tool has been implemented in Matlab and it links to the database of the simulations described above. By selecting the building type and size, building standard and heating system and weather conditions, for each single indicator the best variant (both direct and indirect connections) is extracted.

DISCUSSION

Six different substation types have been implemented in the simulation environment Modelica/Dymola. To validate the feasibility of the method two test scenarios evaluating two parametric variations of the developed substation models have been performed.

As result of the supply temperature variations, for variant 2 GCB, the return temperature is reduced of 5°C when the supply temperature is decreased from 65°C to 35°C. Increasing supply temperatures result in low CO_2 emissions, supporting the concepts of low temperature district heating networks.

For the comparison of variants 1, 2 and 3 at constant supply temperature, variant 1 gives the lowest return temperature and the lowest CO_2 emissions. Nevertheless if the primary energy represents the key indicator, variant 2 HPA simulations shows the lowest among the three configurations.

OUTLOOK

The future work will include the further development of the results and combination with economic indicators (as much as possible) to a decision support methodology targeting planners and operators of DH networks. Additionally, promising variants will be developed further and refined in order to optimize the operation and design. The development of a prototype is the consequent next step to be validated with regards to energetic indicators in lab scale and in a suitable environment.

CONCLUSIONS (RRS)

Low temperature DH networks are beneficial, since they reduce the heat distribution losses and investment costs and enable the exploitation of many renewable energy sources and low temp waste heat. For supply temperatures below 65°C, DHW preparation becomes more challenging. A decision support methodology based on a dynamic simulation model of different substations was developed, targeting planners and operators of DH networks for choosing the appropriate DHW preparation principle.

For presenting the decision support methodology, in this paper, 3 exemplary substations variants with different DHW preparation principles were compared: variant 1: heat pump for instantaneous DHW preparation at 50°C (HP source: supply line), variant 2: using an auxiliary heater (gas boiler, electric heater, heat pump, HP source: air) for storing DHW at 60°C and variant 3 using a heat pump for storing DHW at 60°C (HP source: supply line). As a result, the return temperature and the CO_2 emissions for variant 1 are the lowest, but the primary energy consumption in variant 2 using an air heat pump is the lowest.

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ANNEX

From Figure 13 to Figure 15 the simplified scheme of the indirect connection types of the demand connection 4a, 5a and 6a are reported.

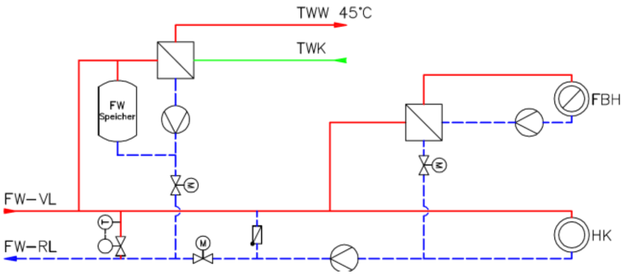

Figure 13: Simplified hydraulic scheme of variant 4a

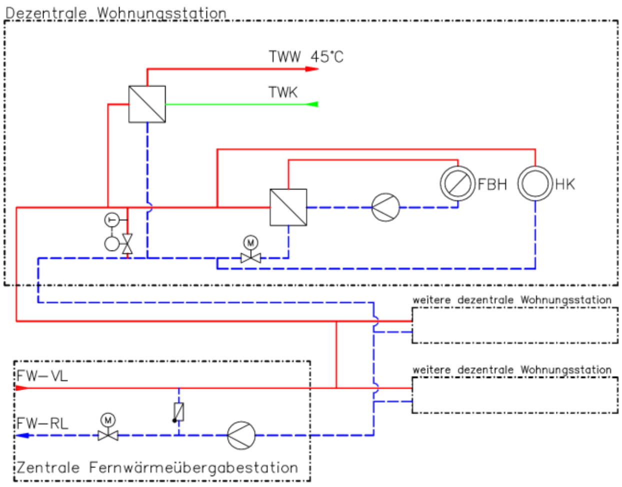

Figure 14: Simplified hydraulic scheme of variant 5a

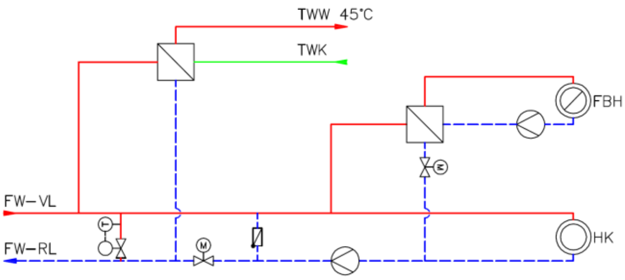

Figure 15: Simplified hydraulic scheme of variant 6a

IDENTIFING THE OPTIMAL SUPPLY TEMPERATURE IN DISTRICT HEATING NETWORKS - A MODELLING APPROACH

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ABSTRACT

The number of low-energy and energy renovated buildings with considerably low heating demand has been continuously increasing in recent years. Combined with utilizing low temperature sources, this development raises the necessity of introducing a new generation of District Heating [DH] Systems with a lowered operational temperature. In order to implement the low temperature concept, adaptation and improvement of existing DH system is required. By lowering the operational temperature, it is further possible to utilize low-grade and renewable energy sources to meet the heating demand.

The main objective of this study is to develop a model for thermo-hydraulic calculation of low temperature DH system. The modelling is performed with emphasis on transient heat transfer in pipe networks. The pseudo-dynamic approach is adopted to model the District Heating Network [DHN] behaviour which estimates the temperature dynamically while the flow and pressure are calculated on the basis of steady state conditions. The implicit finite element method is applied to simulate the transient temperature behaviour in the network. Pipe network heat losses, pressure drop in the network and return temperature to the plant are calculated in the developed model. The model will serve eventually as a basis to find out the optimal supply temperature in an existing DHN in later work.

The modelling results are used as decision support for existing DHN; proposing possible modifications to operate at optimal supply temperature.

INTRODUCTION

District Heating [DH] systems supply heat generated at a central heat plant to consumers by means of a distribution network involving the use of pre-insulated pipes. The main advantages are high-energy efficiency, easy implementation of energy sources of various types and the recovery of waste heat from combustion plants. Increasing the share of renewable energy, the energy savings in network and building energy performance are the main challenges today and in the future for DH systems. Lowering the temperature level in existing networks and identifying the optimal supply temperature in terms of energy efficiency plays an important role in sustaining DH as a competitive option in the heating market and in increasing the share of renewable energy sources. The choice of the right temperature level in a DH system is of major importance, as it directly impacts the effective price of the generated heat, particularly in combined heat and power plants [1]: The higher the temperature level, the lower the electricity generation and vice versa. However, a temperature decrease allows for utilizing a broader range of heat sources in a DH system.

As District Heating Networks [DHN] are used for transporting heat through long distances, heat and pressure losses are unavoidable. Thus, additional pumping power is required to compensate pressure losses in the network and heat losses result in higher primary energy consumption [2]. Due to considerable time delays and heat loss to the surrounding ground in a distribution network, the dynamics of the system has great effect on its operation [3]. Additionally, the variation in consumers' heat load provides extra challenges.

Thus, the dynamic simulation of temperature changes and heat storage in DHN is inevitable to develop efficient system performance. Furthermore, modelling thermal and hydraulic behaviour should be included in such simulations as it is used to perform dynamic temperature control and long term and short term forecasting of DH systems [4,5].

Generally, there are two different approaches in order to model a DH system [3]:

- 1) Physical modelling, which considers the actual network topology, the physical layout and properties of the pipes to calculate flow distribution, temperature distribution, heat loss and pressure loss in the network [1,6].
- 2) Black box modelling, which applies simple modelling methods including classical time series analysis and neural networks [3].

The black box method does not contain much physical information about the network, which is the main drawback of this approach. Therefore, physical modelling is adopted in this study to model transient behaviour throughout the pipe network.

Several studies have been done on dynamic simulation of DHN based on the physical modelling approach. A model introducing the so called node method has been developed by [10,7], at Technical University of Denmark. The model is applied to tree networks and the computations are based on a historical data of temperature and flow at one single point within the network. Another model based on energy balances for each element along the pipe is proposed by [8], which applied explicit and implicit finite element method. The explicit method showed excessive artificial diffusion for small time steps and low water velocities. [9] has introduced an analytical solution to pseudo dynamic modelling, which assumed constant water velocity over time. The same node method [1] is applied based on analytical solution. Other methods [3,7] were focused on operational optimization of DHN by making some simplification to reduce the network complexity. In [4], two models have been employed for modelling and validating temperature dynamics. The node method and commercial software TERMIS are applied to validate the performance of models for an existing DHN. The results revealed noticeable discrepancies for consumers at distant locations. A steady state model for estimation of hydraulic behaviour in DHN is developed in [10]. Another model is also presented in [3] based where there is lack of information for consumers and average consumption is used for some of the consumers. In [7,11] the validation of finite element method has been carried out with measured transient temperature. The results showed very high agreement with the measured data.

As it was discussed earlier, there is need to develop a model which reflects the dynamic of DHN and simulates the time delays, temperature change and pressure losses in the network based on the supply temperature from the plant and heat consumption by consumers in order to perform operational optimization and performing different analysis [1,12]. The main purpose in this study is developing a mathematical model for DH pipe network in MATLAB which simulates thermal and hydraulic performance of network. At this stage, a model is developed for a small DHN. It is assumed that the heat demand by consumers and the return temperature from each consumer is fixed and cannot be influenced by the DH Company. A pseudo-dynamic approach is obtained and the implicit finite element method is used to model transient temperature behaviour in the network. The approach is then applied using technical specifications of an existing DHN together with corresponding historical data (hourly or less time intervals data).

DYNAMIC MODELLING

As mentioned before, considerably time delays can be observed in large distribution networks. The time delay in the network is a result of transportation time from the power plant to the consumers and back again. The required time depends on the distance to the consumers as well as the flow velocity in the network. Thus, in large systems it can take up to 10-12 hours that temperature changes in the plant affect a consumer. Additionally to the distance and flow velocity, the heat capacity of the pipes also affects the time delays since pipes absorb and release heat from and to the water when the water temperature varies [1].

The heat loss is proportional to the difference between the water temperature and the surrounding soil temperature. Further, the insulation material of the pipes, the pipe diameter and configurations influence as well the heat loss of the pipe.

Another important parameter in a DHN is the pressure loss along the pipes. Pressure and flow changes are spreading around 1,000 times faster in the network than temperature fluctuations. While the temperature changes travel as fast as the water flow velocity in the pipe, the pressure waves are traveling with speed of almost 1,200 m/s. Thus, it can be concluded that the dynamic of the temperature changes in the network are much more important than the flow dynamics in the network. Therefore, this study considers a pseudo-dynamic method for modelling the network, which assumes steady-state conditions for pressure and flow**.**

Figure 1 reveals a simplified DH system including one plant, consumers, a pipe network and a pump station, which serves as a basis for the model presented in this work.

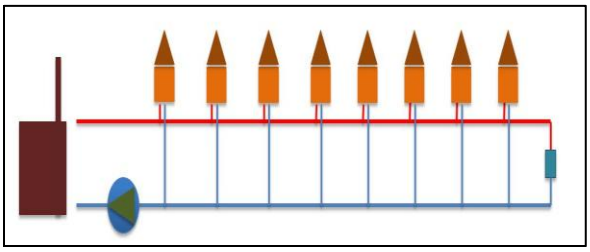

Fig 1. Simplified DH system

In the following section, the mathematical model and numerical method for simulation pressure changes and transient temperature in network are described.

Pseudo dynamic models

The principle of a pseudo dynamic model, which is applied in this study, is to determine the flow and pressure by means of steady state calculation. In opposite, the transient temperature is calculated dynamically. The network is modelled in regular time intervals (hourly or less time intervals), in each time interval the flow is assumed steady-state and it is calculated based on consumers heat load and supply and return temperature at each consumption site. In every time interval the flow is assumed constant and the values for pressure losses and temperature are calculated.

As it has been mentioned, the so-called element method has been used to apply dynamic modelling of transient temperature in DH pipe networks. It is explained briefly in the following.

Dynamic simulation of temperature

Changes in the temperature in DHN affect directly the supply temperature, heat losses from the pipes to the surrounding and the return temperature due to cooling at costumers [3].

Finite element method

In the element method, each pipe is divided into a number of elements. Each element consists of a multi-layered pipe structure including the DH water pipe, insulation and a cylinder of soil surrounding the pipe (Figure 2).

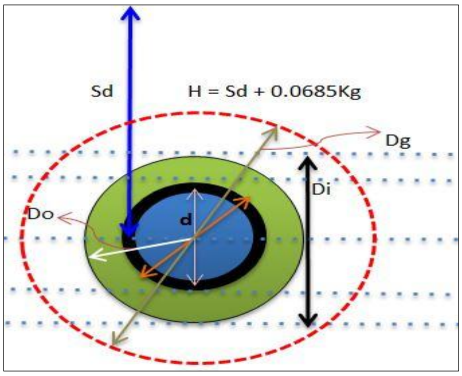

Fig 2. Pipe cross section

Assumptions

In order to apply the mathematical modelling of the temperature in each pipe element, the following assumptions are considered:

- It is assumed that the pipe is following the same temperature as the water since the thermal conductivity of both of them are relatively large compared to insulation and surrounding.
- Hydraulic dispersion is disregarded. Slug flow is assumed, which implies a uniform velocity in radial direction
- Axial heat transmission in both fluid and pipe wall is neglected.
- Temperature rises due to friction losses caused by pumping energy in neglected.
- Interaction between return and supply pipes is neglected as it is relatively small in pre-insulated pipes [3,10].
- Constant water properties corresponding to the average water temperature is assumed.

In order to obtain the simulation model of a DHN by using the element method, the following procedure is followed:

Courant number is important parameter when using finite element method. It is calculated as:

$$C = \frac{\Delta t\,.\,v}{\Delta x} \tag{1}$$

Where

Δt is time step. Δx is element length and v is water flow velocity.

In the implicit method courant number should never exceeds 1 [1]. The courant number in the model developed in this study is assumed 1.

Heat transmission

Thermal resistances for insulation and surrounding soil are calculated as following. The subscript *i, g, o* are used for insulation, ground and pipe respectively. Term *u* is used for undisturbed ground, which assumes that DH water does not have effect on its temperature.

$$Rg = \frac{1}{2\pi Ki}\ln\left(\frac{Di}{Do}\right) \tag{2}$$

$$Rg = \frac{1}{2\pi Kg}\ln\left(\frac{4H}{Di}\right) \tag{3}$$

K denotes the material thermal conductivity. H is obtained from $Sd + 0.0685Kg$, where Sd is the distance between ground surface and pipe centre and Kg is soil thermal conductivity.

Thermal resistance between pipe sections for each pipe elements (Δx) are:

$$Rwi = \frac{1}{2\pi Ki}\ln\left(\frac{1 + Di/Do}{2}\right) \tag{4}$$

$$Rgu = \frac{1}{2\pi Kg}\ln\left(\frac{4H}{Di + Dg} + \sqrt{(\frac{4H}{Di + Dg})^2 - 1}\right) \tag{5}$$

$$Rig = Ri + Rg - Rwi - Rgu \tag{6}$$

Then the heat transfer is calculated by using $h = \Delta x/R$ for each pipe section.

Heat capacities

The heat capacities for each element are calculated in three sections, where C denotes the heat capacities in each element, cp is the specific heat capacity and ρ is the density. The heat capacity for water, pipes, insulation and surrounding ground is calculated as follows:

$$Cwp = \Delta x\frac{\pi}{4}(Do^2\rho_w.cp_w + (Do^2 - d^2)\rho_s.cp_s) \tag{7}$$

$$Ci = \Delta x\frac{\pi}{4}\left((Di^2 - Do^2)\rho_i.cp_i\right) \tag{8}$$

$$Cwp = \Delta x\frac{\pi}{4}\left((Dg^2 - Di^2)\rho_{sg}.cp_g\right) \tag{9}$$

Heat balance equations

The following differential equations for three sections in each element are applied, where m is mass flow in pipe element and T is temperature.

$$Cws.\frac{\partial Tw}{\partial t} + m.cp_w.\frac{\partial Tw}{\partial x}.dx + h_{wi}(Tw - Ti) = 0 \tag{10}$$

$$Ci.\frac{\partial Ti}{\partial t} + h_{wi}.(Tw - Ti) + h_{ig}(Ti - Tg) = 0 \tag{11}$$

$$Cg.\frac{\partial Tg}{\partial t} + h_{ig}(Ti - Tg) + h_{gu}(Tg - Tu) = 0 \tag{12}$$

Numerical solution

In order to solve the mathematical model developed based on the finite element method, implicit and explicit numerical approximations are two common methods [1,3]. As the explicit method showed excessive artificial diffusion for small time steps and low water velocities, the implicit method is applied in this study, where all the heat balance equations are solved simultaneously for each element:

$$T_{w,k}^{j+1} - T_{w,k}^{j} + \frac{m.cp_w\left(T_{w,k}^{j} - T_{w,k-1}^{j}\right).\Delta t}{Cws} + \frac{h_{wi}\left(T_{w,k+1}^{j+1} - T_{i,k+1}^{j+1}\right).\Delta t}{Cws} = 0 \quad (13)$$

$$T_{i,k}^{j+1} - T_{i,k}^{j} + \frac{h_{wi}\left(T_{i,k+1}^{j+1} - T_{w,k+1}^{j+1}\right).\Delta t}{Ci} + \frac{h_{ig}\left(T_{i,k}^{j+1} - T_{g,k}^{j+1}\right).\Delta t}{Ci} = 0 \quad (14)$$

$$T_{g,k}^{j+1} - T_{g,k}^{j} + \frac{h_{ig}\left(T_{g,k+1}^{j+1} - T_{i,k+1}^{j+1}\right).\Delta t}{Cg} + \frac{h_{gu}\left(T_{g,k}^{j+1} - Tu\right).\Delta t}{Cg} = 0 \quad (15)$$

Terms *j* is used for the number of actual time steps in each time interval and *k* is used for the actual number of pipe elements in each pipe segment.

Flow and pressure calculation

In each time interval, the flow is assumed steady-state. After obtaining the flow in each pipe segment, the pressure loss is calculated by the means of the Darcy-Weisbach equation:

$$h = \frac{8f\, L\, m^2}{d^5 \rho_w^2 \pi^2 g} \quad (16)$$

Where h is pressure head in *meter*, *L* is length of the pipe segment, *d* is pipe inner diameter and m is the mass flow rate in each pipe segment.

f is the friction factor, which is dependent on Re (Reynolds number) and relative roughness ($^{\varepsilon}/_{d}$). For developed turbulent flow it is calculated by using Colebrook equation:

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{^{\varepsilon}/_{d}}{3.71} + \frac{2.51}{Re.\sqrt{f}}\right) \quad (17)$$

Simulated model in MATLAB

The developed mathematical model for modelling dynamic performance of a DHN is implemented in MATLAB. The model is applied for a network consisting 8 buildings.

The known variables are the supply temperature from the plant (Tsp), the heat load in each consumer (Ql) and the return temperature from each consumer (Trc) on hourly basis.

The output variables are the supply temperature (Tsc), the mass flow rate in each consumer (m_c) and the return temperature to the plant (Trp). Finally, the total heat loss (Qhl) in the network, total heat demand from the plant (Qs), pressure losses (Δpt) in the network and pump power demand (Wp) are obtained.

RESULTS AND DISCUSSION

For a case study a DHN is assumed, where the heating demand is provided through a combined heat and power plant (CHP). Thus, reducing heat loss in the network leads to a lower heat demand in the network and consequently lower fuel consumption or possibility of increasing the electricity generation in the plant. On the other hand, with the same heating demand from the consumers, reducing the supply temperature from the plant directly affects the mass flow rate in the network. Increase in the mass flow rate results in higher pressure losses and electricity demand for the pump. Furthermore, reducing the return temperature has a direct effect on the economy of CHP plant. Thus, heat generation costs of a CHP driven DH are a function of time, heat load and supply and return temperature as well as the electricity price, as the electrical efficiency is strongly dependent on the temperature level in DH system. All these aspects are needed to be taken into account in order to find out optimal supply temperature.

At this stage of this study a simplified DHN model is developed in Matlab in order to identify the effects of the supply temperature to different parameters in the network. The model is applied for a range of supply temperature [65-85°C] from the plant to investigate changes in heat losses, pump power demand and return temperature to the plant.

The developed model is applied for a network consisting of 8 consumers. The model is performed for a time series of data for supply temperatures from the plant as well as the consumer's heat load and return temperature on an hourly basis. The simulation has been conducted for a DH operation of 24 hours with hourly time intervals. The temperature profile for one time interval is used as an initial condition for the next time interval simulation. The model is calculating transient temperature, supply temperature at each consumer and mass flow rate for each consumer for each consumer.

Figure 3 reveals the hourly supply temperature and flow velocity profile for consumer 8 in the developed network based on its hourly heat load profile and return temperature with a supply temperature of around 70°C from the heat production plant.

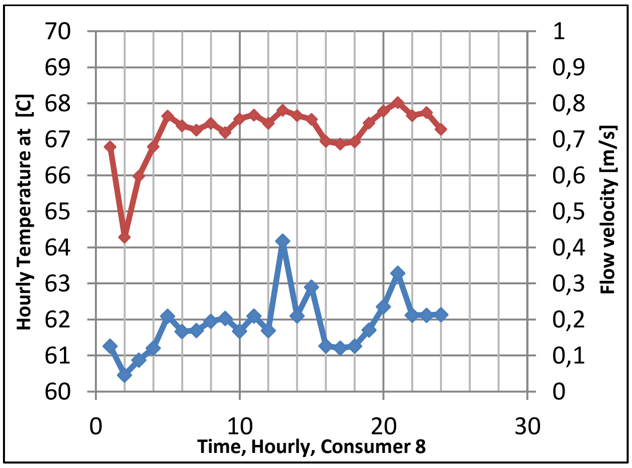

Fig 3. Temperature and flow velocity for consumer 8 on hourly basis

Figure 4 presents the changes of return temperature by varying supply temperature in the developed model. Increasing the supply temperature results in a decreased return temperature, whereas a supply temperature of 65°C (green line) results in higher return temperature.

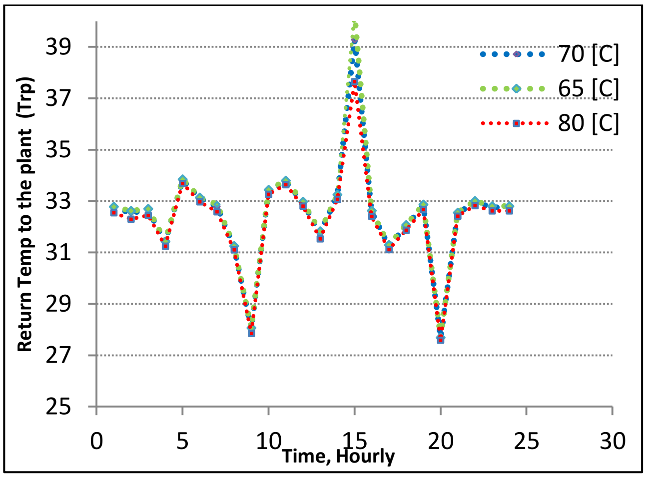

Fig 4. Hourly data for return temperature to the plant at supply temperatures 65, 70 and 80 [°C]

Figure 5 depicts the variation of heat loss and electricity demand for the pump operation by a variation in supply temperatures from the plant. As it was discussed earlier an increase in supply temperature results in higher network heat losses and a reduction in pressure drops and electricity demand for pump operation in the network.

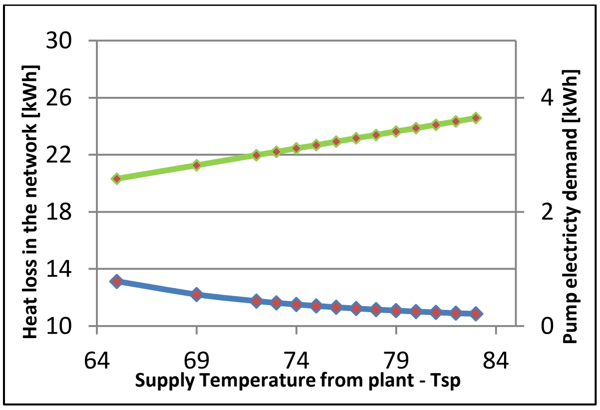

Fig 5. Total heat loss in the network and Pump electricity demand vs. supply temperature from plant

The developed model in this study will be used as a basis for finding optimal supply temperature in the network based on total energy consumption cost, with considering different variables such as the type of the assumed heat generation plant (Boiler, CHP, Renewable sources e.g. Solar), the electricity price and the fuel cost.

OUTLOOK AND CONCLUSIONS

A physical modelling of DHN is developed in Matlab. Pseudo-dynamic approach is used where the flow is assumed steady-state in each time interval and temperature is modelled dynamically. The transient temperature behaviour was simulated by the implicit finite element method. The model was applied for a simplified DH system based on hourly time series data.

The developed model is used as decision support for existing DHN; proposing possible modifications to operate at optimal supply temperature.

In order to validate the developed model, the model will be applied for existing DHN in Harlev, Denmark, where there is access to consumers measured data. Then the model is used for operational optimization of an existing network regarding different scenarios for heat production plant, type of fuel, electricity price.

In the simplified model the variation in supply temperature is not included because of the lack of data; it will be added in next stage of this work.

ACKNOWLEDGEMENT

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SESSION 6

Resource efficiency and environmental performance

LARGE HEAT STORAGES FOR LOAD MANAGEMENT IN CHP BASED DISTRICT HEATING SYSTEMS

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ABSTRACT

Germany is on its way to full energy supply through renewable energies. Of course it is still a long way to go and so there is a need of changeover technology like combined heat and power (CHP) based district heating. But decreasing stock market prices for energy and decreasing heat demand - especially on weekends in the summer - threat the marketability of gas-based CHP plants.

For this purpose the situation of a local municipal energy supplier operating two gas-based CHP plants is examined. Especially in the summer the heat demand and the stock market prices for energy are so low that operating CHP plants is not profitable. So the idea is to build a large sized heat storage (LHS) to switch off one CHP plant on weekends. The necessary heat for district heating on weekends is stored during the week supported by a heat pump and a solar thermal system.

For different scenarios the monetary benefits from the new storage, the heat pump and solar thermal system can be identified. As a result it can be shown that especially the large sized heat storage has a strongly positive effect on the load management and helps so to operate the CHP plants according the variable spot market prices for electricity.

INTRODUCTION

A typical local municipal energy supplier operates a bigger district heating network with maximal thermal load of 250 MW. The required heat comes to 90 % from two gas and steam cogeneration plants (CHP 1 and CHP 2) on two facilities. A small sized heat storage (SHS) also already exists.

The certified primary energy factor is with a value of 0.065 one of the lowest in Germany. Nevertheless decreasing heat demand in the summer months and economical and technical constraints – especially low stock market prices for electricity in off-peak times as well as high and hardly fluctuating prices for gas - threat the marketability of both CHP plants. Combined heat and power based district heating is a changeover technology on the way to Germanys full energy supply through renewable energies. But CHP only can be sustained in the coming years if marketability is given.

Therefore reasonable combination of investment measures and new aspects in unit commitment improving the marketability will be detected for the examined local municipal energy supplier. Furthermore primary energy saving combination of highly efficient CHP, renewable energies (e.g. solar thermal system) and heat pumps is necessary but only reasonable if times without using CHP and accordingly pure heat generation occur.

First preliminary considerations delivered the system configuration illustrated in Fig. 1 and examined in the course of TU-Dresden research project [1]. With help of the self-developed software tool *FWOptH* the optimal unit commitment will be determined and the monetary benefits identified. Furthermore relevant parameters will be varied.

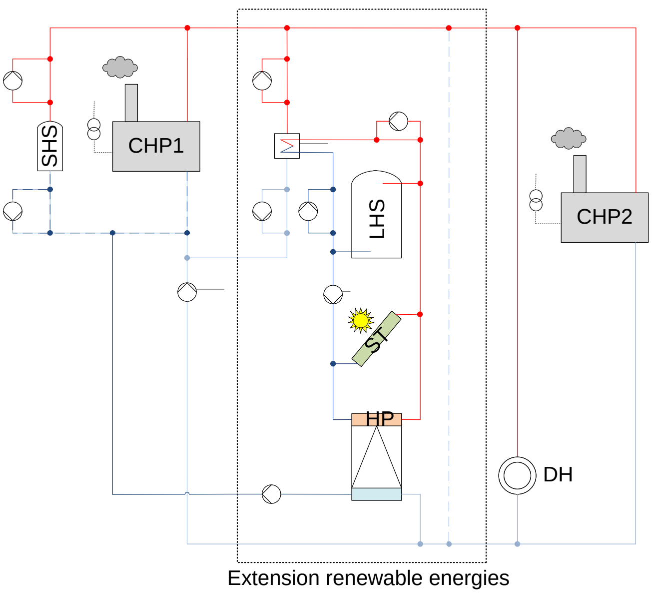

Fig. 1 Configuration diagram current generators as well as planned extension with renewable energies

Most important task is the dimensioning of the new large sized heat storage and the analysis of the CHP 1 turn-off time on weekends before, in and after the summer months May till September (maximum turn-off Friday 8 pm till Montag 8 am) for economic reasons. In the turn-off times the district heating network will be supplied predominantly by the large sized heat storage supported by solar thermal system (ST) and a large sized heat pump (HP). Both gas-based CHP plants CHP 1 and CHP 2 are localized on different places and supply the district heating network. The hydraulic directly connected 8000 m³ small sized heat storage near the CHP 1 is already used for load management. CHP 1 has two identically constructed blocks each with one gas and one steam turbine (extraction back-pressure turbine). CHP 2 in contrast has an extraction condensing turbine and can be used for flexible heat extraction in particular.

The examined extension of the current generators is marked in Fig. 1 through a black dotted frame. The planned extension covers the large sized heat storage, the solar thermal system and the heat pump and is hydraulic indirectly connected with the district heating network. The heat pump uses water from the district heating return line as heat source and so cooled water flows in the small sized storage or is heated up by the CHP 1 directly. The operation of the heat pump benefits by low energy prices and positive outcome of the efficiency of the CHP 1 because of reduced return temperatures.

METHODS

With help of the self-developed software tool *FWOptH* the optimal unit commitment of all generators and both storages of the municipal energy supplier is determined. *FWOptH* is a further development of *FreeOpt* [2,3] and is adapted for the unit commitment of system configuration of typical municipal energy suppliers.

The underlying mixed integer optimization model is written in the mathematical modelling language GAMS [4] and solved with the popular solver CPLEX [5]. Objective function of the optimization model contains the total operating proceeds $\mathrm{p_{TOTAL}}$ as sum of costs and proceeds presented in equation (1).

$$\mathrm{p_{TOTAL}} = \mathrm{p_{GAS}} - \mathrm{c_{GAS}} + \mathrm{p_{ELEC}} - \mathrm{c_{ELEC}} - \mathrm{c_{STARTUP}} - \mathrm{c_{CO2}} + \mathrm{p_{ANA}} \rightarrow \max! \tag{1}$$

$\mathrm{p_{GAS}}\cdots$	Proceeds gas sold on spot market
$\mathrm{c_{GAS}}\cdots$	Costs gas purchased on spot market
$\mathrm{p_{ELEC}}\cdots$	Proceeds electricity sold on spot market
$\mathrm{c_{ELEC}}\cdots$	Costs electricity purchased on spot market
$\mathrm{c_{STARTUP}}\cdots$	Start-up costs
$\mathrm{c_{CO2}}\cdots$	Costs for CO_2-cerfiticates
$\mathrm{p_{ANA}}\cdots$	Proceeds for avoiding network access

Please note that no costs and proceeds for gas and electricity hedges as well as proceeds for heat sale in the district heating network are included in the total operating proceeds because they are fixed parameters and consequently do not influence the optimal unit commitment of the generators. Hence the total operating proceeds are not equal to the real proceeds. They are rather used as comparative evaluation criteria for different generators operations. Furthermore the investment costs are not considered too. Only the unit commitment is examined and so the calculated total operating proceeds can be considered later in investment decisions.

FWOptH based on detailed modelling and approximation of operating performance of single system components. The characteristic operating behavior of both CHP plants CHP 1 and CHP 2 is determined with the help of the engineering and designing energy and power plant systems *EBSILON®Professional* [6]. Additional extensive internal development of measured data based modelling of real part load behavior and technical boundaries (e.g. steam turbine, gas turbine, waste heat boiler) were necessary.

The characteristics for the electric and thermal efficiency as well as the power and heat ratio determined from discrete simulation results are piecewise approximated in subject to the outside temperature and build one part of the optimization model of *FWOptH*.

The generators start-up behaviors (cold and warm start) as well as the operation behavior of the heat pump based on manufacturer's data (prototyping) for the COP value for part load and different temperature strokes are modeled close to reality. The return flow cooling down through the heat pump is considered with the help of a homologous model. The thermal power of the solar thermal system is calculated in subject to the outside temperature and the solar radiation according to a simplified steady model. The most important characteristics for both heat storages (storage capacity, loading performance) are determined for the particular useable volume.

All generators and heat storages characteristics are listed in Table 1 and Table 2.

Significant economic factors are the heat demand for the district heating network as well as the spot market prices for gas and electricity for the year 2010 integrated in FWOptH in form of time series. Beside the spot market trade gas is purchased and electricity is sold on the future market for long term. The required hedges are given by the examined municipal energy supplier. Further costs occur through start-ups of the CHP-plants and purchasing CO_2-cerfiticates (costs for CO_2-cerfiticates: 15 €/t). Proceeds for avoiding network access (CHP 1: 3.4 €/MWh; CHP 2: 3.2 €/MWh) also have to be taken into account. Proceeds for CHP-refund are not considered.

Table 1 Characteristics generators (selection)

	CHP 1 (one block)	**CHP 2**
electrical power	19 MW – 48 MW	42 MW – 63 MW
thermal power	19 MW – 51 MW	0 MW – 43 MW
overall efficiency (full load)	93 %	89 %
power and heat ratio (full load)	0.83	1.24
heat pump		
thermal power	1 MW – 5 MW	
COP (full load)	6.38	
solar thermal system		
collector area (gross)	11800 m^2	
peak performance	7 MW	

Table 2 Characteristics heat storages (selection)

	SHS	**LHS**
supply temperature	91 °C	88 °C
return temperature	65 °C	68 °C
useable volume	6500 m^3	48000 m^3
storage capacity	190 MWh	1081 MWh
max. loading performance	15 MW	34 MW

RESULTS

For simplification and mainly for reducing the computing time the optimization does not consider the whole examined time period May till September but is limited to so called mean week (MW) built by averaging time series by the week.

For better presentation of the planned operation of the large size heat storage in a weekly cycle the results are illustrated for 8 days (Monday to Monday) at which the time series of both Mondays are equal. Furthermore a real warm week (WW) and a real cold week (CW) in the time period May till September are examined. In both weeks the heat demand is lower or rather higher in comparison to the mean week. The time series courses of the warm and cold week highly fluctuate in comparison with the averaged values of the mean week.

The load management is determined for both the current generators configuration containing the CHP 1, CHP 2 as well as the small sized heat storage (notation: reference system – RS) and the planned extension containing both CHP plants, both heat storages, the solar thermal system as well as the heat pump (notation: extended system – ES) in each case for the mean, warm and cold week. Through the unit commitment it is possible to show differences in operating the generators and to estimate possible economic savings.

The optimizations results in form of heat balances courses for the mean week are illustrated in Fig. 2 for the reference system and in Fig. 3 for the extended system.

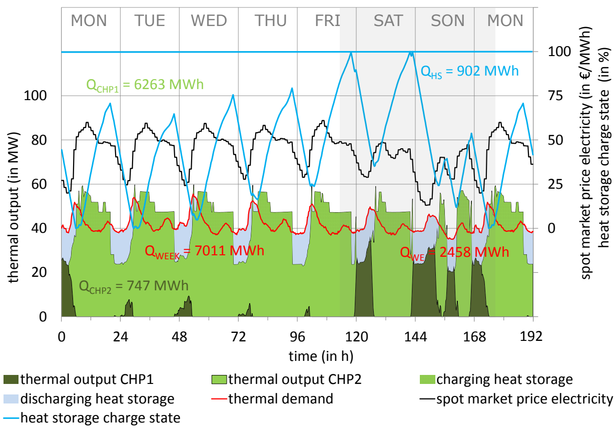

Fig. 2 Reference system – optimal unit commitment mean week (heat storage: only small sized heat storage)

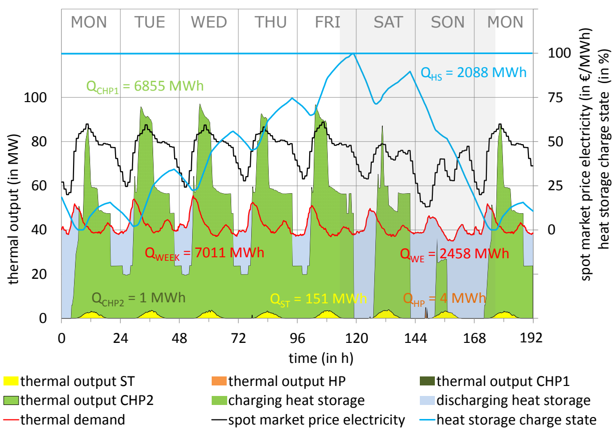

Fig. 3 Extended system – optimal unit commitment mean week (heat storage: sum of small and large sized heat storage)

The thermal outputs of the generators and heat storages (sum of thermal output of small and large sized heat storage) are illustrated in Fig. 2 and Fig. 3 as colored plot. Time period is 8 days that are 192 hours. The time period feasible to switch off the

CHP 1 is marked grey. The lime green plot marks the thermal output of the CHP 1 (= sum of thermal output of both blocks), the darker green plot the thermal output of the CHP 2. The yellow plot stands for thermal output of the solar thermal system, orange for the heat pump. The added thermal output of the whole mean week (without second Monday) is directly given as numerical value for every generator and both heat storages. The light blue plot marks the discharging of the small and large sized heat storage, the light green plot with black dots the charging. The total heat storage charge state is shown as blue line for every point in time. To illustrate the maximum heat storage state (100 %) a blue vertical drawn line is used. The red line marks the heat demand which has to be satisfied at all given time steps through operation of the generators or heat storages. The total heat demand of the mean week (without the second Monday) $\mathrm{Q_{WEEK}}$ = 7011 MWh and the total heat demand for the time period of planned switching off the CHP 1 from Friday 8 pm till Monday 8 am ($\mathrm{Q_{WE}}$ = 2458 MWh) are given also as numerical value. As last element of the heat balances the black line marks the course of the spot market prices for electricity.

Results reference system

It can be clearly seen in Fig. 2 that for the mean week of the reference system most heat supply of the district heating network is provided by the CHP 1. Thereby the thermal output of the CHP 1 ranges from $\mathrm{\dot{Q}_{CHP1,RS}}$ = 25 MW (one block operation) in times of low spot market prices for electricity in the mornings and evenings up to 50 MW, maximum 60 MW (two block operation) in times of high spot market prices for electricity during the day. The total thermal output of the CHP 1 adds up to $\mathrm{Q_{CHP1,RS}}$ = 6263 MWh. During the weekend the CHP 1 is switched off four times because the heat demand and the spot market prices for electricity are comparatively low. In these time periods the CHP 2 is switch on to ensure the heat supply. The same happens sometimes in times of thermal peak loads during the week. The added thermal output of the CHP 2 is $\mathrm{Q_{CHP2,RS}}$ = 747 MWh. The small sized heat storage is charged and discharged daily to smooth thermal peak loads and to ensure operation of the CHP 1 more often in times of high spot market prices for electricity. Thereby the maximum heat storage charge state is reached at Friday and Saturday night. That means possible savings by increasing the storage capacities are expected.

Results extended system

A changed optimal unit commitment of the extended system in comparison to the reference system can be stated in the heat balances in Fig. 3. The operation time of the CHP 1 with a total thermal output of $\mathrm{Q_{CHP1,ES}}$ = 6855 MWh is clearly increased. At the same time only $\mathrm{Q_{CHP2,ES}}$ = 1 MWh of heat are extracted from the CHP 2. So it is possible to draw the conclusion that the CHP 1 is economically more attractive mainly based on higher achievable average efficiencies in comparison to the CHP 2. The total efficiency of the CHP 1 increases from $\eta_{TOTAL,CHP1,RS}$ = 81 % in the reference system to 84 % in the extended system, the total efficiency of the CHP 2 from $\eta_{TOTAL,CHP2,RS}$ = 53 % to 57 %.

The amplitudes of the thermal output of the CHP 1 are much higher in the extended system in comparison to the reference system, i.e. the thermal output of the CHP 1 increases from $\mathrm{\dot{Q}_{CHP1,ES}}$ = 25 MW in the mornings and evenings up to circa 95 MW in times of higher spot market prices for electricity even if for only short time periods. In summery it can be stated that the CHP plants in the extended system are better operated accordingly to the spot market prices for electricity than in the reference system, i.e. in times of low/high spot market prices for electricity the thermal output of the CHP plants are lower/higher too. This economical operation of the CHP plants is possible because of the additional storage capacity in form of the large sized heat storage. So charging and discharging the heat storages does not happen daily like in the reference system rather both heat storages are charged successively during the week until Friday night the maximum charge state is reached. During the weekend both heat storages are discharged accordingly because of partly switching off the CHP 1. The planned full switching off the CHP 1 from Friday 8 pm till Monday 8 am is not possible because the capacity of small and large sized heat storage are too low to satisfy the whole heat demand during the weekend. Furthermore the spot market prices for electricity are partly high enough that switching off the CHP 1 with its comparatively high total efficiencies would not be economical necessary.

The heat pump with a thermal output of $\mathrm{Q_{HP,ES}}$ = 4 MWh is hardly operated because the CHP 1 already provides enough heat. In addition the realizable heat shift through cooling down the return flow of the small sized heat storage is not really necessary because there is already enough heat storage capacity. Above all the heat pump operation needs electricity so operating the heat pump is only useful in an economical way in times of very low spot market prices for electricity. The solar thermal system gives full possible thermal output of $\mathrm{Q_{ST,ES}}$ = 151 MWh.

The total operating proceeds from equation (1) rises so from $p_{TOTAL,RS}$ = 40 T€ in the reference system up to $p_{TOTAL,ES}$ = 56 T€ in the extended system, i.e. through new operation possibilities in form of the large sized heat storage, the solar thermal system and the heat pump the total operating proceeds rises at $\Delta p_{TOTAL,RS}$ =

16 T€ for the mean week. At this point please note again that the total operating proceeds only consists of the sum of the operating proceeds and costs because costs and proceeds for gas and electricity hedges as well as proceeds for heat sale in the district heating network are not considered. So no real total operating proceeds can be stated.

All results as the total operating proceeds p_{TOTAL}, the difference of the total operating proceeds related to the particular reference system $\Delta p_{TOTAL,RS}$ as well as the thermal output of all generators and both heat storages are listed in Table 3. It can be stated that for all examined weeks (mean, warm and cold) the thermal output of the CHP 1 increases in the extended system in comparison to the reference system, the thermal output of the CHP 2 decreases.

Table 3 Overview total operating proceeds p_{TOTAL}, difference of the total operating proceeds related to the particular reference system $\Delta p_{TOTAL,RS}$ as well as thermal outputs in the reference system (RS) and extended system (ES) for mean, warm and cold week

		mean week		**warm week**		**cold week**	
		RS	**ES**	**RS**	**ES**	**RS**	**ES**
p_{TOTAL}	**(in €)**	40	56	-18	10	73	93
$\Delta p_{TOTAL,RS}$	**(in €)**	16		28		20	
thermal output (in MWh)	**CHP1**	6263	6855	3957	4252	8181	8470
	CHP2	748	1	311	1	679	199
	HP	0	4	0	1	0	80
	ST	0	151	0	14	0	111

Comparable to the mean week the heat pump with a thermal output of $Q_{HP,WW,ES}$ = 1 MWh is used practically never in the warm week, the solar thermal with a thermal output of $Q_{ST,WW,ES}$ = 14 MWh quite seldom because the comparatively low heat demand of the warm week of $Q_{WEEK,WW}$ = 4268 MWh and the full operation of the solar thermal system would force the CHP 1 in part load with less efficiency so proceeds of electricity sold on spot market would decrease. Fuel savings does not compare this disadvantage completely even if the solar thermal system has a higher efficiency in the warm week because of higher solar radiation. In the cold week in contrast the solar thermal system with a thermal output of $Q_{ST,CW,ES}$ = 111 MWh is nearly used all along. The heat pump operation time increases noticeable with a thermal output of $Q_{HP,CW,ES}$ = 80 MWh caused by – in comparison to the mean week – clearly higher heat demand of $Q_{WEEK,CW}$ = 8860 MWh.

Altogether total operation proceeds for the warm week increases from $p_{TOTAL,RS,WW}$ = -18 T€[1] in the reference system up to $p_{TOTAL,ES,WW}$ = 10 T€ in the extended system as well as from $p_{TOTAL,RS,CW}$ = 73 T€ up to $p_{TOTAL,ES,CW}$ = 93 T€ for the cold week.

So the total operation proceeds of the warm week are lower than the proceeds of the mean week, the proceeds of the cold week are higher respectively. Reason is the lower/higher heat demand and so lower/higher proceeds of electricity sold on the spot market. Achievable total operating proceeds risings between the reference and extended system are with values of $\Delta p_{TOTAL,RS,WW}$ = 28 T€ for the warm week and $\Delta p_{TOTAL,RS,CW}$ = 20 T€ for the cold week higher than the $\Delta p_{TOTAL,RS,MW}$ = 16 T€ for the mean week because of higher volatility of the spot market price for electricity in comparison to the mean week. Intelligent shifting the CHP 1 operation leads to higher proceeds of electricity sold on the spot market. So the total operating proceeds of the mean week can be interpreted as lower limit.

Variation different parameters

Furthermore different parameters will be varied in the extend system and the optimal unit commitment will be stated for the mean week. The total operating proceeds and the difference of the total operating proceeds related to the particular reference system are listed in Table 4 for the reference, extended and different parameters variations of the extended system.

Total operating proceeds decrease to $p_{TOTAL,ES,I}$ = 55 T€ in the case no solar thermal system is used (scenario I: ST switched off). In comparison to the original extended system with solar thermal only 1 T€ can be saved. That means the solar thermal system influences the total operating proceeds only little because the solar thermal peak load of $\dot{Q}_{ST,PEAK}$ = 7 MW is very small if you compare it to thermal output of both CHP

[1] Total operation proceeds are not equal to real proceeds so negative total operation proceeds are not equivalent to diseconomies.

plants. Furthermore the output of the solar thermal system is not directly connected to increasing the total operating proceeds because the operation of the CHP plants would be partly replaced.

The solar thermal system benefits from relatively high CO_2-cerfiticate costs of 15 €/t. If the CO_2-cerfiticates would be free (scenario II: free CO_2-cerfiticates) total operating proceeds increases up to $p_{TOTAL,ES,II}$ = 141 T€. In this case the solar thermal system is no longer used because possible fuel savings are no longer additional rewarded. Similar conclusions can be obtained for CO_2-cerfiticate costs of 5 €/t stated at the moment in Germany.

Table 4 Total operating proceeds p_{TOTAL} and difference of the total operating proceeds related to the particular reference system $\Delta p_{TOTAL,RS}$ for the mean week

Total operating proceeds	**p_{TOTAL} (in T€)**	**$\Delta p_{TOTAL,RS}$ (in T€)**
reference system	40	0
extended system	56	16
I: ST switched off	55	15
II: free CO_2-cerfiticates	141	101
III: WP renewable energy	56	16
IV: 98 °C supply temperature	53	13
V: reduced prices for electricity	42	2
VI: minimizing CO_2-emissions	16	-24

The return line is used as heat source for the heat pump in the original extended system. The cooled water has to be reheated by the CHP 1 later. To increase the operation of the heat pump renewable energy (e.g. river or sewerage water) will be used as heat source in a further case (scenario III: WP renewable energy). Total operating proceeds remains at $p_{TOTAL,ES,III}$ = 56 T€ because of the small size of the heat pump of $\dot{Q}_{HP}$ = 5 MW (in relation to the CHP plants) and low thermal output of the heat pump of Q_{HP} = 31 MWh.

Increasing the CHP plants supply temperature (ST) from ϑ_{ST} = 91 °C up to 98 °C (scenario IV: 98 °C supply temperature) occurs higher temperature spread between supply and return line and so over 30 % higher capacities of both storages. The expected raise of the total operating proceeds through even more flexible operation of the CHP plants does not happen because higher supply temperatures cause decreasing overall efficiency of the CHP plants too. Altogether total operating proceeds decrease in comparison to the original extended system to $p_{TOTAL,ES,IV}$ = 53 T€.

Variations of the spot market prices for gas and electricity can effect huge changings in the unit commitment and achievable total operating proceeds. The optimization calculations are stated exemplarily for reducing the spot market prices for electricity down to 66 % of the original value (scenario V: reduced prices for electricity). The total operating proceeds decrease in comparison to the original extended system down to $p_{TOTAL,ES,V}$ = 42 T€ because electricity proceeds strongly decreases when low prices occur. This effects decreasing operation of the CHP 1. At the same time the heat pump operation increases up to Q_{HP} = 146 MWh. The CHP 2 is switched off all the time.

As last variation a new optimization objective function is used. The total operating proceeds maximization is replaced through total CO_2-emissions minimization (scenario VI: minimizing CO_2-emissions). In this case the total operating proceeds decreases down to $p_{TOTAL,ES,VI}$ = 16 T€ because operating the CHP plants is no longer relayed to spot market price for electricity but both CHP plants are operated equally with high overall efficiency. Interestingly neither the solar thermal system nor the heat pump is used because their operation would partly replace the CHP plants operation and so less electricity in the public grid would be substituted. Electricity substituted out of the grid comes according to the merit order curve from plants with less overall efficiency and so from plants with high CO_2-emissions. Both CHP plants have high overall efficiency and so in the global scheme of things CO_2-emissions can be saved.

CONCLUSIONS

In summary it can be stated that the system extension in form of the large sized heat storage, the solar thermal system and the heat pump has a positive influence on the unit commitment and the total operating proceeds. With the help of the extended system the CHP plants operation can be better adopted to the spot market prices for electricity mainly caused by gained flexibility through the large sized heat storage. Operation of the heat pump and the solar thermal system cause only a significant raise of the total operating proceeds when spot market prices for electricity are very low or costs for CO_2-cerfiticates are very high.

ACKNOWLEDGEMENT

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FIBER-OPTIC DISTRIBUTED TEMPERATURE SENSING OF LARGE HOT WATER STORAGE TANKS

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ABSTRACT

With fiber-optic distributed temperature sensing (DTS) it is possible to read some ten thousands measurement values along a several kilometers long fiberglass cable within few seconds. This paper presents a novel concept of utilizing the DTS technology in large hot water storage tanks. This new technology allows obtaining space and time resolved information about the temperature distribution inside the storage. Hence this technology opens a completely new option to gain detailed measurement data for empirical modeling of large hot water heat storages.

After detailed tests of the DTS measurement principle performed under laboratory conditions, a system was successfully installed inside a 43,000 m^3 heat storage tank in summer 2013. Based on this first large field implementation the applicability of DTS in large hot water storage tanks could be proven.

The evaluation of the first data confirms the expected behavior of the investigated type of heat storage regarding the stratification and its symmetry.

Fluid entering the storage as a free flow might have a big impact on the stratification. To better understand the stability limits of the free flow in a thermal stratified setting a concept for an extended arrangement of fiberglass cable is currently being implemented.

INTRODUCTION

Large hot water storage tanks offer a technically approved and cost efficient way to store energy at the temperature level of district heating systems.

A common and widely realized type is the storage tank design of HEDBÄCK. Hot water storage tanks of this design are built as pressure-less standing cylinders with one radial nozzle at the bottom and one at the top of the storage volume. During the charge process, hot water is entering the tank through the top nozzle and cold water is leaving through the bottom nozzle. While discharging the hot water storage tank, the flow is directed reversely. As both radial nozzles are concentric with the cylindrical storage tank, they induce a free rotationally symmetric flow in the storage tank. In most cases of application the charging and discharging temperature are well defined so that one zone of high temperature is stratified above one zone of low temperature, with a mixed layer in between (see Fig. 1). The storage tank design of HEDBÄCK is optimized for capacities of up to several 10,000 m^3 of water with a realized maximum height of 70 m and maximum diameter of 42 m. More than 100 of these storages have been build during the past decades. Recent projects are located in Mannheim (DE), Vimmerby (SE) and Nürnberg (DE).

The grade of stratification inside the storage tank limits the amount of heat which can be discharged from the storage at the required supply temperature level. Therefore a good understanding of the main factors that have an impact on the stratification is important for both: to give advice to the operation management and to generate valid models of this type of heat storage tank.

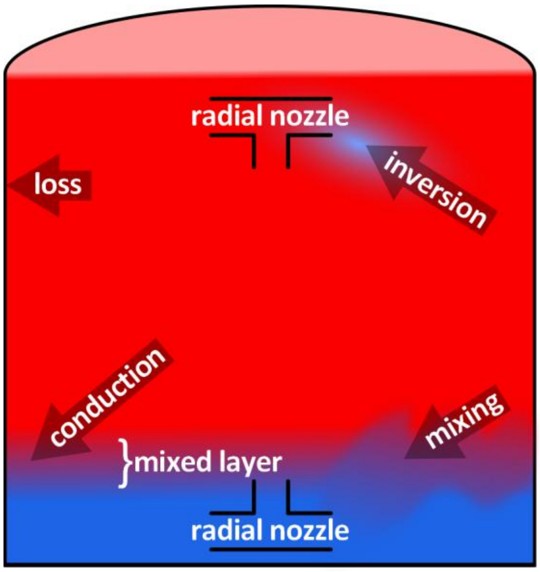

Fig. 1 Main impact factors on stratification in a hot water heat storage tank (e.g. storage tank design of HEDBÄCK).

The main impact factors on the grade of stratification are shown in Fig. 1. These are

- "Mixing" of fluid from the hot and the cold zone due to the flow induced by the upper or lower radial nozzle
- "Conduction" which denotes the diffusive heat flow from the hot zone to the cold zone through the mixed layer
- Convection induced by "inversion" which occurs when the fluid that streams into the storage tank is colder than the surrounding fluid

(upper radial nozzle) or warmer than the surrounding fluid (lower radial nozzle)

- “Heat loss” over the surface of the storage tank which causes a vertically falling liquid film of colder fluid on the inner walls of the tank

To develop a valid simplified simulation model of hot water heat storage tanks following the design of HEDBÄCK it is crucial to understand these impact factors by analyzing measurement data of the temperature distribution inside the storage tank.

STATE OF THE ART

At the present time there are no detailed, spatially resolved measurement data for large hot water storage tanks of the type according to the design of HEDBÄCK available. For operation control, these storage tanks are standard equipped with PT100 temperature sensors, which are arranged in a regular spacing over the storage height. Since by default, only one sensor chain with a distance of typically about two meters between the PT100 measuring points is present, there is not sufficient data obtained for a reliable modeling.

The literature ([1],[2]) describes mainly simulation approaches for heat storage tanks, which are used on the scale level of individual buildings and thus are significantly smaller. These approaches cannot be applied to the described large hot water tanks due to lack of hydraulic and thermal similarity. With the work of Varghese [3] there is a study for a large seasonal heat storage tank. This storage tank, however, differs in its design and operation mode strongly of the heat storage tanks under consideration. Therefore a direct transfer of the results is not possible. According to the described lack of sufficiently resolved measurement data, validated modeling approaches for heat storage tanks of the HEDBÄCK type are not known from the literature.

The measurement of large transient temperature fields plays a role in many fields of research where it is partly achieved through the use of fiber-optic DTS. For example, in [4], the temperature distribution in air-conditioned subway cars is analyzed by the DTS measurement technique and in [5], the temperature field of atmospheric surface-layer flow is detected multidimensional. The use of fiber-optic DTS in an aquatic environment is described for the one-dimensional determination of the temperature profile of hydrologic systems in [6].

Within this research project, this measurement technique is tested for the first time to detect the temperature field in a large hot water storage tank.

METHODS

Measurement technology

Fiber-optic DTS was introduced to the market in the 1980s, thus it is a relatively young technology which allows a space-resolved measurement of temperature along a fiberglass cable. The measurement principle is based on the Raman-effect that describes a temperature depending inelastic backscattering of light. Due to the Raman-effect a very small share of photons launched to a fiberglass cable by a laser pulse is backscattered shifted to lower frequency (Stokes Raman scattering) and another small share is backscattered shifted to higher frequency (Anti-Stokes Raman scattering), see Fig. 2. The ratio of Stokes-signal compared to Anti-Stokes-signal thereby depends on the temperature of the fiber. In order to evaluate this temperature information the backscattered light is detected at the beginning of the fiber resolved to Stokes and Anti-Stokes signal and to its origin along the fiber.

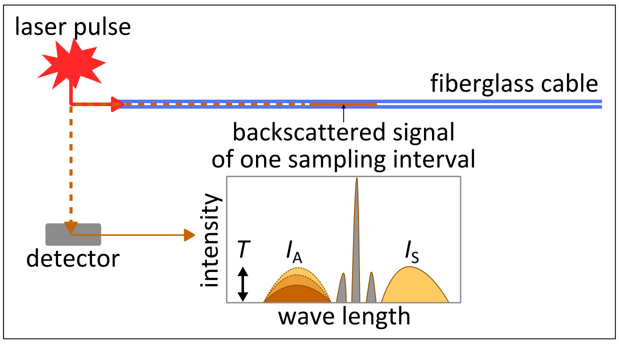

Fig. 2 Scheme of the fiber-optic DTS. T denotes the temperature, I_A the intensity of the Anti-Stokes signal and I_S the intensity of the Stokes signal.

By resolving the backscattered signal to its origin along the fiber, the DTS unit creates a chain of measurement values along the fiber. Each value represents the average temperature of a short section of cable. To assign each of these measurement sections to a precise spatial position along the cable, the DTS unit applied in this research project utilizes optical time domain reflectometry.

The intensity of the backscattered Stokes- and Anti-Stokes-signal underlies a statistical noise. This noise causes a significant random error to a single measurement which limits the temperature resolution. The random error can be reduced by repeating the measurement over a period of sufficiently constant conditions and then averaging these measurement values. As the noise is normally distributed the random error decreases by a factor which corresponds to the square root of the number of repeated measurements included in the average value. To reduce the random error, DTS measurement units usually perform several thousand single measurements every second. In terms of the measurement inside the large hot water heat storage, a period of 10 s is regarded to generally guarantee sufficiently constant conditions for the averaging. In addition to the averaging time, the random error and thus the temperature resolution depends on the distance between the measured cable section and the DTS unit as well as on the size of the sampling interval. Sampling interval means the spatial distance between two measurement values recorded by the DTS unit along the cable. Within this project an “Ultima-S” manufactured by Silixa Ltd. (UK) is used. At a cable length of 500 m and the finest sampling interval possible of 0.126 m the data sheet of the Ultima-S gives a temperature resolution of 0.24 K for a 10 s averaging and 0.1 K for a 60 s averaging. The temperature resolution is defined as the 1-σ standard deviation of the measurement values and corresponds to investigations in [7].

Besides the random error the overall error includes a systematic error. The systematic error cannot be reduced by extending the averaging time but by calibration methods. However, after calibration a systematic residual error remains. This systematic error does not significantly influence the temperature resolution on short cable ranges (up to some 10th of meters) but, as it is not necessarily constant all over the cable, it might limit the resolution on long cable ranges. The systematic error can be reduced by calibration to ±0.5 K.

The spatial resolution of the DTS measurement system does not only rely on the sampling interval but also on the length of the laser pulse sent to the fiber as well as on further effects caused by signal dispersion and signal processing. According to the data sheet, the spatial resolution of the Ultima-S is 0.3 m. This value is based on the fact that the temperature range from 10 % to 90 % of a sharp temperature step is detected as a 0.3 m long section. Due to the effects shown in Fig. 1 no sharp steps can occur in the temperature field of a hot water storage tank. The steepest gradients of the temperature distribution are to be expected in the area of the mixed layer. Extensive investigations in [7] evidence that the DTS system is capable to observe a mixed layer with a magnitude of 1 m (as defined in Fig. 6) with no remarkable deviation between measured data of the DTS system and reference measurement data. During the experiment in [7] the fiberglass cable was arranged as a straight vertical line through the mixed layer, though it went along the steepest gradient of the temperature field. The rough size of mixed layers of heat storages designed by HEDBÄCK was reconstructed from data of the standard PT100 sensor equipment of existing storages. These results do not show mixed layers considerably thinner than 1 m. This fact corresponds to what should be expected due to the influence of heat conduction and mixing caused by the free flow out of the radial nozzle. That means that the DTS system employed in this research project is capable to detect the magnitude of the mixed layer correctly without need for a special arrangement of the fiberglass cable other than a straight vertically arrangement.

Measurement setup

The measurement setup put into realization at the current state of the project is shown in Figures 3 and 4. With a storage capacity of 43,000 m^3, a height of 36 m and a diameter of 40 m, the investigated heat storage is one of the largest facilities of its kind.

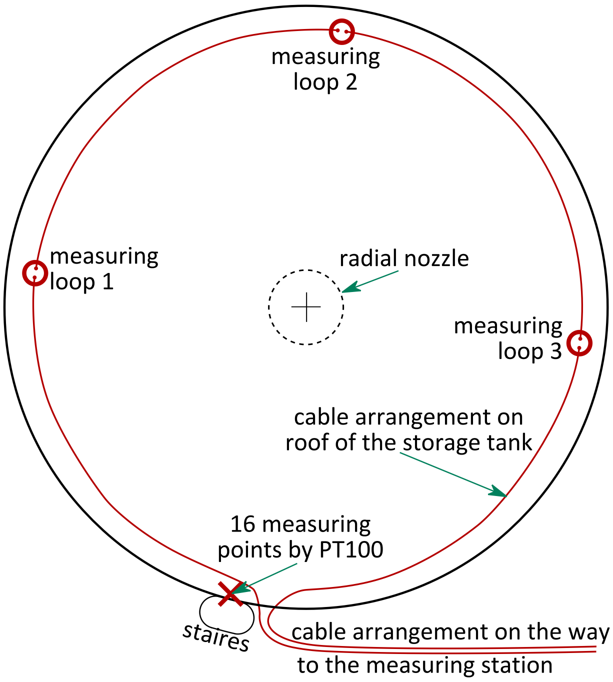

Fig. 3 Top view (not to scale): Arrangement of the fiberglass cable with the position of the three vertical measuring loops

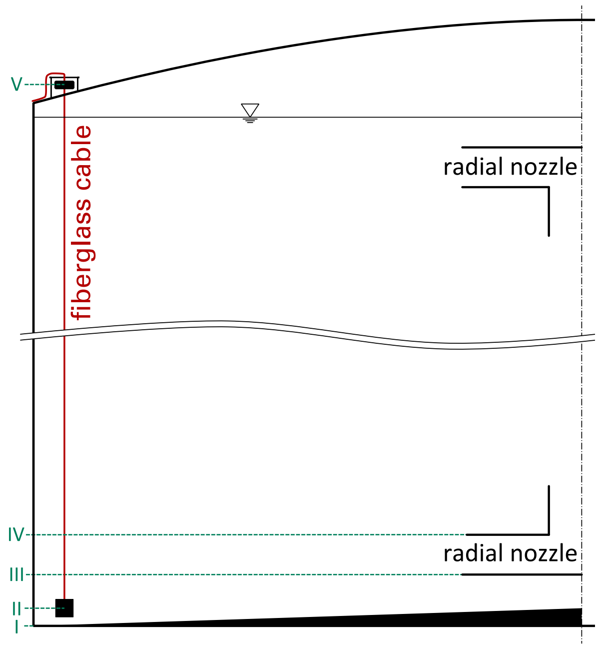

Fig. 4 Side view (not to scale): Arrangement of a vertical loop of fiberglass cable inside the storage tank.
Significant positions (height over storage tank bottom):
I Storage tank bottom (0.0 m)
II Weight to ensure vertical course of the cable (0.2 m)
III Lower edge of the lower radial nozzle (0.7 m)
IV Upper edge of the lower radial nozzle (1.2 m)
V Cable holder inside the safety flap (36.95 m)

Approximately 550 m of cable has been used in order to achieve a measurement set-up capable to detect the vertical temperature profile at three positions of the heat storage tank. At each measurement position the cable enters the storage tank through a safety flap and is fixed by a holder (position V in Fig. 4) inside the safety flap. Coming out of the holder, the cable runs vertically downwards through the tank. The vertical course is ensured by a weight which is clamped to the cable at 0.2 m above the storage floor (position II in Fig. 4). Behind the weight the cable takes a u-turn, is clamped again by the weight and then runs straight up to the holder in the safety flap. From there, it leaves the inner region of the heat storage tank again through the safety flap and runs to the next measuring loop. According to this structure, each measuring loop consists of two parallel, vertical measurement sections. Both ends of the cable are routed from the roof of the storage tank to a measuring station in a fixed building. The DTS measurement is designed as a medium-term measurement. Data is recorded in a 10 s raster over a total period of many months.

As a part of its calibration method the fiber-optic temperature measurement requires an offset correction to adjust the measurement to the Kelvin scale. This step reduces the systematic error mentioned above. In the presented measurement setup, the reference values for this correction are provided by 16 PT100 temperature sensors that belong to the standard equipment of the storage tank (Fig. 3). These PT100 temperature sensors detect the storage temperature at regular intervals over the storage height. The offset correction is carried out separately for each measuring loop. For each measuring loop only a single value is calculated for offset correction. The correction value is defined as the difference between the temperature average measured by the PT100 sensors and by the DTS system. This implies that the offset correction value is constant over the storage tank height within each measuring loop. Therefore the calibration only shifts the absolute value but does not influence the shape of the measured vertical temperature profile.

RESULTS AND DISCUSSION

Data basis

The results presented in the following section are based on measurements by fiber-optic DTS system in the period from 14-05-24 to 14-05-25. During this measurement time, the maximum flow rate at the radial nozzles of the storage tank was 1500 m^3/h. A horizontally positioned zone in the storage, such as the mixed layer, is shifted vertically 2 cm/minute by this maximum volume flow. The temporal averaging to suppress the statistical noise of the DTS system smears the recording of transient temperature distributions. This effect increases the longer the averaging period lasts. The main focus of this work is to study the development of the mixed layer. To detect the mixed layer correctly, it has to be ensured that the movement of the mixed layer during the averaging time is small compared to the thickness of the mixed layer itself. As stated above no mixed layer widths of considerably less than 1 m are expected. Therefore, always 6 consecutive 10 s-average recordings of the DTS unit are combined to a one-minute average value. This reduces the statistical noise compared to the 10 s-average recordings and is still considered to be sufficiently small (maximum displacement of the mixed layer is 2 cm within this period) for all following analysis.

Fiber-optic DTS versus PT100 temperature sensors

Fig. 5 shows the temperature distribution over the heat storage height determined by the fiber-optic temperature measuring compared to the values measured by the 16 PT100 temperature sensors. The mean of both measurements is identical, which is a direct consequence of the offset correction method described above. However, a pronounced correlation between the two measurement methods can be stated at each individual measuring point as well. The maximum deviation is 0.4 K at 6.7 m above the storage floor. In the upper storage tank area, the temperature readings of the PT100 sensors do not increase strictly monotone with the storage height. This contradicts the natural density stratification, especially since the measurement was carried out during a resting phase of the heat storage. Therefore these fluctuations of the PT100 data can be led back to a measurement uncertainty. The coincidence results between the two measurement methods at every position allow concluding that the fiber-optic DTS system is able to resolve the temperature distribution in the storage.

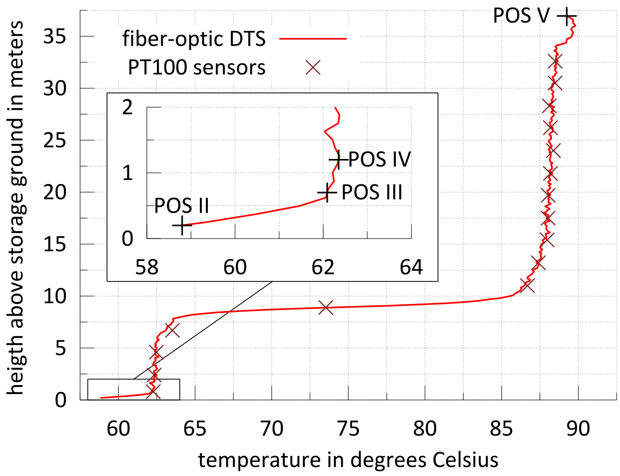

Fig. 5 Temperature profile over storage tank height at measuring loop 1, time: 14-05-25 - 15:00. Comparison between fiber-optic DTS data and 16 PT100 temperature sensors. Positions II – V according to Fig. 4.

Determination of the mixed layer size

The size of the mixed layer is determined, as shown in Fig. 6, by means of the 10 % - 90 %-method. For this purpose, an upper reference temperature T_u (the temperature of the hot storage zone) and a lower reference temperature T_l (temperature of the cold storage zone) are defined. The size of the mixed layer then is the vertical distance, for which the temperature T at the position h above the storage ground satisfies the following condition

$$[T_\mathrm{l} + 0.1(T_\mathrm{u} - T_\mathrm{l})] \leq T(h) \leq [T_\mathrm{l} + 0.9(T_\mathrm{u} - T_\mathrm{l})] \qquad (1)$$

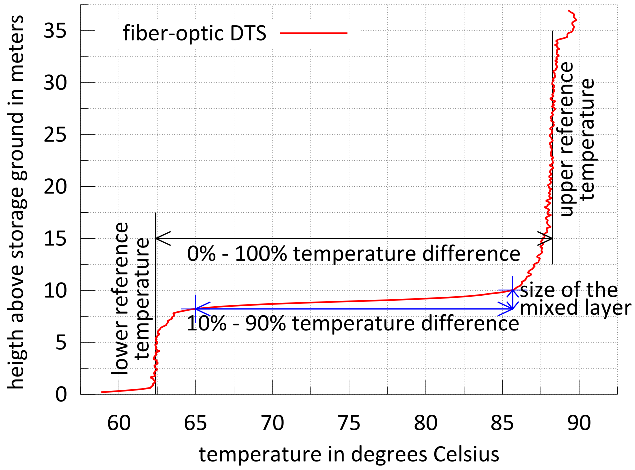

Fig. 6 The 10 % - 90 %-method to determine the size of the mixed layer; measuring loop 1, time 14-05-25 - 15:00

Temporal development of the mixed layer

Applied to the measurement data of two days, the 10 % - 90 %-method gives the time dependent development of the mixed layer thickness shown in Fig. 7-III. Within the first 6 hours the course is at a slight upward trend in the range of 1.4 m. On 14-05-24 around 06:00, a significant increase in thickness to 1.7 m takes place. Afterwards the mixed layer grows until the end of the period slowly but fairly steadily to a thickness of about 1.8 m.

To analyze the development of the mixed layer, the general heat storage state (Figures 7-I and -II) and the mode of operation (Fig. 7-IV) are shown additionally. At the beginning of the investigation the heat storage is fully charged. Beginning from 06:00 on the first day the heat storage starts to be partially discharged. In the following period, interrupted by intervals of rest, it is discharged further and re-charged, subsequently (see the profile of volume flow at the radial nozzle in Fig. 7-IV). The charging level is transmitted directly in Fig. 7-I as a 2D plot with color-coded temperature. The lower cold zone and the upper hot zone, with a narrow mixed layer between both, are well defined during the entire period. Even for the fully charged state at the beginning, a layer of cold water can be found in the lowermost area of the storage tank, since the bottom radial nozzle is located slightly above the storage tank floor. The color plot shows in a good approximation a linearly increasing cold zone during the first discharge (14-05-24 - 06:00). This corresponds to the almost constant discharge flow rate and the fairly constant inlet temperature (Fig. 7-IV). During the following period there is, as well, always a plausible connection between the mode of operation of the heat storage shown in Fig. 7-IV and the temperature profile shown in Fig. 7-I.

A more detailed analysis is possible by the temperature profiles over the storage height, which are plotted in Fig. 7-II-a and II-b in 6-hour intervals. The slightly falling inlet temperature at the lower radial nozzle (Fig. 7-IV, blue curve on the y2-axis) during the first discharge is reflected by the temperature profile of the lower zone. The graph at 15:00 in Fig. 7-II-a shows a stratified temperature profile in the region of the cold zone up to 7.5 m above the storage ground. The temperature interval of this stratification corresponds with the degree, to which the temperature at the lower radial nozzle has fallen. During the second period of discharge (begin: 14-05-24 - 18:00) the temperature at the lower radial nozzle increases slightly over time. This creates an inversion inside the pre-existing density profile of the cold zone. Out of this inversion results a mixing within the cold zone. This mixing dissolves the former density stratification, but only up to the storage height, at which the temperature previously was below the maximum inlet temperature of the lower radial nozzle (63 °C at 21:00). Hence the pre-existing stratification of the cold zone from 15:00 maintains above about 7.5 m, as visible in the temperature profile at 21:00 in Fig. 7-II-a.

The actual mixed layer between the cold and the hot zone is not penetrated at any time, neither by cold water entering at the lower radial nozzle, nor by warm water entering at the upper radial nozzle during the charging process on the second day. The sudden increase of the mixed layer width at the first day at 06:00 solely results from the fact that the heat storage was previously charged to the limit. Therefore, the lower part of the mixed layer had already been removed from the storage tank. By the discharge process starting at 06:00 the typical profile of the mixed layer is recreated.

The further increase of the mixed layer partly results from the heat conduction between the hot and cold zone and can therefore be observed even at the heat storage's rest phases. Secondly, a slightly accelerated increase of the mixed layer width is apparent on the second day during the charging process of the heat storage. The transition to the mixed layer from the hot zone is shallower than to the cold zone (in particular noticeable on the second day in Fig. 7-II-b). The water entering the storage at the upper radial nozzle induces a flow in the hot zone, which may contribute to the flattening of the profile of the upper half of the mixed layer. On the cold side of the mixed layer, the temperature profile and therefore the density gradient is steeper. This creates, at this position, a more effective barrier against a mixing effect that might be caused by the flow of the lower radial nozzle.

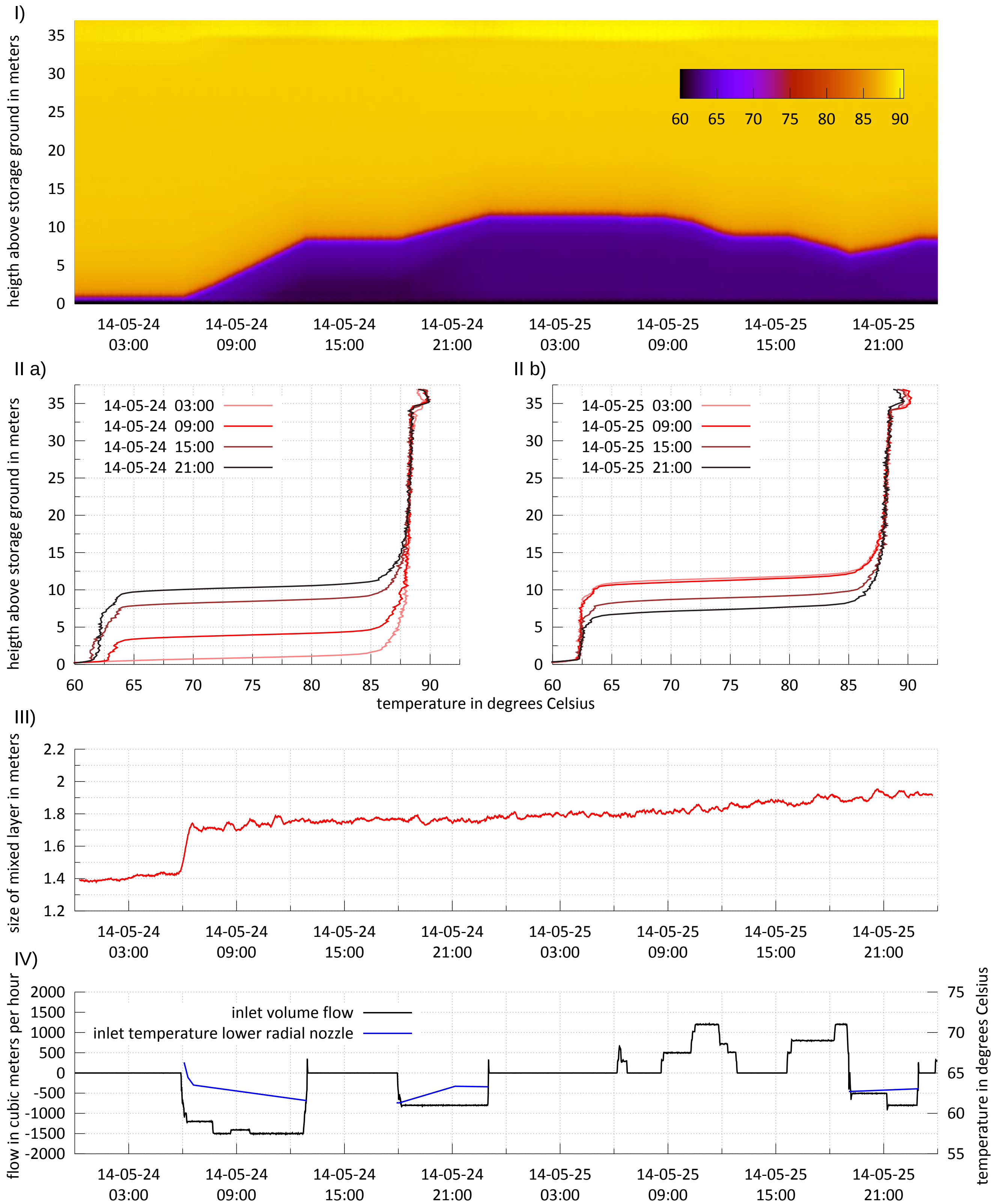

Fig. 7 State of the heat storage tank during the 2 days of measurement from 14-05-24 - 00:00 to 14-05-25 - 24:00 at measuring loop 1

I) Color-coded temperature distribution over the storage tank height.
II) Temperature profile over the storage tank height at particular times. Distance in time between each plot: 6 hours.
III) Development of the mixed layer size determined by the 10 % - 90 %-method and shown as a running average over 30 one-minute-values.
IV) Inlet volume flow: Negative values = discharging (inlet flow at the lower radial nozzle); positive values = charging of the heat storage (inlet flow at the upper radial nozzle). The temperature of the fluid which enters the storage tank at the lower radial nozzle is given by the blue inlet temperature graph.

Symmetry of the vertical temperature distribution in the circumferential direction

Being of rotationally symmetric shape, the heat storage tank is expected to comprise a rotationally symmetric temperature field. The degree of symmetry is examined with the help of the three measuring loops distributed around the circumference of the storage. As can be seen in Fig. 8, the three measuring loops show (nearly) congruent temperature profiles to the illustrated time (14-05-24 - 09:00) during a storage discharge with 1500 m^3/h. At the left part of Fig. 8 a closer view of the temperature difference between each pair of measuring loops ΔT_{i-j} is plotted on the x2-axis.

$$\Delta T_{i-j}(t,h) = T_i(t,h) - T_j(t,h) \quad (2)$$

Here T_i and T_j denote the temperatures of measuring loop i and measuring loop j, t is the time and h is again the height above the storage ground.

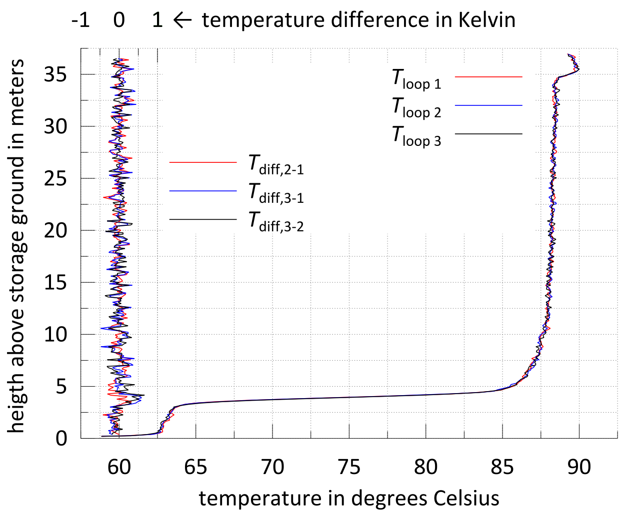

Fig. 8 Temperature profile over storage tank height at the three measuring loops. Left side of the graph: temperature difference between each pair of measuring loops with the scale on x2-axis. Time: 14-05-24 - 09:00.

As Fig. 8 shows, the size of the temperature difference remains within a single area over the entire storage height, except for the region of the mixed layer. However, due to the steep temperature gradient in this region the smallest inaccurateness in the vertical position assignment of the measuring loops causes a significant additional systematic error. The average value of the temperature differences over the height of the storage is zero. This results from the calibration method where the 16 PT100 temperature sensors were used as unified reference values to calibrate each of the three measuring loops.

To analyze the graphs on the left side of Fig. 8, which seem to be quite noisy, it is necessary to take the statistical noise into account caused by the DTS system. The statistical noise of the temperature measurement values is transmitted to the temperature differences calculated in (2). The errors caused by statistical noise are normally distributed and are not correlated over different measurement points. Thus the impact of statistical noise on ΔT_{i-j} can by described by the standard deviation of the measurement data. The standard deviation increases with increasing distance along the fiber and is therefore separately referred to as $\sigma_{T_{\mathrm{MS},i}}$ for each individual measuring loop i. The share of the temperature difference ΔT_{i-j} which is merely caused by the statistical noise of the measurement system, then can be evaluated by

$$\sigma_{\Delta T_{\mathrm{MS},i-j}} = \sqrt{\sigma^2_{T_{\mathrm{MS},i}} + \sigma^2_{T_{\mathrm{MS},j}}} \quad . \quad (3)$$

All measured values of the two observed days were analyzed. It is found that the temperature differences ΔT_{i-j} are almost normally distributed (Fig. 9). These temperature differences show a standard deviation $\sigma_{\Delta T_{i-j}}$ that is only 9 % ($\sigma_{\Delta T_{2-1}}$) to 30 % ($\sigma_{\Delta T_{3-1}}$) higher than the standard deviation which is expected according to (3) solely due to the statistical noise of the measurement system. Outside the mixed layer the standard deviation of the temperature differences is only 4 % ($\sigma_{\Delta T_{2-1}}$) to 10 % ($\sigma_{\Delta T_{3-1}}$) higher than the values given by (3). Temperature irregularities in the circumferential direction of the heat storage tank which are significantly larger than the standard deviation of the temperature measurement, would leave a clear trace in $\sigma_{\Delta T_{i-j}}$. The values of $\sigma_{\Delta T_{i-j}}$ would have to exceed the value of $\sigma_{\Delta T_{\mathrm{MS},i-j}}$ noticeably. However, particularly outside the mixed layer, this is not the case.

Very rare but relevant events of irregularities in the circumferential direction might not be recognized by the value of $\sigma_{\Delta T_{i-j}}$ due to the large number of data. But they would have to cause at least temporary and locally large values of ΔT_{i-j}. Outside the mixed layer the maximum value of ΔT_{i-j} is 0.83 K within the entire measurement period. This value must be set in relation to the impact of the statistical noise described above. More than 2.4 million measurement values were analyzed by (2) for this period of two days. Due to the normal distribution of the statistical noise at least once a value ΔT_{i-j} of 0.65 K (five times the standard deviation $\sigma_{\Delta T_{\mathrm{MS},i-j}}$) is to be expected within the period simply as a result of the random error of the DTS-unit. Thus the observed temperature difference of 0.83 K is close to the statistical noise of the measurement system and therefore does not indicate a significant asymmetry in the circumferential direction. Within the mixed layer, the maximum value of temperature difference ΔT_{i-j} found is 1.50 K. This is just 0.7 K higher than outside of the mixed layer. For the investigated storage conditions, 0.7 K correspond to a vertical change in position within the mixed layer of only 4.5 cm. Thus even small positioning inaccuracies of the measuring loops might cause this deviation at least partly. Temperature differences of 1.50 K between two measuring loops inside the mixed layer therefore can be explained without the existence of a significant asymmetry in the circumferential direction as well.

In Fig. 9, the relative frequency of ΔT_{3-1} based on a class width of $\sigma_{\Delta T_{\mathrm{MS},3-1}}$ is shown in comparison to the normal distribution with a standard deviation of $\sigma_{\Delta T_{\mathrm{MS},3-1}}$. The mean of ΔT_{3-1} is zero due to the calibration of all measuring loops to the same PT100-reference values as described above. It is obvious that the temperature differences between the two regarded measuring loops are close to the range given by the statistical noise of the measurement system (blue curve in Fig. 9). Furthermore Fig. 9 proves that ΔT_{i-j} from (2) is almost normally distributed.

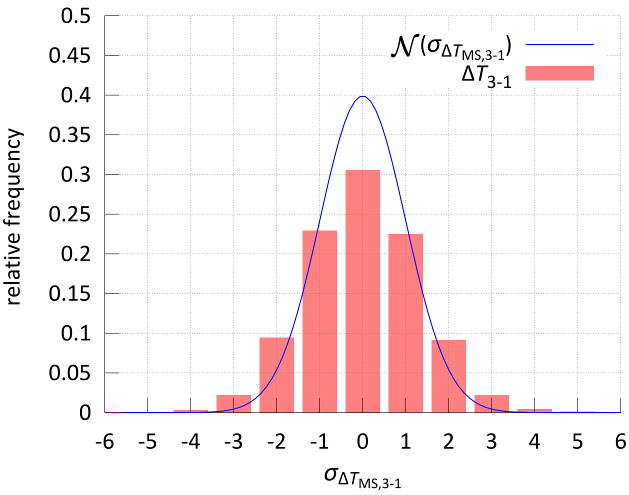

Fig. 9 Relative frequency of ΔT_{3-1} (based on a class width of $\sigma_{\Delta T_{\mathrm{MS},3-1}}$) compared to the normal distribution with a standard deviation of $\sigma_{\Delta T_{\mathrm{MS},3-1}}$.

For the reason that both, the variation of ΔT_{i-j} and the maximum values of ΔT_{i-j} does not exceed the range that is to be expected due to the statistical noise of the measurement system and small positioning inaccuracies of the measuring loops, a circumferential symmetry in the heat storage tank can be assumed for the period under consideration.

OUTLOOK

A second measurement setup is under construction in a newly built thermal storage (system HEDBÄCK) in Vimmerby (SE) to be completed in summer 2014. This setup has measuring loops at different radii of the tank to enable a more accurate observation of the mixed layer developing along the radius of the heat storage.

CONCLUSIONS

The suitability of fiber-optic DTS in conjunction with the selected setup is demonstrated for the investigation of the temperature field of large hot water storage tanks. The time stability of the measurement setup proven up to now is not least a step on the way to establish fiber-optic DTS as a standard tool to provide the monitoring of large hot water heat storages.

ACKNOWLEDGEMENT

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UTILIZING BUILDINGS AS SHORT-TERM THERMAL ENERGY STORAGE

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ABSTRACT

Heat demand in a district heating system can exhibit significant variation within one day, which sets problematic conditions for efficient heat generation. Short-term thermal energy storage can decrease this daily variation and make the conditions for generating heat more favourable. By periodically overheating and under-heating buildings, causing small variations in the indoor temperature, their thermal inertia can be utilized as short-term thermal energy storage. This study presents the results from a pilot test where the potential to function as short-term thermal energy storage was tested in five multifamily residential buildings in Gothenburg, Sweden. These results are then up-scaled to study the consequences for a whole-district heating system from a large-scale implementation. The signal from the outdoor temperature sensors in the test buildings were adjusted in different cycles over a total of 52 weeks. The delivered heat and indoor temperature were measured during the test. The results show that heavy buildings with a structural core of concrete can tolerate relatively large variations in heat delivery while still maintaining a good indoor climate. Storing 0.1 $kWh/m^2_{floor\ area}$ of heat will very rarely cause variations in indoor temperature greater than ±0.5°C in a heavy building. Utilizing about 500 substations for short-term thermal energy storage in large residential buildings would provide capacity for storing heat equivalent to that of a hot water storage tank with a volume of 14,200 m^3 for the city of Gothenburg. This would decrease the daily variations in heat load by 50%, reduce the need for peak heat generation, and reduce the number of starts and stops of heat-generation units.

INTRODUCTION

The heat generation in district heating (DH) systems is mainly demand driven. When customers increase their heat consumption, the heat supplier must increase the heat generation or the temperatures in the distribution network will drop. The heat demand can exhibit significant variation within short periods and, hence, heat generation, causing many starts and stops of heat sources. This gives the heat supplier limited freedom to control the heat generation. These conditions can drastically reduce the ability to plan and control heat generation, hence reducing efficiency. With a larger variation in heat load comes a larger need for peak heat generation, which often runs on fossil fuels with large operational costs and high environmental impact. Short-term thermal energy storage (TES) can decouple heat demand and heat generation in district heating systems and have many positive effects, such as the following:

- Reduced load variation
- Better fuel economy
- Fewer starts and stops in heat generation
- Increased security of supply
- Less need to invest in peak load heat generation
- Operate combined heat and power plants (CHP) according to electrical price
- Operate heat pumps and direct electrical heaters in DH systems according to electrical price

As presented in [1], there are mainly four different strategies for short-term TES in district heating systems: hot water storage tanks; phase change materials (PCM); varying temperature in the DH network; and utilizing building thermal inertia. This study has focused on utilizing building thermal inertia for short-term TES in district heating systems. Such strategies are commonly included in the term “demand side management” (DSM).

The purpose of this study is to evaluate the potential for load shifting in a large-scale implementation of buildings as short-term TES in a DH system. “Short term” can, in this case, be defined as normally a few hours, but a period of up to a few days is also possible. A few studies known to the authors have treated this subject, but this is the first study to base a full-scale simulation on the actual behavior of buildings in a pilot test. Earlier work has either assumed the full-scale effects [2], focused on nighttime setback [3] or on energy-saving potential [4]. The energy-saving potential in buildings utilized as short-term TES probably comes from a reduction of excessive temperatures due to the implementation of indoor temperature measurements for control of the building heating system. This study is also the first study known to the authors to make a comparison of utilizing building thermal inertia and hot water storage tanks for short-term TES purposes.

The study can be divided into mainly two parts. The first part focuses on determining the potential for short-term TES in individual buildings. A pilot test has been carried out to determine what quantities of thermal energy can be stored and how the indoor climate is affected. A more in-depth study of this pilot test can be found in [1]. The second part scales the results from the first part and studies how an overall DH system could benefit from utilizing buildings as short-term TES.

STATE OF THE ART

For the purposes of this study, it is most relevant to study residential buildings with a large thermal mass, e.g. concrete structures, that are heated by radiator systems connected to DH. The reasons are that such buildings are common in many large DH systems and that they are well suited for utilization as short-term TES. A large thermal mass has been shown to increase a building's suitability as short-term TES in [1, 5]. Buildings with radiator heating systems are better suited for short-term TES than buildings with airborne heating systems, according to [6].

The most common way of describing how the indoor temperature is affected by an increase or decrease in the heat delivered is to assume a correlation based on a time constant. It was shown in [1] that this measure does not reflect reality in an accurate way. It is, however, true that the indoor temperature in a building with a higher measured time constant will be less affected then in a building with a lower measured time constant for the same relative change in delivered heat. The progression of the indoor temperature in such a model is, however, inaccurate and may lead to over-usage or under-usage of a building's capacity for storing heat if implemented in the control method.

Earlier pilot tests

Utilizing building thermal inertia as short-term TES in a district heating system is not a new concept. The oldest pilot test known to the authors is from 1982 [7]. The main aim of this test was to increase the supply security for the heat customers located farthest away from a heating plant in case of a shortage. Eighty residential and office buildings located in Stockholm, Sweden participated, and their heat deliveries were remotely reduced by a control system. The magnitude and durations of the reduced heat deliveries were based on assumed time constants for the buildings and a maximum accepted drop in indoor temperature of 3°C. The indoor temperature was measured in two of the buildings. The variations were at a normal level except during the test with the longest duration (48 h).

Another pilot test was conducted during the winter of 2002–2003 in two Finnish buildings with concrete structures and radiator heating systems [6]. The test revealed that the heat load could be reduced by 20–25% over 2–3 h, causing a drop in indoor temperature of up to 2°C. These tests were performed at outdoor temperatures of -10°C to 0°C. The same study demonstrated a smaller potential for load shifting in a building complex consisting of offices and facilities for streetcar maintenance in Mannheim, Germany. The peak demand for heating was reduced by 4.1% during the tests. The main reason for the lower potential was that the heating system was mainly airborne. The main aim of these tests was to evaluate the potential for the reduction of peak load production in the district heating system. This was also the main focus of the subsequent studies presented here.

A residential area in Karlshamn, Sweden, was the subject of a pilot test where DSM was implemented in the form of agent-based load control [8, 9]. The control was distributed among agents on the production side, on a cluster level, and on a customer level. These agents monitored and controlled the local systems. They also communicated with each other to achieve system-wide peak reduction and optimization. The system displayed the potential for reducing peaks as well as reducing the energy consumption by 4%, even though the thermal storage capacity was only partly utilized in this test. The average return temperatures to the district heating system were also reduced by 2°C while the system was in operation [10]. A subsequent larger test of this technology was performed in three major Swedish district heating systems [11]. A total of 58 substations serving one to several buildings each were included in this test. Peak load reductions of approximately 15–20% and energy savings of 7.5% were achieved.

The effect of the utilization of buildings for short-term TES on the indoor temperature was studied in [12]. The test was performed in an office building with a light construction and concrete slabs. The heat load was reduced during short periods of up to 1 h and longer periods of 4 to 8 h. Both single and frequently recurring heat load reductions were tested. The average deviation was chosen as the measurement for the variation in indoor temperature. During periods with load reductions, the average deviation increased to 0.29°C from the normal 0.19°C.

A study with the aim of estimating the possible heat storage potential of different building types was conducted in Gothenburg, Sweden [5]. The heat deliveries to the different buildings were reduced over periods of 24 h, and the heat deliveries and indoor temperatures were measured. Time constants for each building were calculated based on these measurements. Wooden buildings reported time constants of 102 h, stone buildings 155 h, and tower blocks 218 to 330 h.

Large-scale implementation

The effects of the large-scale implementation of buildings' thermal inertia as short-term TES in district heating systems has been studied in a few publications. They have adopted very different approaches.

A case study of how the implementation of DSM would affect the fuel and operational costs of the DH system in Næstved, Denmark was included in [2]. Two cases were considered where the heat load was assumed to be adjusted by 20% and 80%, respectively, toward the mean heat load. They resulted in total savings of 1% and 2.6%.

District heating systems where a considerable number of the buildings utilize nighttime setback can have large peaks in heat demand in the morning hours. A simulation study regarding the DH network of Altenmarkt im Pongau, Austria studied the effects of applying DSM strategies to buildings utilizing nighttime setback [3]. The buildings were controlled so that they recovered from their nighttime setback at different hours. Up to 35% peak shaving would be achieved if applied to the overall district heating network.

The effects of three energy conservation measures on the local energy system in Linköping, Sweden were compared in [4]. The compared measures were heat load control (utilizing buildings' thermal inertia), attic insulation, and electricity savings. Heat load control showed a potential for energy savings primarily in the spring and autumn. It would also be economically profitable for both the DH provider and the residents. The analyzed installation for heat load control was described in [11].

METHODOLOGY

Since this study consists of several parts, their methodologies are described here separately, starting with the pilot test. This is followed by a description of how the results from the pilot test are up-scaled to describe a large-scale implementation of buildings as short-term TES. Last follows a description of how the large-scale implementation is simulated and evaluated.

Description of test buildings

During 2010 and 2011, the ability of five buildings to function as thermal energy storage in a district heating system was tested in Gothenburg, Sweden. The five buildings that were included in the analysis are all residential buildings with 3 to 5 stories. A summary of the building data is presented in Table 1. There are some differences in the buildings, and they can be grouped into two categories: light and heavy. This classification is based on the thermal mass of the building. A light building typically has a core of steel or wood, which results in a low capacity for storing heat. A heavy building typically has a core of concrete, which results in a higher capacity for storing heat. One of the buildings can be classified in the light category. All of the buildings were constructed between 1939 and 1950 and have a yearly heating demand of approximately 150 $kWh/m^2_{floor\ area}$ per year. This is a normal energy performance for these types of buildings in the city of Gothenburg, Sweden, which has a yearly average temperature of 8°C. A major portion of the large public housing stock that was built in the 1960s and 1970s is similar to the buildings tested in this study regarding energy performance [13]. More recently constructed buildings generally have superior energy performance.

Table 1. Building Data.

Building	A	B	C	D	E
Year of construction	1950	1939	1934	1939	No info
Living area [m^2]	1,178	904	900	904	No info
Stories	3	5	3	5	3
Apartments	20	24	19	24	25
Estimated thermal mass	Heavy	Heavy	Light	Heavy	Heavy
Facade	Plast-ered	Plast-ered	Wood, brick	Brick	Brick

The heat deliveries to the buildings were increased and reduced during specified periods, and the indoor temperature, T, was measured in two apartments in each building. Temperature meters were placed on a wall in the hall in each apartment. All buildings were connected to district heating and had a radiator heating system.

Control of test building

All of the buildings in the pilot test adjusted the heating power by controlling the supply temperature to the radiator system using a conventional feedback controller. The supply temperature was set based on the outdoor temperature and a control curve. Fine adjustment of the heating power within each individual apartment was performed via thermostats on the radiators. To control the heating power delivered to the buildings in this test, the signal from the outdoor temperature sensor, u, was adjusted in different cycles as shown in Fig. 1. This affected the set point for the water supply to the radiators in the feedback controller. For example, to discharge a building, 7°C was added to the outdoor temperature signal. The real outdoor temperature was 3°C, but the control system receive the signal 10°C (3°C + 7°C). According to the control curve, this resulted in a lower supply temperature to the radiator system. The apartments then received radiator water with a lower temperature than they needed to maintain their indoor temperature, T, at the current outdoor temperature. The indoor temperature, T, slowly started to drop in the apartments, and the building affected the district heating system, similar to discharging a hot water storage tank. This test setup was similar to the one used in [12].

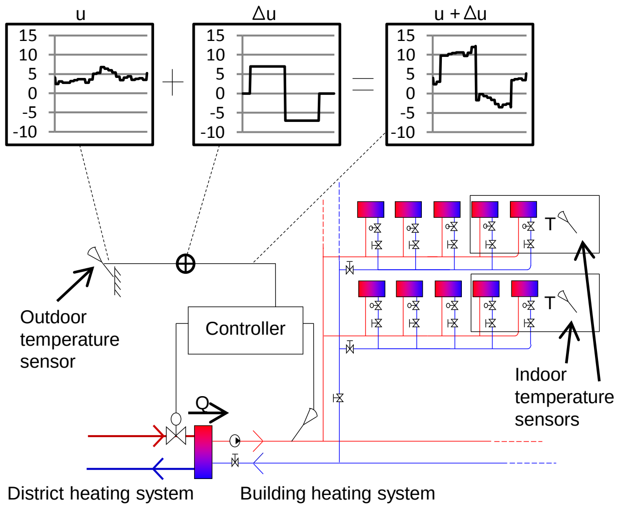

Fig. 1. Schematic sketch of how the control was implemented in the pilot test.

In this test, the adjustments to the outdoor temperature signal were performed in 21-h cycles. Most of the tested control cycles contained one 9-h period of discharging, one 9-h period of charging, and one 3-h period of normal operation. The reason to use a test cycle that was 21 h (and not 24 h) was that this caused the charging and discharging to occur at different times each day. This made it possible to separate variations in indoor temperature caused by the test from normal variations caused by, e.g., sunlight and the tenants' behavior. Eight cycles of 21 h make one full week.

Five different cycles of charging and discharging were tested; they are shown in Fig. 2. The following notations are used to describe them:

CP—Charge period; the building receives more heat than it normally would at the current outdoor temperature.

DP—Discharge period; the building receives less heat than it normally would at the current outdoor temperature.

NOP—Normal operation period; the building heating system operates as it normally would.

Δu—Adjustment to outdoor temperature signal

Cycle II was the most extensively tested. It was tested in all five buildings and produced 19 complete weeks of measurement data without any obvious measurement errors. Cycle II is also the cycle with the largest variation in Δu and therefore should be the cycle that provided the largest utilization of the building's thermal energy storage capacity and produced the largest variations in indoor temperatures.

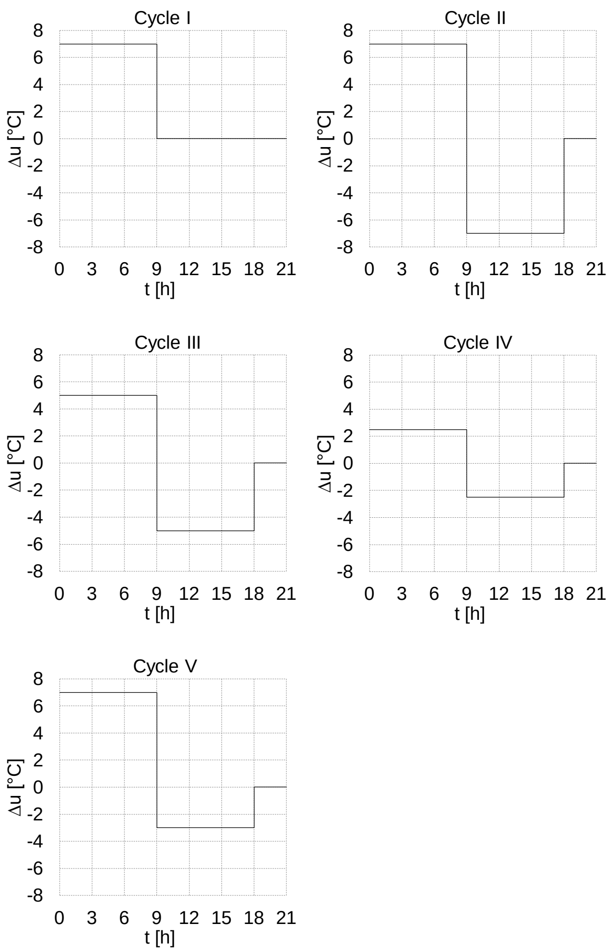

Fig. 2. The five test cycles from the pilot test.

Large-scale implementation

To study a large-scale implementation of short-term TES in buildings, a group of buildings suitable for implementation needs to be analyzed. For this purpose, Västra Gårdsten, a residential area in Gothenburg, was selected. The area has 13 substations, each supplying heat to a group of 2–3 buildings. There is a total of 1,000 apartments in the area with an average living area of 76 m². The average annual heat consumption for the area is 12.1 GWh. The buildings are all residential except for one small dental practice and one office for about 20 persons. All buildings are 3 to 5 stories and have a core of concrete. They are very similar to the heavy buildings in the pilot test. This building type is also very common in Sweden, as many large residential areas similar to Västra Gårdsten were built in the 1960s and 1970s. Due to their similarities, it is assumed in this study that the buildings in Västra Gårdsten will perform identically to the heavy buildings in the pilot test with regard to the ability to function as short-term TES. To scale the results from pilot test to Västra Gårdsten, the heating power signature is used. The heating power signature is the heat demand dependency of the outdoor temperature. It is determined by finding the linear dependency with the smallest squared error based on three years of measurements of the delivered heat and the outdoor temperature.

For the full-scale study of the potential of buildings as short-term TES in DH networks, the city of Gothenburg is studied. The study consists of four cases: buildings consuming 10% of the yearly heat generation in the Gothenburg DH network, the same case but with 20%, 30%, and a reference case with no thermal storage. It is assumed that there are enough residential areas similar to Väsra Gårdsten that can be utilized for short-term TES in Gothenburg to cover the four cases. This evaluation is based on a comparison of the actual heat generation (the reference case) and fictive heat generation that would be possible with access to thermal storage. The heat generation data are from the DH system in Gothenburg from 2010–2012.

Properties of a short-term TES

Based on the findings from the pilot test and the heating power signature of Västra Gårdsten, two main parameters defining the short-term TES can be established for each case:

- Power limitation [MW]—The maximum power that the short-term TES can be charged/discharged with.
- Storage capacity limitation [MWh]—The amount of heat that the short-term TES can store.

The power limitation of the storage is valid when the outdoor temperature is 8°C or less. When the outdoor temperature is higher, the heating power in the buildings is less than the limitation. Since negative heating power cannot be delivered to the buildings, the power limitation for discharging decreases linearly from 8°C to 15°C, where it reaches zero. Charging of the buildings can still be done at higher temperatures, and the power limitation then starts to decrease linearly at 15°C and reaches zero at 22°C.

Simulation model

An optimization problem was formulated with the aim of minimizing the variation in heat load. The parameter to be optimized is the maximum peak load reduction, and the limitations for adjustments to the heat load are the power limitation and the storage capacity limitation. With a resolution in time of 1 h and a heating power of 1 MW, the number of solutions is small enough to be solved with a brute force iteration approach, testing all possible solutions.

The progression for the iterative solution is first to split the data set into periods of 200 h each to speed up the simulation. For each time period, the highest hourly heat load $P_h(t)$ is reduced by one step (1 MW) and the lowest hourly heat load $P_h(t)$ is increased by one step (1 MW). A check is performed to see whether any of the two limitations was violated. If the check passed the iteration, the test was started over, and if not, the program proceeded to test all combinations of decreasing points in descending order where $P_h(t) > P_h(t\text{-}1)$ and/or $P_h(t) > P_h(t+1)$ and increasing points in ascending order where $P_h(t) < P_h(t\text{-}1)$ and/or $P_h(t) < P_h(t+1)$. The iteration continued until no further improvements could be made. The method is quite computational heavy (solving at about 10,000 times real time) but guarantees a solution with the maximum possible peak reductions. To avoid boundary constraints from the 200-h periods influencing the results, the full iteration was performed a second time with overlapping time periods.

Evaluation of results

To evaluate the results, the relative daily variation was studied for each case. Relative daily variation is defined in [14] as follows:

“The relative daily variation is the accumulated positive difference between the hourly average heat load and the daily average heat load divided by the annual average heat load and the number of hours during a day. The relative daily variation is expressed with 365 values per system and year.”

$$G_d = \frac{\frac{1}{2}\sum_{h=1}^{24}|P_h - P_d|}{P_a \cdot 24} \cdot 100\ [\%] \tag{1}$$

P_h—hourly heat load
P_d—daily heat load
P_a—annual heat load
G_d—relative daily variation

RESULTS

All the heavy buildings in the test showed that it is possible to utilize them as short-term TES with the restrictions from Cycle II and still maintain a good indoor climate. Cycle II is the cycle with the largest variation in Δu and therefore should be the cycle that provided the largest utilization of the building thermal energy storage capacity and produced the largest variations in indoor temperatures.

Effect on heat delivery in the pilot test

The relation between the heat delivered to the buildings, Q, and the adjustment to the outdoor temperature signal, Δu, was studied. Cycles I, II, and V in Building A were selected for this study, as these tests have the most measurement data available. To separate the variation in Q caused by the test from the normal variations, an average profile for each week was created based on the eight cycles of 21 h each. To make different periods of time comparable, the average heating power for the present week, Q_{mean}, was subtracted from each weekly profile. Graphs showing these heating profiles are presented in Fig. 3.

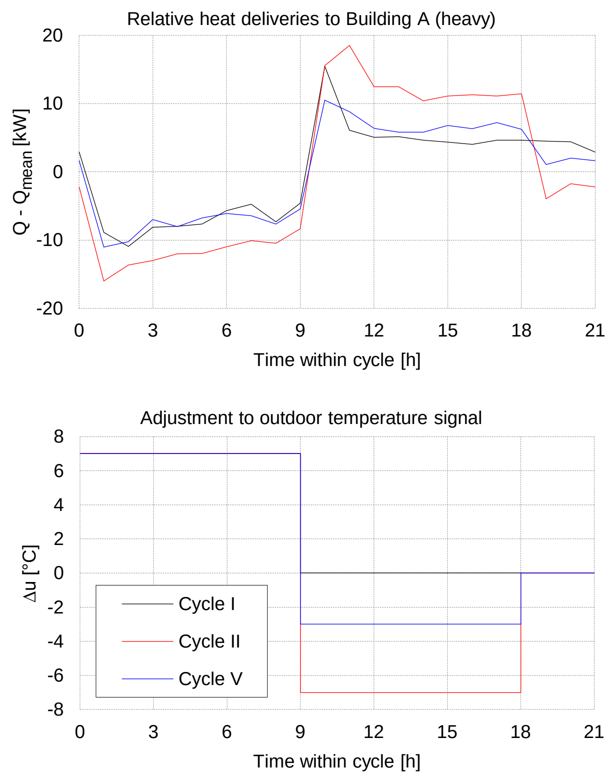

Fig. 3. Heat delivery profiles relative to control cycle average for Building A. Each profile is based on 5–8 weeks of measurements.

Based on the same dataset used to create Fig. 3, a more qualitative analysis of how the heat delivered to the buildings, Q, relates to the adjustment to the outdoor temperature signal, Δu, was performed. The ratio between relative heat deliveries, $Q–Q_{mean}$, and the relative adjustment of the outdoor temperature signal, $\Delta u–\Delta u_{mean}$, was studied. The average adjustment to the outdoor temperature signal during one control cycle, Δu_{mean}, is defined in equation 2 The reason for studying $\Delta u—\Delta u_{mean}$ instead of just Δu is that Cycles I and V are not symmetrical like Cycle II, and their $\Delta u_{mean} \neq 0$.

$$\Delta u_{mean} = \frac{\Delta u_{DP} \times t_{DP} + \Delta u_{CP} \times t_{CP} + \Delta u_{NOP} \times t_{NOP}}{t_{DP} + t_{CP} + t_{NOP}} \text{ [°C]} \quad (2)$$

Δu_{mean} = 0°C for Cycle II (because it is symmetric), 1.79°C for Cycle I, and 3°C for Cycle V. The results from the study are presented in Table 2. As observed in this table, the ratio is between -1.44 kW/°C and -1.83 kW/°C for all but two cases. The NOP for Cycle V differs from the other results. This is most likely because the length of this period was only 3 h and approximately half of that time is the time it takes for the water in the radiator system to circulate once and reach steady supply and return temperatures. The fact that all other values have only a small variation in their ratios implies that the change in heat deliveries and the adjustment of the outdoor temperature signal, Δu, have close to a linear relation.

Table 2. Ratio between heat deliveries and adjustment to the outdoor temperature signal for Building A.

Period	$\Delta u–\Delta u_{mean}$ [°C]	$Q–Q_{mean}$ [kW/°C]	$(Q–Q_{mean})/(\Delta u–\Delta u_{mean})$ [kW/°C]
Cycle I			
DP	4.00	-7.32	-1.83
CP	n/a	n/a	n/a
NOP	-3.00	5.49	-1.83
Cycle II			
DP	7.00	-11.84	-1.69
CP	-7.00	12.71	-1.82
NOP	0.00	-2.62	NaN
Cycle V			
DP	5.29	-7.63	-1.44
CP	-4.71	7.10	-1.51
NOP	-1.71	1.58	-0.92

Indoor temperature variation in the pilot test

To separate the variations in indoor temperature, T, caused by the test from the normal variations, an average indoor temperature profile for each week was created based on the eight cycles. These profiles were created in the same manner as the profiles for the relative heating power in Fig. 3. An example of these profiles in one of the heavy buildings is presented in Fig. 4. As only the variation in temperature is of interest, the temperature profiles have been made more easily comparable by centering them on the Y-axis. Thus, $T_{min} + (T_{max} – T_{min})/2$ is subtracted from each weekly profile.

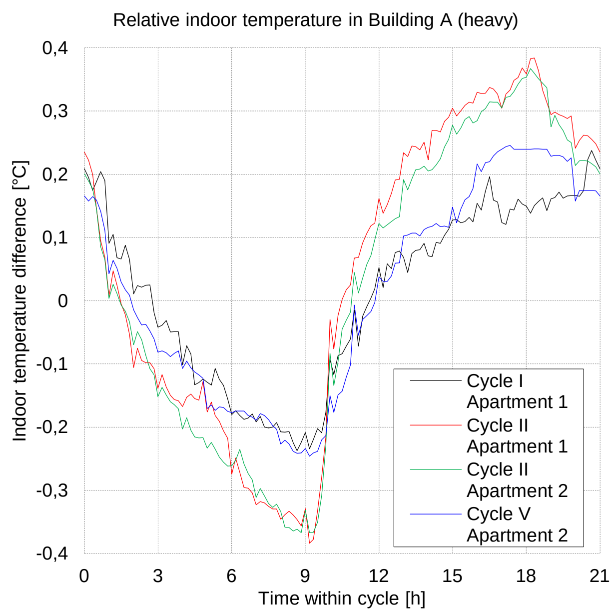

Fig. 4. Indoor temperature variations caused by the pilot test. Each curve is based on the average values over a period of 4–6 weeks.

From Fig. 4, it can be observed that the effect on indoor temperature, T, from Cycle II is, as expected, larger than the effect from Cycle I and Cycle V. It should also be noted that there is a time delay from when the mode of operation changes and when the effect on the indoor temperature, T, starts to be displayed. This is due to the circulation time in the radiator heating system; it takes some time before the temperature front reaches the radiators and affects the indoor temperature. Thus, dead time is added to the system.

For each week in each apartment in each building, the indoor temperature variation, $T_{var.21h}$, caused by the pilot test was calculated. $T_{var.21h}$ is defined as the difference between the maximum and minimum temperature for a weekly 21-h profile divided by two. A summary of the variations is presented in Table 3.

Table 3. Average variation in indoor temperature caused by the pilot test.

Test cycle	Building	$T_{var.21h}$ Apartment 1 [°C]	$T_{var.21h}$ Apartment 2 [°C]	Number of test weeks
I	A—heavy	±0.26	-	8
	C—light	±0.23	±0.39	18
II	A—heavy	±0.40	±0.40	6
	B—heavy	±0.29	±0.29	6
	D—heavy	±0.09	±0.19	5
	E—heavy	±0.06	±0.27	1
III	E—heavy	±0.11	±0.22	2
IV	E—heavy	±0.06	±0.10	1
V	A—heavy	-	±0.30	5

As shown in Table 3, all four heavy buildings have average values for the indoor temperature variation caused by Cycle II of ±0.40°C or less. If we look at each individual week, there is only one week in one of the apartments in one of the buildings that caused variations in indoor temperature larger than ±0.50°C. In that case, the variation was ±0.53°C. It is unlikely that the variation caused by Cycle II combined with the normal variations will cause a total variation in indoor temperature larger than ±1.0°C on any given day. Therefore, most heavy buildings similar to those studied in the test should be able to utilize their thermal inertia with restrictions similar to those in Cycle II without jeopardizing the quality of service provided by the heating system. Hence, the restrictions from Cycle II are used to decide the limiting parameters for the full-scale simulation.

Limiting parameters of a building's short-term TES

When utilizing buildings as thermal energy storage, it is beneficial to have more freedom in the control than what is entailed by Cycle II. It might be beneficial to have several shorter DPs on one day or store heat from one day to utilize the next day. A simple yet accurate enough model for utilizing buildings as short-term TES can be established based on the restrictions from Cycle II and three important relations between the adjustment to the outdoor temperature signal, Δu, heat delivery, Q, and indoor temperature, T, that were presented in [1]. With the restriction of |Δu| < 7°C, the thermal energy storage capacity can then be measured in degree hours [°Ch]. The thermal energy storage capacity of the heavy building in this case is then simplified to 63°Ch (7°C × 9 h).

To find the power limitation [MW] and storage capacity limitation [MWh] for a large-scale, short-term TES, we need to combine the results from the pilot test with the heating power signature for the intended building stock. The power signature for Västra Gårdsten, which has an average annual heat consumption of 12.1 GWh, is shown in Fig. 5.

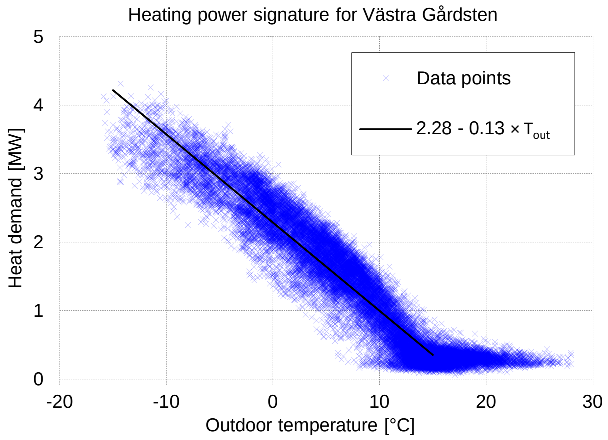

Fig. 5. The inclination of the trend line is the heating power signature for the residential area Västra Gårdsten, Gothenburg.

Fig. 5 shows that an increase in the outdoor temperature of 1°C would result in a decrease in the heat delivered to the area of 0.13 MW. Hence, an increase in Δu of 1°C would result in a decrease in the heat delivered to the area of 0.13 MW. With the limitations of |Δu| < 7°C and 63°Ch of thermal storage capacity, this area could be utilized as thermal storage with a power limitation of 0.13 MW/°C × 7°C = 0.91 MW and a storage limitation of 0.13 MW/°C × 63°Ch = 8.19 MWh. This corresponds to a storage limitation of about 0.1 $kWh/m^2_{floor\ area}$. These substations, like many others, already have a data connection that sends consumption data each hour. All that is required to utilize this area as thermal storage is adjusting the 13 substations so that the adjustment to the outdoor temperature signal, Δu, can be controlled remotely. There are many areas similar to Västra Gårdsten in Gothenburg (and in other cities), so it is possible to scale these results for a city-wide implementation.

Full-scale implementation

Since the cost of implementing building short-term TES is proportional to the number of substations that need adjustments, it is better to utilize the substations with the largest yearly heat demand first. From 2010–2012, the DH system in Gothenburg had an average annual heat generation of 4.26 TWh. The total amount of delivered heat to customers was 4.04 TWh, of which 2.12 TWh was delivered to the 4,457 substations in multifamily residential buildings. The heat deliveries to these substations are sorted in Fig. 6 to find the required number of substations for each case presented in Table 4.

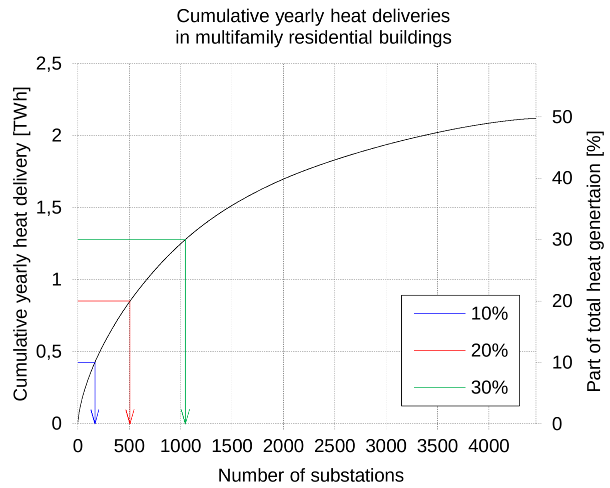

Fig. 6. Cumulative yearly heat deliveries to all substations in multifamily residential buildings in Gothenburg, Sweden.

Based on the data from Fig. 6 and the parameters found from the study of Västra Gårdsten, the five simulation cases can now be summarized in Table 4.

Table 4. Summary of the four simulation cases.

Case	Yearly heat delivery to utilized substations [GWh]	Number of utilized substations	Power limitation [MW]	Storage capacity limitation [MWh]
0% (ref)	0	0	0	0
10%	426	165	32	285
20%	852	507	63	571
30%	1,279	1046	95	856

Based on the data from Table 4 and the hourly heat generation data for Gothenburg from 2010–2012, a full-scale simulation was performed. An example showing a five day period of the results can be found in Fig. 7.

Around the 24 h mark in Fig. 7 the short-term TES is discharging for the 10%, 20% and 30% cases. This can be seen from the reduced heat generation in the top graph, the positive Δu in the middle graph and the falling indoor temperature in the bottom graph. The effect on indoor temperature in the bottom graph is estimated for the most affected buildings, those similar to Building A in the pilot test. The bottom graph can also be seen as the charging level of the TES, where at +0.5°C, the storage is charged to its full storage capacity limitation.

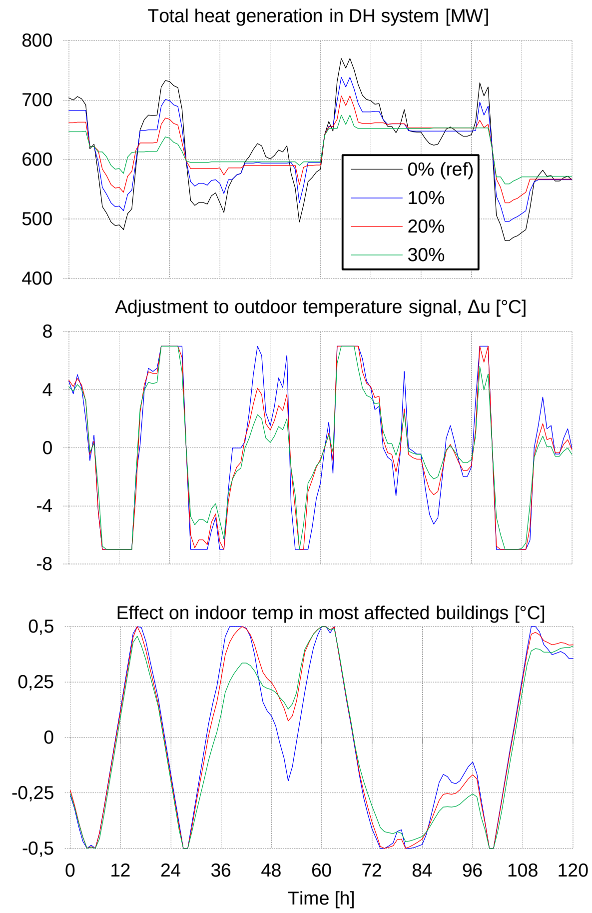

Fig. 7. Utilizing buildings as short-term TES in Gothenburg DH system; effect on heat generation, outdoor temperature signal and indoor temperature in utilized buildings.

Relative daily variation

It can be clearly seen in Fig. 8 that the variation in heat generation has decreased and that the conditions for generating heat are more favourable with a building's short-term TES.

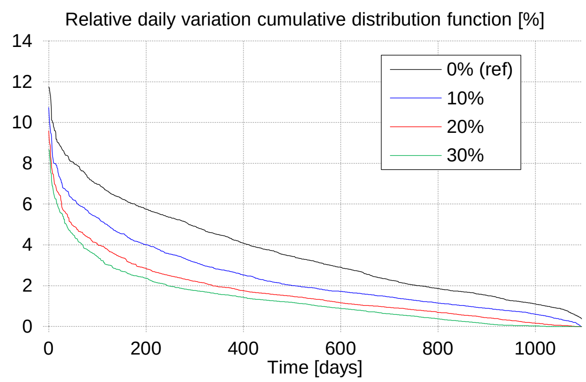

Fig. 8 Relative daily variation cumulative distribution function for three years (2010–2012).

It can be seen in Fig. 8 that the relative daily variation has significantly decreased when some of the buildings are utilized as thermal storage. The decrease from no storage to 10% is larger than the decrease from 10% to 20%. This is because, in some cases, 10% is enough to cut a peak, and there is then no need for larger storage. The utilization is then larger for the smaller storage of 10%. This can also be seen in the middle graph in Fig. 7 where the buildings more often receive a stronger control signal in the 10% case than in the 20% and 30% cases.

If we look at the average values of the relative daily variation, we get a simple measurement for comparing the four cases:

0% (reference):	3.63%
10%:	2.44%
20%:	1.74%
30%:	1.38%

In the 20% case, the average relative daily variation is reduced by 50% compared to the reference case. This comes at the cost of increasing the variation in indoor temperature in the customers' buildings in most cases by less than ±0.5°C and the investment in adjusting the substations. This should be compared with the value of reducing the variation in the heat generation and other storage options.

For the specific case of Gothenburg, the 20% case would require adjustments in about 500 substations. This can be compared with investing in a storage tank with a storage capacity of 576 MWh and a power limitation of 64 MW. With a supply temperature of 80°C and a return temperature of 45°C, this would result in a hot water storage tank of 14,200 m^3 with a maximum flow of 0.44 m^3/s. Such a storage tank would have an investment cost of roughly 3–6 M€. This estimation includes all related costs required to get the storage tank in operation and is based on interviews with three Swedish district heating companies. Assuming that the required adjustments to the substations can be made cheaper than 6,000–12,000€ per substation, utilizing buildings as short-term TES can be a more economical alternative than hot water storage tanks. It should, however, be noted that this is a very rough economic comparison that only includes the investment cost.

DISCUSSION

The capacity for storing heat in buildings is highly dependent on the restrictions on the indoor temperature variation. No study of how the tenants experienced the indoor climate during the pilot test was carried out, but the landlords all stated that the complaints were at a normal level. For this study, the restriction of not increasing the variation in indoor temperature more than ±0.50°C was used. These variations are small compared to the normal variation caused by variations in sunlight and tenant activity. Allowing a larger variation in the indoor temperature would increase the thermal storage capacity in the buildings. What limits the potential to utilize buildings as short-term TES is how the tenants experience the indoor climate. Here, the operative temperature and sociological factors are of importance. The operative temperature in an apartment is mainly affected by the indoor air temperature and surface temperatures. This puts a power limitation on the charging/discharging of buildings to avoid radiators that are too warm or cold. What sets the power limitation for the utilization as short-term TES might not even be the thermal comfort of the tenants. It could be tenants experiencing unreasonable hot or cold radiators, believing that something is wrong with the heating system, and complaining or adjusting their thermostats in an unfavorable way. In the simulation, especially the 20% and 30% cases, it was the power limitation rather than the storage capacity limitation that restricted the capacity.

The potential for a large-scale implementation might be underestimated since it is based on results from the worst performing building in the pilot test. The benefit is that buildings could be utilized to the calculated potential without risking large variations in indoor temperatures. For a higher degree of utilization, it might be recommended to measure the indoor temperature in the buildings continually and implement it in the control.

OUTLOOK

Utilizing buildings as short-term TES can have great potential as a cost-effective method for storing heat, but there are two main potential obstacles that need to be studied further before this technology can take the step from pilots to large-scale applications.

First is the method for controlling such storage. Several practical methods for controlling thermal energy storage utilizing buildings' thermal inertia have been studied in earlier works. They include direct load control [1, 6, 7, 12, 15], control through price incentives [6, 15-17], and other more indirect DSM strategies [4, 6, 8-11, 15, 17, 18].

Second is what type of business model is to be used and what the contract between the DH providers and the customers should contain. This can be difficult since there might be three parties involved: the DH provider, the customer/landlord, and the tenants. Questions that need to be addressed include the following:

- Who is responsible for the indoor climate when load control is active?
- How should the investment cost be financed?
- Is it beneficial to combine installations of short-term TES with energy-efficiency measures?
- How (if at all) should customers be compensated for allowing the DH provider to utilize their buildings as short-term TES?

Both these obstacles should be easy to overcome if a major DH provider is willing to invest in a large-scale building short-term TES. It is hoped that such an investment in a technical solution and business mode can be exported to other DH providers.

CONCLUSIONS

The pilot test in this study has shown that heavy buildings with a structural core of concrete can tolerate relatively large variations in heat deliveries while still maintaining a good indoor climate. Storing 0.1 $kWh/m^2_{floor\ area}$ of heat will very rarely cause variations in indoor temperature larger than ±0.5°C in the most affected heavy buildings. This corresponds to adjusting the outdoor temperature signal, Δu, by 7°C over 9 h. Most heavy buildings will experience even smaller variations in indoor temperature and could possibly be utilized to a larger extent than the parameters found in the pilot test.

Utilizing about 500 substations for short-term thermal energy storage in large residential buildings would provide a capacity for storing heat equivalent to constructing a hot water storage tank with a volume of 14,200 m^3 for the city of Gothenburg, Sweden. This would decrease the daily variations in heat load by 50%, reduce the need for peak heat generation, and reduce the number of starts and stops of heat generation units. Assuming that the required adjustments to the substations can be made cheaper than 6,000–12,000€ per substation, utilizing buildings as short-term TES can be a more economical alternative than hot water storage tanks.

ACKNOWLEDGEMENT

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ENERGETIC PERFORMANCE OF SHORT TERM THERMAL STORAGES IN URBAN DISTRICT HEATING NETWORKS

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ABSTRACT

Serving the heat demand of customers is the main objective of operating district heating (DH) systems with combined heat and power (CHP) plants. However nowadays, profitable CHP production highly depends on the electricity price on the market, effecting the availability of inexpensive CHP heat.

Unfortunately, the heat demand of a DH system does not necessarily coincide chronologically with the electricity price. Thus, CHP operation may become non-profitable, leading to the operation of heat-only plants. Moreover, the electricity demand is subject to extreme fluctuations throughout short term periods. As a result, especially the ecological value of electrical power is strongly volatile.

In order to decouple the production and allocation of heat for spatial and tap water heating as well as electrical power, operators of CHP-systems install (de-) centralized thermal short term storage tanks within their DH networks. Thus, a more flexible load management, more efficient CHP plant operation and a more profitable operation of the whole energy supply concept can be obtained.

In this paper, the energetic performance of sensible thermal storage tanks will be described by mathematical models, whereas measures for optimization will be evaluated. For that reason, results of a parameter study concerning thermal losses basing on different physical mechanisms will be presented. Modelling and simulating this DH network component enables the quantification of external and internal heat flows. This increases the primary energy efficiency of DH systems.

INTRODUCTION

Thermal storages will play a major role for the economic operation of DH networks. Integrating these into constituent (large) urban DH systems, the production and allocation of electrical power and heat for

- spatial heating,
- tap water supply and
- industrial purposes

can be decoupled possible [1 to 4]. Thus, a further and essential degree of freedom operating CHP plants is given for energy suppliers running these systems. Manifold positive effects result:

1. Raise of profitability [3, 5],
2. Reduction of heat supply capacities [6],
3. Enhancement of the overall primary energy efficiency of DH networks [6] and
4. Enhancement of the life span of the system's components [6]

In addition, against the background of future scenarios on the development of wind and solar power, thermal storages are suitable for the utilization of regenerative peak loads supplied [7, 8].

A multitude of studies on thermal storages indicate the strong influence of different heat loss mechanisms on the operational performance of this technology in situ, see e.g. [9 to 12]. However, within these studies, small scale applications are mainly considered.

Within this paper, the heat losses of a large scale thermal storage applied within urban areas (and DH networks) is examined. For this purpose, conductive heat losses are approximated. External losses to the environment as well as internal losses due to conductive effects and turbulences within the hot water itself are considered. Concerning the latter, mass flows occurring are taken into account.

THERMAL STORAGES WITHIN URBAN DISTRICT HEATING NETWORKS

Commonly, within urban DH networks, stratified, sensible heat storage tanks are applied, cf. e.g. [2 to 5]. These non-pressurized systems, operating at atmospheric pressures of roughly 10^5 Pa, conserve a constant water table and pressure level. Adjusting these parameters to the corresponding DH network, thermal storages serve as passive pressurising component. Furthermore, within these storages, radial diffusors for (dis-) charging the thermal storage are applied. These support the thermal stratification due to the radial direction of mass flows entering and leaving the storage.

Concerning the overall structure, the thermal storage media and internal installations (such as pipes or diffusors) are cased by a bearing structure (casing; e.g. steel) surrounded by the insulation and a water diffusion barrier (e.g. steel or PVC layers). In order to avoid heat losses and leakages, the design of the casing must be carried out most carefully, as water seeping into the insulation strongly diminishes its effectiveness, cf. [13]. Finally, a non-pressurized, saturated steam cushion above the water table prevents damages due to thermal expansions of the storage media, cf. Fig. 1.

Basing on the storage system mentioned above, an approximation of the heat losses and mass flows due to conduction, free and forced convection as well as turbulences is given. For this purpose, however, a definition of typical thermodynamic characteristics, geometries and operational parameters of a thermal storage in an urban area is necessary. Regarding literature data, this multitude of parameters is given exemplarily in Table 1, see also illustrating Fig. 1 and cf. [2 to 5].

EXTERNAL LOSSES

Due to temperature differences ΔT between the heat storage media and the surrounding environment, thermal losses inevitably occur, see equation (1a). These, however, depend on the heat transfer coefficients $\alpha_{in/out}$ in- and outside the storage as well as the heat conductivities λ_i of the wall structure and foundation and storage media itself, see equation (1b).

$$\dot{Q} = kA\Delta T \Rightarrow \dot{q} = k\Delta T \qquad (1a)$$

$$^1/_k = {^1/_{\alpha_{in}}} + \Sigma {^{s_i}/_{\lambda_i}} + {^1/_{\alpha_{out}}} \qquad (1b)$$

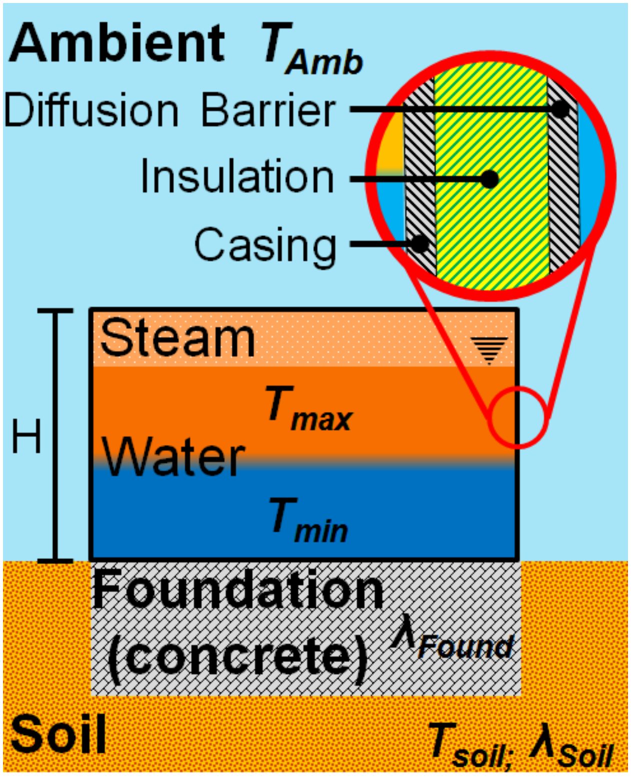

Fig. 1: Scheme of large scale heat storage

Thus, depending on the part and operational mode considered, the heat transfer coefficients have to be adjusted for the

- Wall,
- Steam cushion and the
- Foundation/Soil.

For this purpose a multitude of Nusselt-correlations depending on the heat transfer mechanism, are applied for each part of the heat transfer problem, see equations (2) to (8) in Table 2. The corresponding parameters of water, air and steel are given in chapter D [14].

Table 1: Geometry, material properties and operational parameters of the heat storage system (example)

Geometry			
Dimension of:	[m]		[m]
Casing	0,04	Diameter D	40
Diffusion Barrier	0,04	Height H	37
Insulation	0,5	Water-tableH_{H20}	36
Fundament	2,5		
Operational Parameters		**Material Properties**	
$\dot{m}_{max}$ [kg/s]	1,500	*Heat conductivity:*	[W/mK]
Temperatures:		Insulation λ_{Ins}	0.035
$T_{max/min}$ [°C]	98/60	Steel λ_{Steel}	50
$T_{minSupply}$ [°C]	88	Foundation λ_{Found}	2.1
Ambient T_{Amb} [°C]	-20	Soil λ_{Soil}	1.4
Soil T_{Soil} [°C]	0		

Table 2: Nusselt correlations applied for calculating the heat transfer to the environment

Free convection, see [14], chapter F

Vertical Wall:

$$Nu_{free} = [0.825 + 0.387(Ra * f_1(\mathrm{Pr}))^{1/6}]^2 \qquad (2a)$$

$$f_1(\mathrm{Pr}) = [1 + (0.492/Pr)^{9/16}]^{-16/9}, \text{ cf. [15, 16]} \qquad (2b)$$

Horizontal Plate:

Cooling from bottom side

$$Nu_{free} = 0.15[Ra * f_2(Pr)]^{1/3} \qquad (3a)$$

$$f_2(\mathrm{Pr}) = [1 + (0.322/Pr)^{11/20}]^{-20/11}, \text{ cf. [17]} \qquad (3b)$$

Cooling from top side

$$Nu_{free} = 0.6[Ra * f_2(Pr)]^{1/5}, \text{ cf. [18]} \qquad (4)$$

Forced convection, see [15], chapter G

$$Nu_{lam} = 0.664\sqrt{Re}\sqrt[3]{Pr} \qquad (5)$$

$$Nu_{turb} = 0.037Re^{0,8}Pr/[1 + 2.443Re^{-0,1}(Pr^{2/3} - 1)] \qquad (6)$$

$$Nu_{tot} = 0.3\sqrt{Nu_{lam}^2 + Nu_{turb}^2}, \text{ cf. [19 to 23]} \qquad (7)$$

Superposition, see [15], chapter F

$$Nu_{tot} = \sqrt[3]{Nu_{forced}^3 + Nu_{free}^3}, \text{ cf. [24, 25]} \qquad (8)$$

In order to approximate the maximum heat losses, the corresponding material properties for the calculations are chosen. Thus, Prandtl-numbers Pr, viscosities ν, heat conductivities λ and densities ρ are fitted, cf. equations (2 to 10). The dimensionless parameters applied are defined as follows, cf. e.g. [14]:

$$Nu = \alpha l/\lambda \qquad (9)$$

$$Gr = \frac{gl^3}{\nu^2} * \frac{\rho_\infty - \rho_0}{\rho_\infty}, \text{ cf. [26]} \qquad (10)$$

$$Pr = \nu/a \qquad (11)$$

$$Ra = Gr * Pr \qquad (12)$$

EXTERNAL LOSSES VIA THE WETTED WALL

The heat transfer resistance via the wetted wall, excluding the steam cushion above the water table is divided into four subparts, cf. Fig. 2:

a) Conduction within the hot water,
b) Conduction through the internal thermal boundary layer of the storage,
c) Conduction through the casing (steel), insulation and diffusion barrier (steel) and
d) Conduction through the external thermal boundary layer of the storage.

Concerning the temperature profile within the thermal hot water itself, a constant (maximum) value T_{max} is assumed. This seems to be reasonable, as a manifestation of strong temperature profiles within the hot water being superimposed by gravitational forces due to gradients in densities. Thus, volumes of water at lower temperatures (and higher densities) near the wall, inevitably fall downwards and towards the centre of the storage as densities are lower, cf. e.g. [9, 10, 14].

Furthermore, the thermal layers and heat transfer coefficients in- and outside of the storage (within the thermal boundary layers), depend on the operational state

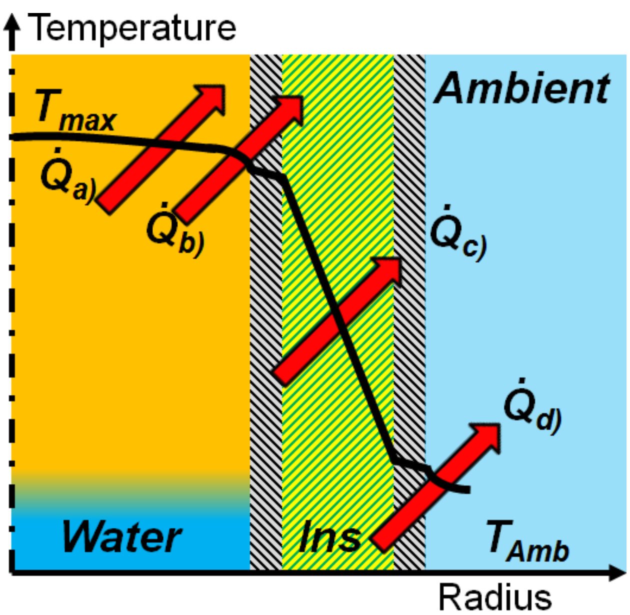

Fig. 2: Radial Heat losses via the wall

and meteorological conditions (wind; approximate maximum velocity of 30m/s). Therefore, heat transfer coefficients (α_{in} and α_{out}) resulting from free and forced convection must be calculated separately. Resulting, by superimposing these coefficients according to equation (8), an approximation of the maximum heat loss is possible.

Moreover, constant values for the heat conductivity λ of the diffusion barrier, insulation and casing structure as well as other material properties (e.g. ρ_{H20} or c_{pH2O}) applied within calculations, are assumed. Finally, the interactions of the roof, bottom, steam cushion and wall of the thermal storage are not considered. The resulting heat transfer coefficients are given in Table 3.

The maximum heat losses $\dot{q}_{loss}$ via the wetted wall excluding the steam cushion is 8.216W/m² for a given ambient temperature of -20°C, whereas the operating temperature of the whole storage is set to 98°C. The corresponding heat loss via the wetted wall $\dot{Q}_{Wall}$ for the given heat storage is 37.2kW. This value drops slightly for operation in windless conditions (35.25kW).

Table 3: Heat transfer coefficients of the wetted wall

b) Thermal boundary layer inside thermal storage, see [14], chapter Fa & Gd
$Pr = 1.753;\ \rho_\infty = 1000 kg/m^3;\ \rho_0 = 958.5 kg/m^3$
$\lambda = 0.678 W/m^2K;\ \nu = 0.294 * 10^{-6} m^2/s$
$Nu_{free} = 1240$ with eq. (2)
$Ra = 10^{12}; l = 36m$
$Nu_{lamforced} = 313$ with eq. (5 to 7)
$Re = 1{,}52 * 10^5$
$Nu_{tot} = 1233$ with eq. (8)
$\Rightarrow \boldsymbol{\alpha_{in} = 23.23 W/m^2K}$
c) Conduction through the solid parts of the wall, see [14], chapter Ea
$k_{Steel} = 1{,}250 W/m^2K$, see eq. (1b)
$k_{insulation} = 0.07 W/m^2K$
$\Rightarrow \boldsymbol{k_{solid} = 0.0699 W/m^2K}$
d) Thermal boundary layer outside thermal storage, see [14], chapter Fa & Gf
$Pr = 0.7004;\ \rho_\infty = 1.4 kg/m^3;\ \rho_0 = 0.93 kg/m^3$
$\lambda = 0.031 W/m^2K;\ \nu = 113.5 * 10^{-7} m^2/s$
$Nu_{free} = 1104$ with eq. (2)
$Ra = 10^{12};\ l = 36m$
$Nu_{forced} = 70{,}000$ with eq. (5 to 7)
$Re = 1{,}06 * 10^8$
$Nu_{tot} = 70{,}000$ with eq. (8)
$\Rightarrow \boldsymbol{\alpha_{out} = 60{,}28 W/m^2K}$

EXTERNAL LOSSES VIA THE STEAM CUSHION

The heat transfer resistance via the steam cushion must be subdivided into a heat loss via the vertical wall (cf. Fig. 2) and the horizontal roof (cf. Fig. 3). The heat transfer via the roof/vertical wall consists of four sub-parts:

a) Conduction within the steam cushion itself,
b) Conduction through the internal horizontal/vertical thermal boundary layer of the storage,
c) Conduction through the casing (steel), insulation and diffusion barrier (steel) and
d) Conduction through the external horizontal/vertical thermal boundary layer of the storage.

Again, the assumptions mentioned above concerning temperature profiles within the steam cushion are adapted (constant temperature within the steam).

However, in contrast to the hot water itself, the thermal boundary layer of the steam cushion inside the storage is independent of the operational state of the storage, as the water table is at a constant level. Nevertheless, horizontal and vertical boundaries must be differentiated in order to obtain the correct heat transfer coefficients outside the storage due to wind. Finally, any interactions between the roof and vertical wall are neglected again, whereas the material properties of the steam cushion are approximated with those of air. The resulting heat transfer coefficients are given in Table 4.

The heat losses $\dot{q}_{loss}$ through the roof and vertical wall of the steam cushion are 6.75W/m² and 8.17W/m². Thus, for a given operating temperature of 98°C and a minimum ambient temperature of -20°C the heat fluxes $\dot{Q}_{WallSteam}$ and $\dot{Q}_{Roof}$ are 8.48kW and 1.03kW. These values drop significantly to 3.13kW for the roof and slightly to 1.02kW for the vertical wall surrounding the steam cushion, in windless operating conditions.

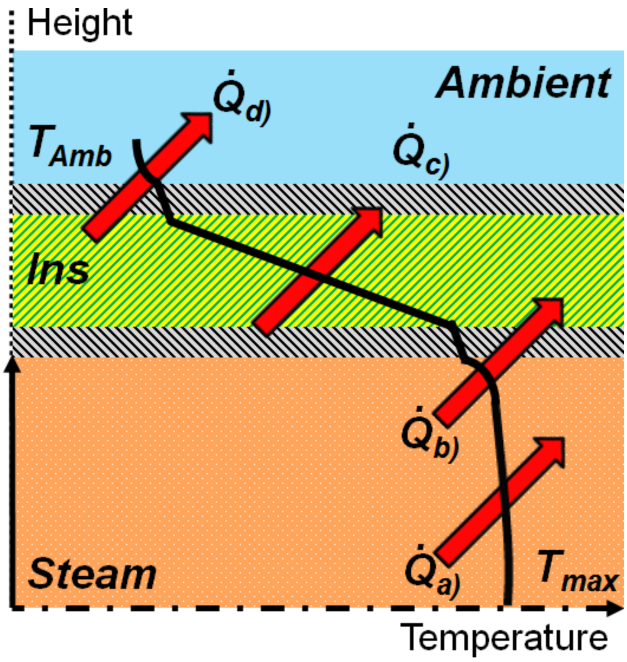

Fig. 3: Vertical Heat losses via the steam cushion

Table 4: Heat transfer coefficients of the steam cushion

$Pr = 0.7004;\ \rho_\infty = 1.4kg/m^3;\ \rho_0 = 0.93kg/m^3$

$\lambda = 0.031W/m^2K;\ \nu = 234.6 * 10^{-7}m^2/s$

<u>b) Thermal boundary layer inside thermal storage, see [14], chapter Fa</u>

<u>Vertical Wall:</u>

$Nu_{free} = 217.7$ *with* eq. (2)

$Ra = 6.31 * 10^{12}; l = 1m$

$\Rightarrow \boldsymbol{\alpha_{in} = 6.75W/m^2K}$

<u>Horizontal Plate:</u>

Cooling from top side

$Nu_{free} = 404.53$ with eq. (4)

$Ra = 4.04 * 10^{14}; d = 40m$

$\Rightarrow \boldsymbol{\alpha_{out} = 0.314W/m^2K}$

<u>c) Conduction through the solid parts of the wall, see [14], chapter Ea</u>

$k_{Steel} = 1{,}250W/m^2K$, see eq. (1b)

$k_{ins} = 0.07W/m^2K$

$\Rightarrow \boldsymbol{k_{solid} = 0.0699W/m^2K}$

<u>d) Thermal boundary layer outside thermal storage, see [14], chapter Fa, Fe & Gf</u>

<u>Vertical Wall:</u>

$Nu_{free} = 344.8$ with eq. (2)

$Ra = 2.96 * 10^{10};\ l = 1m$

$Nu_{forced} = 70{,}000$ with eq. (5 to 7); $Re = 1{,}06 * 10^8$

$Nu_{tot} = 69{,}999.9$ with eq. (8)

$\Rightarrow \boldsymbol{\alpha_{out} = 54.25W/m^2K}$

<u>Horizontal Plate:</u>

Cooling from bottom side

$Nu_{free} = 139.26$ with eq. (3)

$Ra = 1.72 * 10^{15};\ l = 40m$

$Nu_{forced} = 70{,}000$ with eq. (5 to 7); $Re = 1{,}06 * 10^8$

$Nu_{tot} = 70{,}000$ with eq. (8)

$\Rightarrow \boldsymbol{\alpha_{out} = 54.25W/m^2K}$

EXTERNAL LOSSES VIA FOUNDATION AND SOIL

Finally, the heat loss via the foundation and soil below the thermal storage is calculated. Again, the heat transfer between the hot water and the environment is subdivided into four parts, cf. Fig. 4:

a) Conduction within the hot water itself,
b) Conduction through the internal thermal boundary layer of the storage,
c) Conduction through the casing (steel), insulation and diffusion barrier (steel) and

d) Conduction through the foundation and soil outside the storage.

Vertical temperature profiles within the hot water near the foundation are neglected. Thus, the maximum heat loss via the soil and foundation can be calculated for a thermal storage fully loaded (T = 98°C). Furthermore, interactions between the heat fluxes via the wetted wall and the foundation/soil are neglected.

Unfortunately, the geometric boundary conditions (Fig. 1) are quite complex. Therefore, an analytical calculation of the heat losses is not possible. For this purpose, the thermodynamic boundary conditions are adjusted in order to approximate the maximum heat losses via the foundation/soil. Thus, a constant heat conductivity of the soil/foundation of $\lambda_{Found} = \lambda_{Soil} = 2.1W/mK$ is assumed (worst case approximation). Moreover, the temperature of the insulation or casing structure in touch with the soil/foundation is assumed to be 98°C. Finally, convective effects within the storage are modelled for a horizontal surface cooled from the bottom side.

Basing on these assumptions, the heat transfer coefficients of the thermal layer and wall structure are calculated. Moreover, the heat transfer from the storage towards the ground is calculated. According to equation (13), an isothermal surface (bottom side of the insulation) on a semi-infinite media (soil) with a temperature T_{Soil} = 0°C far away from the contact surface is assumed, see [14], chapter E. The resulting heat transfer coefficients are given in Table 5.

$\dot{q} = 8\lambda\Delta T/\pi D$ with $k = 8\lambda/\pi D$ (13), cf. [14].

The heat losses $\dot{q}_{loss}$ through the foundation/soil are 4.31W/m². Thus, for a given operating temperature of 98°C (fully loaded thermal storage) and a minimum temperature of the soil (0°C), a total heat flux $\dot{Q}_{soil}$ of 5.42kW is resulting.

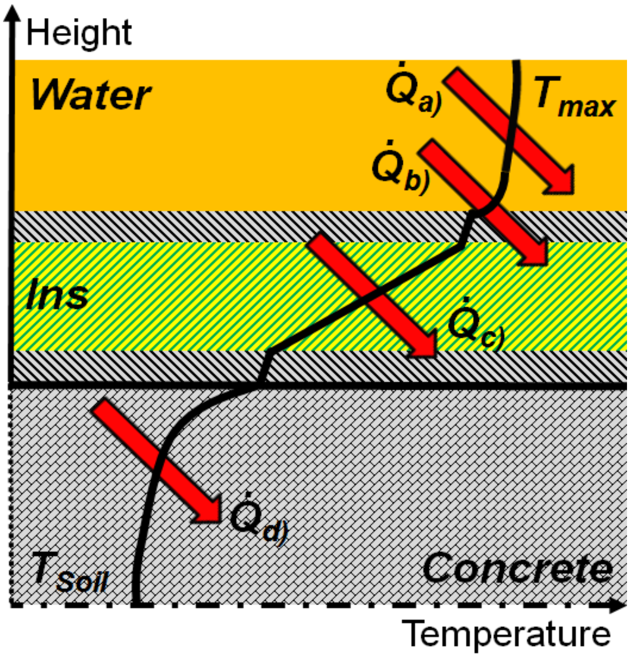

Fig. 4: Vertical Heat losses via the soil

CONCLUSIONS ON EXTERNAL LOSSES

Summarizing the calculations presented above, the heat losses $\dot{Q}_{max}$ of the thermal storage are 52.13kW. Roughly 71.4% of these losses are lost via the wetted wall, whereas 16.1%, 10.4% and 2% are lost via the roof, bottom and vertical wall above the water table. The shares of surfaces are 63% (wetted wall), 17.5% (roof and bottom) and 2%. Thus, the insulation of the wetted wall seems to be under-proportional.

However, considering the temperature losses ΔT_{96h} inside the thermal storage for a representative downtime of τ=96h [5], see equation (14), the insulation of the wetted wall seems to be well dimensioned.

$$T(\tau) = (T_{max} - T_0)\exp[-\bar{k}A\tau/(m_{H2O}c_{pH2O})], \quad (14)$$

$\Rightarrow \Delta T_{96h} = 0.100K$, cf. [27, 28] with

$\bar{k} = \dot{Q}_{max}/A\,(T_{max} - T_{Amb}) = 0.0617W/m^2K$

$c_p = 4{,}150J/kgK;\ \rho_{H2O} = 958kg/m^3$

Furthermore, regarding external heat losses, the energetic efficiency for a minimum supply flow temperature $T_{minSupply}$ = 88°C is quite excellent as well, see equation (15), cf. e.g. [27].

$$\eta_{enExt} = 1 - [\Delta T_{96h}/(T_{max} - T_{minSupply})] = 99\% \quad (15)$$

The energetic performance diminishes however for

a) lower heat transfer resistances, especially smaller dimensions of the insulation and
b) decreasing relative temperature drops Θ allowed for further utilization of the hot water within the attached DH system, see equation (16):

$$\Theta = (T_{max} - T_{minSupply})/(T_{max} - T_{min}) = 0.26 \quad (16)$$

Table 5: Heat transfer coefficients via the foundation/soil

$Pr = 1.753;\ \rho_\infty = 1000kg/m^3;\ \rho_0 = 958.5kg/m^3$ $\lambda = 0.678W/m^2K;\ \nu = 0.294 * 10^{-6}m^2/s$
<u>b) Thermal boundary layer inside thermal storage, see [14], chapter Fa</u> <u>Horizontal Plate:</u> *Cooling from bottom side* $Nu_{free} = 1226$ with eq. (3); $Ra = 10^{12}$; $d = 40m$ $\Rightarrow \boldsymbol{\alpha_{in} = 20.70W/m^2K}$
<u>c) Conduction through the solid parts of the wall, see [14], chapter Ea</u> $k_{Steel} = 1{,}250W/m^2K$, see eq. (1b) $k_{insulation} = 0.07W/m^2K$ $\Rightarrow \boldsymbol{k_{solid} = 0.0699W/m^2K}$
<u>d) Conduction through foundation and soil, see [14], chapter Ea</u> $\lambda = 2.1W/m^2K$ $\Rightarrow \boldsymbol{k_{soil} = 0.113W/m^2K}$

Moreover, within the insulation, up to 99.5% of the temperature difference ΔT between the ambient and media is degraded (see Table 3). On the other hand, the minimum share via the foundation/soil (62%) is clearly connected to the inherent insulating character of the soil, see Table 5, whereas the roof is moderately influenced by the thermal boundary layer within the thermal storage, see Table 4.

Thus, the heat losses of the large scale storage are strongly independent of the heat transfer coefficients α within the thermal boundary layers. This is valid for all thermal boundary layers except for horizontal layer inside the storage. Free convective resistances have a moderate influence on the heat transfer resistance, see Table 4.

Because of the dominant role of the heat transfer resistance within the insulation, the calculation of thermal losses neglecting

- any impacts of thermal boundary layers as well as
- any impacts of the the casing and diffusion barrier,

lead to reasonable approximations of the energetic performance of large scale thermal storages. For the given system, the heat transfer coefficient k_{ins} of the insulating layer is 0.07W/m²K. Thus, for given operating temperatures, an overall heat loss $\dot{q}_{loss}$ of 8.26W/m² is calculated for the wetted wall. Considering the insulating character of the foundation/soil as well, this simplified model results in a heat loss of 54.2kW overestimating the more detailed model by just 3.9%. Resulting, the temperature drop within the storage and its energetic efficiency forecasted are technically identical to the ones obtained from equations (14) and (15).

Considering the additional computational effort for a more detailed consideration of the thermal boundary layers, the simplified model is recommended regarding the insulation and soil. Furthermore, especially for a given relative heights H/D below 0.5 (being rather untypical), the influence of the foundation/soil must be considered.

INTERNAL LOSSES DUE TO VERTICAL CONDUCTION

Stratifying hot water inside thermal storages results in energetic losses due to vertical temperature gradients. Furthermore, as the thermal conductivity of the diffusion barrier, e.g. $\lambda_{Steel} \approx$ 50W/mK, is considerably higher than the heat conductivity of the hot water itself ($\lambda_{H2O} \approx$ 0.678W/mK) the influence of the wall on the thermal stratification must be considered as well, cf. e.g. [9, 29]. Moreover, additional components and installations within the hot water such as pipes, radial diffusors for (dis-) charging, piping accesses or sensors interact thermodynamically with the storage media and the stratifying layer, causing thermal short-circuits. Resulting, gravitational mass flows falling down vertically arranged components may diminish the performance of these storages disturbing the thermal boundary layer.

LOSSES VIA THE WALL AND INSTALLATIONS

According to literature, vertical losses due to conductive effects inside the wall (diffusion barrier) are negligible for large scale storages. Thus, for diminishing relative wall-dimensions D/s_{Steel} >100, the influence of the casing on stratifying the thermal storage media is of minor importance. Therefore, additional conductive effects via the wall are not considered, cf. [9].

The reason for this numerically observed phenomenon is the vanishingly low heat amount stored inside the wall C_{Wall}, comparing it to the heat amount stored within the storage media (water) itself C_{H2O}, see equation (17). Thus, regarding the storage system defined in Table 1 and Fig. 1, the influence of further components and installations may be neglected as well, see equation (18).

$$C_{Wall} = m_{Wall} * c_{pWall};\ C_{H2O} = m_{H2O} * c_{pH2O}, \quad (17)$$

$$0.95 < C_{H2O}/(C_{H2O} + C_{Wall} + \sum C_{Comp}),\ \text{cf. [30]} \quad (18)$$

Resulting from equation (18), another 17,000 tons of steel could be installed within the thermal storage in addition to the masses of the wall (a cube of 12.84 x 12.84 x 12.84m³), which is rather unrealistic. Thus, transient processes of these components are not effecting the stratification of thermal storages in large scale. Nevertheless, vertical pipes and piping accesses should be avoided in order to support the thermal stratification of the storage tank.

LOSSES DUE TO INTERNAL CONDUCTION

Regarding the statements above, the energetic losses of a thermal storage within urban DH networks are technically independent of conductive effects via the wall and further components. Thus, the development of the temperature distribution merely results from temperature diffusion inside the storage media (water). Compiling a model for heat storages in Visual Basic (VBA), the growth of this diffusion zone can be mapped.

Generally, the local temperature within thermal storages or any figure in transient state depends on the position and time. This physical context is described by the heat transfer equation (19a) for a cylindrical system, cf. [27]. Assuming no internal heat sources $\dot{\Xi}_s$ and homogeneous properties of matter within this figure as well as an adiabatic system, angular and radial dependencies are eliminated. Thus, a one-dimensional, time dependent model of the thermal storage results, see equation (19b).

$$c_p \rho \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda\frac{\partial T}{\partial r}\right) + \frac{1}{r}\frac{\partial}{\partial \varphi}\left(\frac{1}{r}\lambda\frac{\partial T}{\partial \varphi}\right) + \frac{\partial}{\partial H}\left(\lambda\frac{\partial T}{\partial H}\right) + \dot{\Xi}_s \quad (19a)$$

$$c_p \rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) \quad (19b)$$

In order to map axial conductive effects in axial direction within the thermal media (water), two adjacent layers on different temperature levels are assumed. This assumption accounts for the stratifying character of the thermal storage. The transitional zone between these layers is assumed to be vanishingly small, maximising the transitional heat flows.

Subsequently, the unsteady development of the temperature distribution and temperature diffusion zone is mapped numerically by applying the method of finite volumes. For this purpose, every layer n of the thermal storage is divided into several elements m, s. Fig. 5.

Basing on the assumptions above, the temperature gradient of each element is exactly in vertical direction of the thermal storage. Thus, representative temperatures for each element independent of the radial position are calculable. The algorithm for calculating these representative temperatures and the temperature distribution within the storage for a given time scale τ is:

1. Definition of
   - time step Δt, e.g. $\Delta t = 1s$
   - maximum time scale τ_{max} , e.g. $\tau_{max} = 96h$ and
   - starting temperatures for time step i=0, within each layer n and its elements m, $T_{i,nxm} = T_{i=0,1...n \times 1...m}$, e.g. $T_{0,1 \times 1...m} = T_{max} = 98°C$ for layer n=1 and its elements and $T_{0,2 \times 1...m} = T_{min} = 60°C$ for layer n=2 and its elements.
2. Calculation of the heat flux between adjacent layers n and n±1 as well as elements m and m±1 of a height h_{el} and temperature difference ΔT_{el}, see equation (20)

   e.g. $\dot{Q}_{i,n\,x\,m \Rightarrow m\pm1}(t_i \neq 0) = \lambda_{H2O} A \Delta T_{el} / h_{el}$ (20)
3. Calculation of the heat transferred between adjacent elements m and m±1within the time step $t_{k=0...\tau}$, see equation (21)

   e.g. $\dot{Q}_{i,n\,x\,m \Rightarrow m\pm1} * \Delta t = Q_{i,n\,x\,m \Rightarrow m\pm1}$ (21)

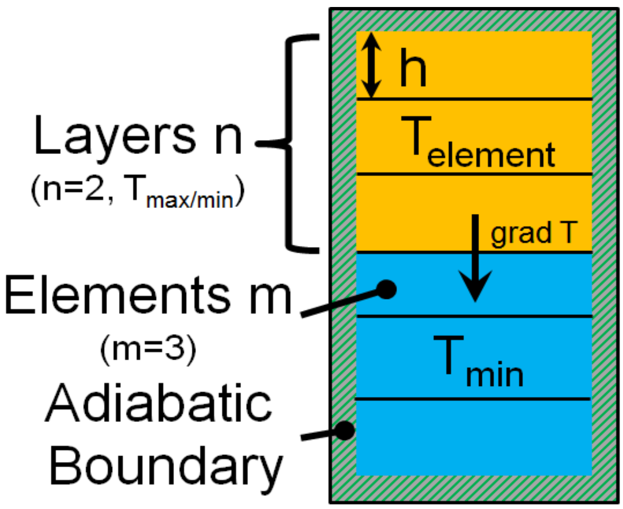

Fig. 5: Scheme of the finite volume model

4. Calculation of the temperature shift/drop of the time step i $\Delta T_{i,m}$ of each element m considering its mass m_{el}, see equation (22)

   e.g. $\Delta T_{i,n\,x\,m\pm1}(t_i) = Q_{i,n\,x\,m \Rightarrow m\pm1} / (m_{el} c_{pH2O})$ (22)
5. Calculation of the new representative temperature of the element m for the next time step $t_{i+1}=t_i+\Delta t$

   $T_{i+1,n\,x\,m}(t_{i+1}) = T_{i,n\,x\,m}(t_i) + \Delta T_{i,n\,x\,m \Rightarrow m\pm1}(t_i)$ (23)

The steps 2 to 5 are repeated as long as $t_{i+1} \leq \tau_{max}$. The resulting temperature distribution within the thermal storage is shown in Fig. 6.

Considering this algorithm, it is vital to adjust the time step Δt and mass (height) of each element m_{el} (h_{el}) in order to obtain correct results for the temperature distribution. Diminishing the time scale may lead to very small shifts/drops of the temperature $\Delta T_{i,m}$ (t_i) of an element m defined. Thus, rounding errors may result in static temperature distributions. On the other hand, increasing the number of elements m, causes numerical diffusion as well as significantly higher computational effort.

For this purpose, equation (24) is giving a rough indication for the time scale necessary in order to obtain realistic and stable results.

$\Delta t = h_{el}^2 \rho_{H2O} c_{pH2O} / \lambda_{H2O}$, cf. [31] (24)

Concerning the quality of the temperature profiles, an excellent correspondence to numerical results published in literature as well as measured data can be stated, cf. [2, 3, 4, 6, 9, 10, 12]. This quality, however, is generally independent from the initial temperature differences ΔT_{el} as long as interactions between:

a) The thermal diffusion zone and the boundaries of the heat storage and
b) Multiple thermal diffusion zones (n>2)

are excluded from calculations.

Finally, the energetic performance of the thermal storage is calculated. For this purpose, the energetic contents of each element m within the storage above a critical temperature level ($T_{minSupply}$ = 88°C) and a given configuration of thermal layers (n=2, T_{max} = 98°C, T_{min} =

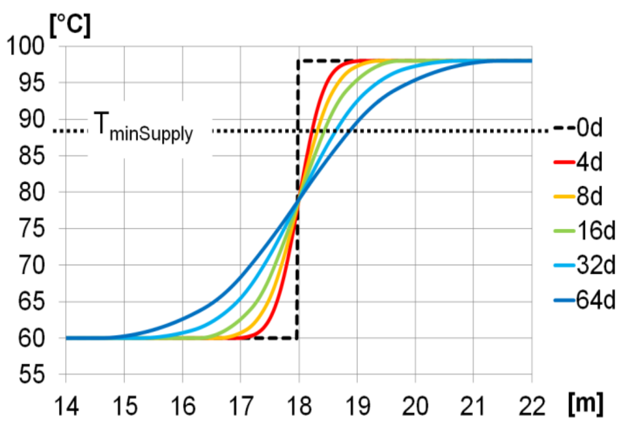

Fig. 6: Development of the temperature diffusion zone of the thermal hot water storage

60°C) must be calculated. The resulting energetic efficiencies η_{ex} are given in Table 6, according to equation (25).

$$\eta_{en} = \frac{\sum m_{el} c_p \left(T(\tau)_{\,element} - T_{minSupply}\right)}{m_{el} c_p \left(T_{max} - T_{minSupply}\right)} \tag{25}$$

Table 6: Energetic efficiency of the thermal hot water storage

τ [days]	η_{enCond} [%]	τ [days]	η_{enCond} [%]
2	98.34	16	95.60
4	97.60	32	93.46
8	96.73	64	91.02

CONCLUSIONS ON ENERGETIC LOSSES DUE TO VERTICAL CONDUCTION

Additional energetic losses due to axial conduction via the wall and vertical installations and components are negligible for large scale storages applied in urban areas, see equations (17) and (18). The heat amount stored within the thermal media dominates the heat amounts stored within the wall and further installations by far. Thus, for the given geometry, see Table 1, a huge amount of thermal masses in addition to the wall (17,000 tons of steel) could be installed. Nevertheless, the orientation of pipes and further components should be horizontal for stabilising the stratification. Following general suggestions on the orientation of these installations guarantees the stability of the thermal boundary layer, cf. [30].

Resulting, the energetic performance of these storages depends merely on conductive effects inside the hot water. These effects are modelled for a maximum temperature gradient of 38K between the stratified thermal layers, as well as for different maximum time scales τ. The energetic performances according to equation (25) diminish at constant time scales, for decreasing

a) Heights H of the storage and
b) Relative temperature drops Θ, see equation (16).

The energetic efficiency η_{enCond} is still excellent for representative maximum time scales τ of less than 96h, see Table 6. Furthermore, the energetic losses of these storages are comparatively high in comparison to external losses.

LOSSES DUE TO MIXING

Finally, losses due to turbulences induced by (dis-) charging and free convective effects shall be approximated for technical purposes. This task, however, must be subdivided into two independent parts. At first, the additional heat losses to the environment caused by internal flows and diminished dimensions of the thermal boundary layer have to be calculated. Considering the results of the corresponding chapter, the heat transfer coefficients of boundary layers are not influencing the heat losses significantly. Thus, the resulting increase of the heat and energy losses are negligible due to the insulating layer of the storage, cf. e. g. Table 3.

On the other hand, the thermal boundary layer may be disturbed or destroyed by inertial forces of the mass flows induced during (dis-) charging periods or free convective effects. The latter are caused by gravitationally driven mass flows falling down the cold bearing structure inside the storage. Thus, due to gradients in temperature and density within radial direction of the storage, volumetric and energetic contents are lost for further utilization. Therefore, these mass flows have to be approximated for representative time scales.

TURBULENCES INDUCED BY CHARGING

According to literature, radial diffusors are state of the art for (dis-) charging thermal storages. Utilizing these components, the momentum of fluid, entering or leaving small or large scale storages is reduced to a minimum and generally directed in radial direction. This supports the stability of the stratification inside the storage and minimizes energetic losses. Concerning the (relative) proportions of radial diffusors, general guidelines for the technological design are given in [30]. Resulting, the mixing zone induced by (dis-) charging the thermal storage is minimized.

Assuming a thorough geometrical adaption of radial diffusors within large scale storages, a constant ration ζ between the height of the mixing zone and the height of the radial diffusor inlet h_{diff} can be assumed, cf. [6, 10, 30, 32, 33]. According to literature, ζ is restricted to a maximum of ζ_{max} = 12 for most unfavourable operating conditions. Resulting, within large scale storages as described in Table 1, approximately 5,600m³ are lost due to (dis-)charging the storage (h_{diff} = 375mm).

VOLUMETRIC FLOWS INDUCED BY FREE CONVECTION

Within thermal storages, mass flows due to gradients in temperature and density occur. In order to approximate these losses, correlations basing on numerical and analytical approaches are considered, compared and evaluated. Thus, the calculation of volumes and thermal masses applicable for DH heating purposes becomes possible.

Generally, correlations for mass flows induced by free convective effects are sparsely given in literature. On the other hand, several experimental reports on the thermodynamic performance of (small scale) thermal storages give velocities v_{fall} for falling films. These are typically within a range of 0.05 to 20mm/s. Furthermore, the thickness δ_{Flow} of these falling films are typically reported to be below 5mm, cf. [30, 34]. Thus, within a fully loaded thermal storage a volume of up to 2,200m³ is lost for further utilization according to equation (26). A representative time scale τ_{max} of 96h is assumed.

$$V = \tau_{max} * c_{Fall} * \pi/4\,[D^2 - (D - \delta_{Flow})^2] \quad (26)$$

$V = 54.3 \ldots 2{,}171m^3$ with $\tau_{max} = 96h;$

$\delta_{Flow} = 0.005m;\ \ v_{Fall} = 0.005 \ldots 0.02m/s$

Continuative to numerical examinations on the heat capacity flux of gravitationally driven mass flows [34], an equation for calculating the falling film velocities v_{fall} is derived in [30], see equation (27). Within this equation, the heat losses $\dot{q}_{loss}$ via the wall, a vertical temperature gradient ∂T/∂z, the dimension δ_{Flow} of the flow boundary layer as well as the geometry of the thermal storage are considered. The falling film velocity v_{fall} < 0,4mm/s calculated results in a maximum volume of just 41.6m³ lost within 96h. The temperature gradient ∂T/∂z is minimized for the purpose of a worst case approximation, see operational parameters in Table 1.

$$v_{fall} = -0.953\,\dot{q}_{loss}/\left[\rho_{H2O}c_{pH2O}\delta_{Flow}(\partial T/\partial z)\right] \quad (27)$$

$v_{fall} \approx 0.38mm/s$ with

$\delta_{Flow} = 5mm;\ \dot{q}_{loss} < 8.4W/m^2;\ \partial T/\partial z = 38K/36m$

According to the given equations and ranges for falling film velocities, a broad deviation of the volumetric flows and lost volumes must be stated. However, this is clearly connected to most different operating and geometrical boundary conditions. Thus, the given equation (27) fits numerically derived mass flows for vertical temperature differences of ∂T/∂z = 25 to 200K/m.

Furthermore, heat losses $\dot{q}_{loss}$ via the wall of roughly 80W/m² are assumed, whereas the heat transfer coefficient k of the storage examined is roughly around 2W/m²K, cf. [30, 34]. Against this background, these numerically derived equations are not necessarily adjusted for large scale thermal storages insulated significantly better. Therefore, analytical approaches for deriving the approximate dimension of the thermal and flow boundary layer as well as falling film velocity are considered.

Interpreting the heat transfer coefficient α of a thermal boundary layer geometrically, its dimension δ_{Temp} may be approximated by equation (28), see also Fig. 7. Furthermore, as the Prandtl-number Pr=ν/a, correlates the flow and temperature field and corresponding boundary layers. Thus, the the flow boundary layer δ_{Flow} within the thermal storage may be calculated basing on equation (29) and the results from Table 3 cf. e.g. [27, 35, 36].

$$\delta_{Temp} = \lambda_{H2O}/\alpha_{free} \quad (28)$$

$$\delta_{Flow} = Pr * \lambda_{H2O}/\alpha_{free} = 5.1cm \quad (29)$$

$\lambda_{H2O} = 0.678W/mK;\ \alpha = 23.23W/m^2K;\ Pr = 1.753$

Furthermore, the velocity for falling films v_{fall} is derived by balancing frictional, inertial and gravitational (buoyancy) forces. Whereas, frictional forces dominate the balance of powers next to the wall (adhesion), inertial forces are dominant outside the flow boundary layer. Resulting, within the transfer zone of the layer itself, all forces are of the same magnitude. This finally leads to a correlation describing the velocities of a free convective flow, see equation (30). Within the context of this paper, further details on the derivation of this equation as well as on the function f'(η) will not be given here, see e.g. [35, 36].

$$v_{Fall} = 2\nu Gr^{0.5} f'(\eta)/l_{Wall} \quad (30)$$

Distinguishing from calculations for the maximum heat transfer via the thermal boundary layers, the densities of the hot water must be applied as exact as possible, as the equation (30) strongly depends on Gr, see. For this purpose, the temperature drop within the thermal boundary layer inside the thermal storage is calculated, see equation (31) and Fig 7.

$$\dot{q}_{Wall} = k\Delta T = \alpha_{in}\Delta T_{in} = \lambda_{Ins}/s_{Ins} = \ldots \quad (31)$$

$\Delta T_{in} \approx (8.216/23.23)K = 0.3616K$

Thus, the densities of the water next and far off the wall ρ_0 and ρ_∞ are:

$\rho_\infty(98°C) = 959.94kg/m^3$ and

$\rho_0(97.65°C) = 960.20kg/m^3$.

(Sampling points given in [14] are interpolated linearly.)

Basing on equation (30), the falling film velocity and volumetric flow are 1.24mm/s and 1,372m³ within 96h. Thus, the resulting volumetric and energetic efficiency of the thermal storage is 96.9%, see equation (32).

$$\eta_{enfall} = (V_{tot} - V_{loss})/V_{tot} = 96.9\% \quad (32)$$

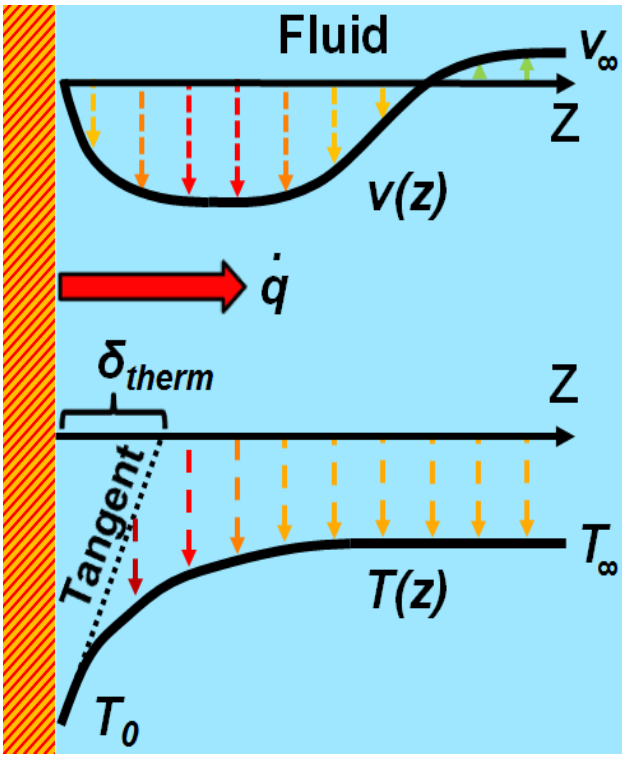

Fig. 7: Interaction of thermal and flow boundary layer cf. [35, 36]

CONCLUSIONS ON ENERGETIC LOSSES DUE TO MIXING

Generally, turbulences due to (dis-) charging cycles influencing the stratifying layer can be avoided by applying radial diffusors. Guidelines for a successful implementation of these components in situ are given in [30]. Key factors for conserving the stratification and minimizing the mixing zone are

- an adequate distance between the stratifying layer and the radial diffusor, of course,
- laminar in- and outlet conditions for the mass flows, ($Re_{charge} \approx 300$), cf. [6].

This conclusion is supported by simulations and experimental results as well, cf. e.g. [6, 10, 30, 32, 33]. Thus, volumetric losses of the mixing zone are restricted to 5,600m³ within the storage system defined. However, mixing cause an inevitable volumetric and energetic loss, being of the same magnitude as the dimensions of the thermal diffusion layer approximated above, cf. also Fig. 6.

Furthermore, volumetric and energetic losses due to free convective effects are approximated. For this purpose, numerically derived correlations from literature are applied, showing broad deviations, s. [30, 34]. Moreover, these correlations seem to be inappropriate for large scale thermal storages of urban areas.

Against this background, analytically derived correlations for the dimensions of the flow boundary layer δ_{Flow} as well as falling film velocities v_{fall} are regarded, cf. [35, 36]. Thus, for the given thermal storage, a maximum volumetric loss of <1,400m³ within a representative period of 96h is calculated, resulting in and volumetric and energetic efficiency of η_{enfall} of 96.9% concerning free convective effects.

SUMMARY AND PROSPECTS

Thermal storages will become an essential component of DH networks in future. Applying this technology, the operation of CHP plants is more flexible, enhancing their energetic efficiency due to shifting full load hours as well as the profitability of DH systems. However, external and internal losses of these storages must be considered for a successful integration. Against this background, different heat loss mechanisms are approximated for a worst-case scenario. Thus, operating conditions, time scales, gradients of temperature and density and further material properties are adjusted for a representative thermal storage of an urban DH network, see Table 1 and Fig. 1.

External losses to the environment are strongly dominated by the thermal insulation. For a given (representative) dimension and conductivity of this layer (s_{Ins} = 40mm; λ_{Ins} = 0.035W/mK), up to 99.5% of the temperature drop occur within the insulation. Disregarding any thermal boundary layer, a maximum heat loss $\dot{q}_{loss}$ of 8.26W/m² is calculated. This value is representative for the vertical wall surrounding the hot water and the steam cushion. More detailed calculations give small deviations, cf. Table 3 and Table 4 Concerning the losses via the roof and foundation this value drops to 6.75W/m² and 4.31W/m². However, the latter drop is influenced by the lower temperature gradient between the hot water and the soil.

Resulting, a simplified model of the heat losses considering the insulation and soil (especially for H/D<0.5, which is rather untypical), is recommended. Thus, the overall heat flows and temperature drop within the storage is calculable quite exactly (ΔT_{max} = 0.1K within 96h). The energetic efficiency η_{enExt} for a maximum operating temperature (T_{max} = 98°C) and a minimum acceptable supply temperature ($T_{minSupply}$ = 88°C) is 99%.

Within a second step, internal losses due to transitional and conductive effects within thermal masses (wall and storage infrastructure such as radial diffusors or pipes) and between different layers of the thermal storage media, are examined. According to literature, additional conductive losses in axial direction via the wall are negligible. This is due to vanishingly low heat capacities of the wall in comparison to the heat capacity of the hot water, see equation (17) and (18), cf. [9, 30].

Against this background, transitional effects within any components incorporated inside the thermal storage are negligible, as a huge amount of additional thermal masses (17,000 tons of steel) would be necessary to induce a significant disturbance of the thermal stratification. However, vertically directed piping systems and pipe accesses should be avoided in order to stabilize stratification, see [6, 30]. Resulting, merely the propagation of the thermal boundary layer within the thermal storage media itself is relevant.

Thus, a finite volume model of a thermal storage is compiled, mapping, the development of the thermal diffusion layer. Results obtained are in good accordance with literature, cf. e.g. [2 to 4, 9 to 12 and 30]. For the given operating conditions of the storage, an energetic efficiency η_{enCond} of 97.6% is obtained for a representative time scale of 96h.

Moreover, mixing losses induced by (dis-) charging cycles are approximated. Assuming the application of radial diffusors, the ratio ζ between the height of the mixing zone and the height of the inlet h_{diff} at the radial diffusor is constant for any storage system. Thus, for the given system, the share of the mixing zone is restricted to 12.5% which corresponds to a volumetric loss of 5,600m³ for the given storage system. Underlying assumptions will be validated with operational parameters of large scale thermal storages parameters in future.

Finally, energetic losses induced by falling films are approximated basing on numerically and analytically derived correlations. Whereas numerical correlations show broad deviations and seem to be inappropriate for large scale storages, analytically derived correlations can be adjusted to the given storage system. The resulting volumetric and energetic efficiency η_{enfall} considering falling films are 96.9%, which corresponds to a volumetric loss of <1,400m³ for the given storage system.

Summarizing energetic losses, the efficiency of thermal large scale storages for short term periods, as usually applied in urban areas, are quite excellent. Despite of a worst case approximation, basing on most unfavourable operating conditions and material properties assumed, the energetic efficiency η_{enTot} is 93.6% for a time scale of 96h, see equation (33).

$$\eta_{enTot} = \eta_{enExt} * \eta_{enCond} * \eta_{enfall} = 93.6\% \quad (33)$$

This efficiency is basically supported by three underlying mechanisms counting for large scale storages of urban areas:

1. Small share of surface area per volume,
2. Small share of surface area per heat stored inside the hot water/ the storage media and
3. Small share of heat stored inside the wall/components incorporated and the hot water/ the storage media.

In addition to these losses, inevitably occurring volumetric losses induced by (dis-)charging must be considered as well. These, however can be reduced by shifting the relative height H/D of the storage system.

Thus, thermal short term storages within urban areas support the adaption of constituent DH networks for future challenges concerning energy efficiency, flexibility of operation and profitability. In order to quantify the impact of these components on the operation of a DH system, the results obtained have to be implemented into an overall DH network-simulation. On this basis, the operation of thermal storages can be examined and optimised, basing on typical scenarios coupling the heat load and electricity market.

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NOMENCLATURE

Greek Symbols

α	Heat Transfer Coefficient Layer [W/mK]
δ	Strength of Boundary Layer [m]
ζ	Relative height [-]
λ	Heat Conductivity [W/mK]
ν	Kinematic Viscosity [m²/s]
$\dot{\Xi}$	Density of internal Heat Sources [W/m³]
ρ	Density of Matter [kg/m³]
τ	Maximum Duration [s] or [h]
φ	Angle [°]

Latin Symbols

A	Area [m²]
a	Thermal Diffusivity [m²/s]
C	Stored Heat [J/K]
c_p	Isobaric Heat capacity [J/kgK]
D	Diameter [m]
g	Gravitational Accelaration [m²/s]
k	Overall Heat Transfer Coefficient [W/mK]
l	(Characteristic) Length [m]
H	Height [m]
m	Mass [kg]
$\dot{m}$	Mass Flow [kg/s]
$\dot{Q}$	Heat Flow [W]
$\dot{q}$	Heat Flow per Area [W/m²]
r	Radius [m]
s	Thickness of Wall [m]
t	Time [s]
V	Volume [m³]
v	Velocity [m/s]

Non-Dimensional Symbols

$f_1/f_2/f'$	Function, see [36]
Gr	Grasshof-Number
Nu	Nusselt-Number
Pr	Prandtl-Number
Ra	Rayleigh-Number
Re	Reynolds-Number
Δ / ∂	Difference
η	Efficiency [%]
Θ	Overtemperature

Indices (selction)

Amb	Ambient
Comp	Components
Cond	Conductive
Ext	Exterior Losses
Flow / Temp	Flow / Thermal Boundary Layer
Found	Foundation
free / forced	Free / Forced Convective
H2O	Water
Ins	Insulation
in/out	In-/Outside Storage
n / m	Number of Layers /Elements
tot	Overall; Summarizing
turb/lam	Turbulent/Laminar

SESSION 7

Key elements in District Heating and Cooling systems

MEASURED LOAD PROFILES FOR DOMESTIC HOT WATER IN BUILDINGS WITH HEAT SUPPLY FROM DISTRICT HEATING

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ABSTRACT

In the actual development towards nearly zero energy buildings (nZEB), the heat demand for domestic hot water in buildings will be relatively more important concerning the economy of district heating. It might also be assumed that the amount of domestic hot water in nZEBs will be relatively constant as today even if the heat demand for space heating and for heating of ventilation air will be reduced. This means that measured values in buildings of today might be fairly relevant also for future buildings.

This paper is presenting load profiles for domestic hot water for buildings with heat supply from district heating. The load profiles are based on hourly values measured by the regular heat meter and show average specific values for single family houses and apartment blocks, office buildings, educational buildings, hospital buildings and hotel and restaurant buildings. It also presents estimated values for the system efficiency of the domestic hot water system in the buildings. The presented information in the paper is expected to be useful in the planning of district heating in the future.

INTRODUCTION/PURPOSE

The presented load profiles will be fairly easy to use for estimating yearly heat demand for domestic hot water for the respective building categories. The results also indicate that the system efficiency of the domestic hot water system should be improved by better pipe insulation.

METHODS/METHODOLOGY

The load profiles are developed from measured hourly values of the delivered heat to buildings from district heating systems in Bergen, Norway for ("Apartments"), and in Trondheim, Norway for the other buildings. The measured hourly values of delivered heat are treated statistically by a method developed through a PhD theses [1] made at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway.

STATE OF THE ART

Measuring heat demand of buildings have until recently been time consuming and rather expensive. There are therefore not too many results from such measurements shown in the literature. This is especially true for measured values for domestic hot water.

RESULTS

In Figure 1 we see heat load profiles throughout the day showing average hourly values for single family houses, row houses and apartment blocks as a group (Named "apartments") where the average floor area of the "apartments" was 95m^2. As it could be expected there is a clear difference between weekdays and weekends. This fact might also be considered as a verification of the quality of the measurements and the method used for treating the data.

The heat load profiles indicate also that the system efficiency of the domestic hot water system is rather poor. The average specific heat load throughout the day for weekdays can be calculated to 8.1 W/m^2. If we assume that the lowest measured values during night time represent the heat loss from the distribution system, this value can be estimated to be in the range of 5 W/m^2. The heat from the discharge cocks per year can then be calculated to be about (8.1-5)/1000) • 24 • 365 • 95~2580 kWh/Year.

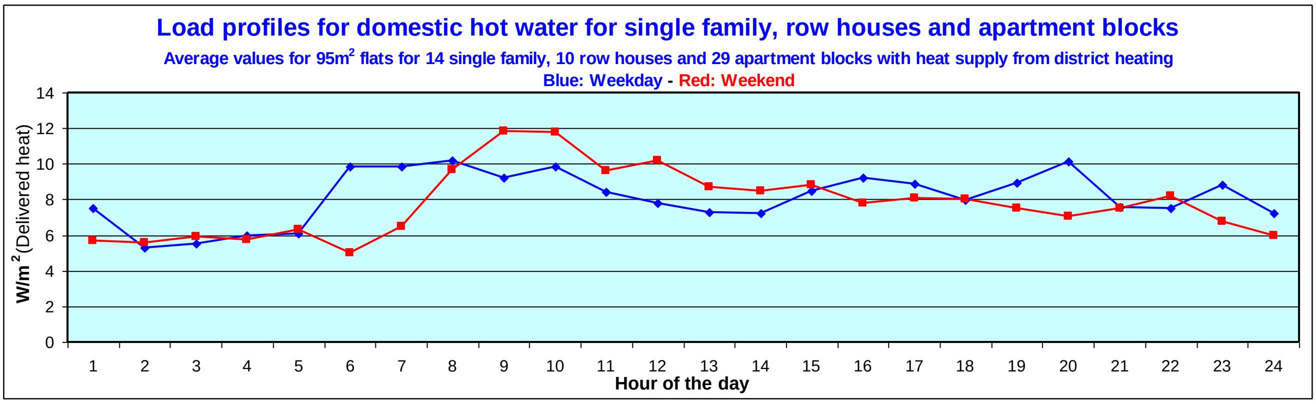

Figure 1

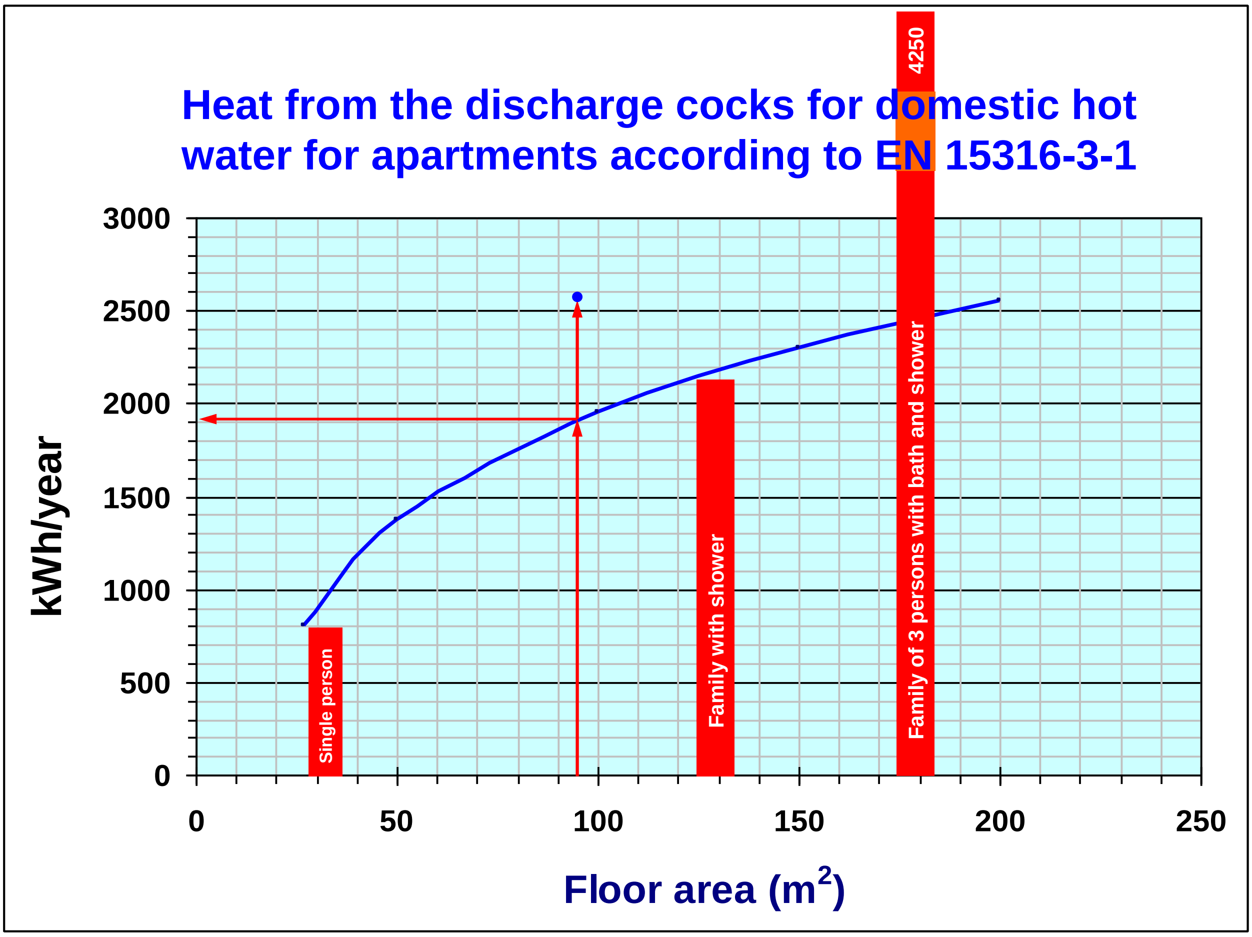

Figure 2

From Figure 2 we can see that the measured value for heat use for domestic hot water in the actual apartments is in the range of 35% higher than the estimated use we get by calculation from the equation given in the European standard EN 15316-3-1 (Blue curve). This equation presupposes that only showers are installed in the apartments. In the measured buildings a bath might be installed in addition to the shower since bath and shower are rather common in Norwegian homes.

Figure 3 displays average hourly heat load profiles for office buildings throughout the day. The peak load occurs in the morning at about 8 a.m. as one could expect. The peak values about 3 p.m. and 22-23 p.m. are in line with what we might expect from the daily routines in office buildings where some people are working overtime until rather late evening. The heat load profiles for weekends indicate that there are some activities in the office buildings also during weekends. For some reasons there are somewhat high values of heat use at 5-6 a.m. on weekends. The hypotheses here might be that some floor washing activities might be scheduled at that time of the week.

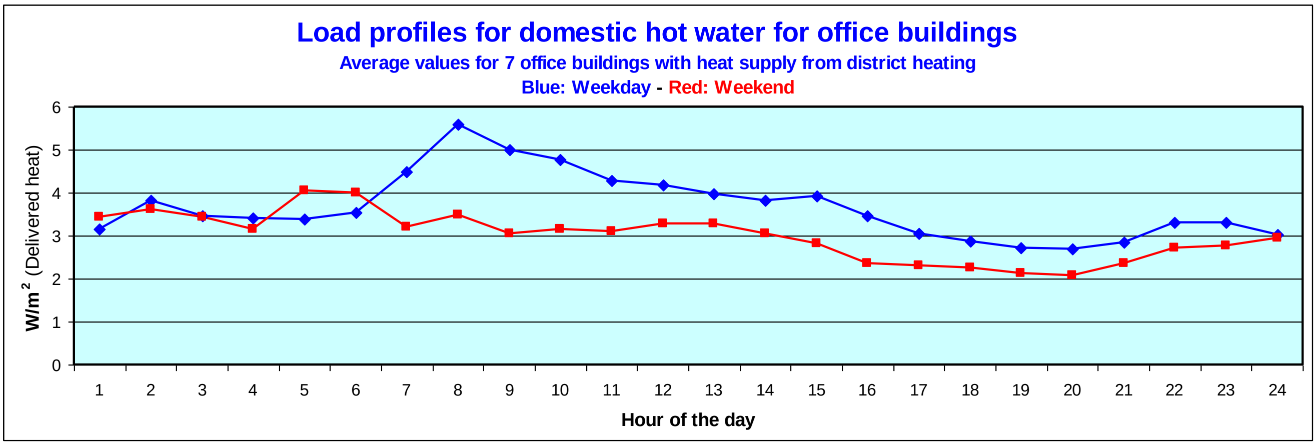

Figure 3

In Figure 4 we see average hourly values for heat load profiles for educational buildings throughout the day. Here we see typically tree peaks during the day on weekdays. The peaks at 8 a.m. and 2 p.m. are just as

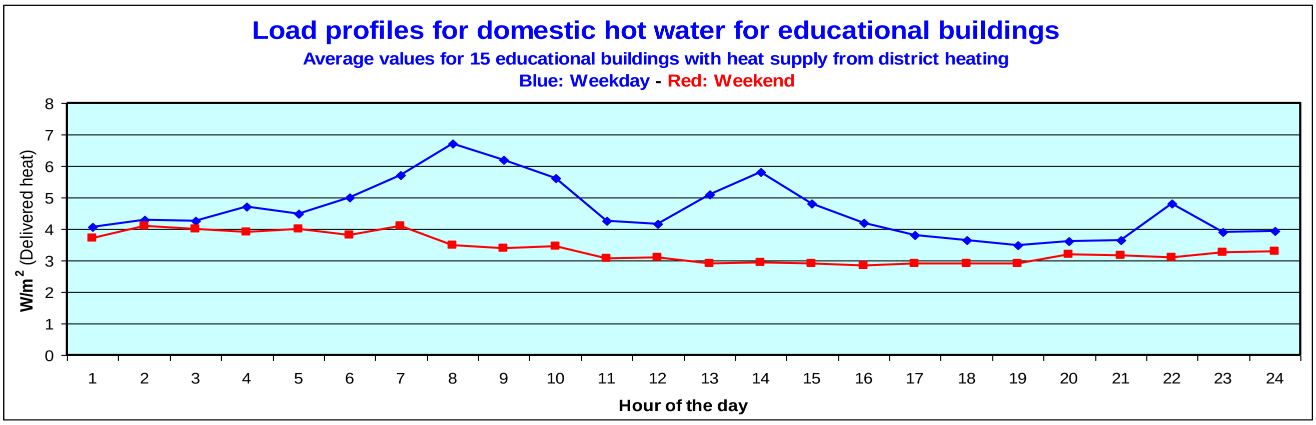

Figure 4

we could expect due to the scheduled activities in educational buildings. The peak at 10 p.m. on weekdays is as expected since educational buildings normally have some activity in the evenings.

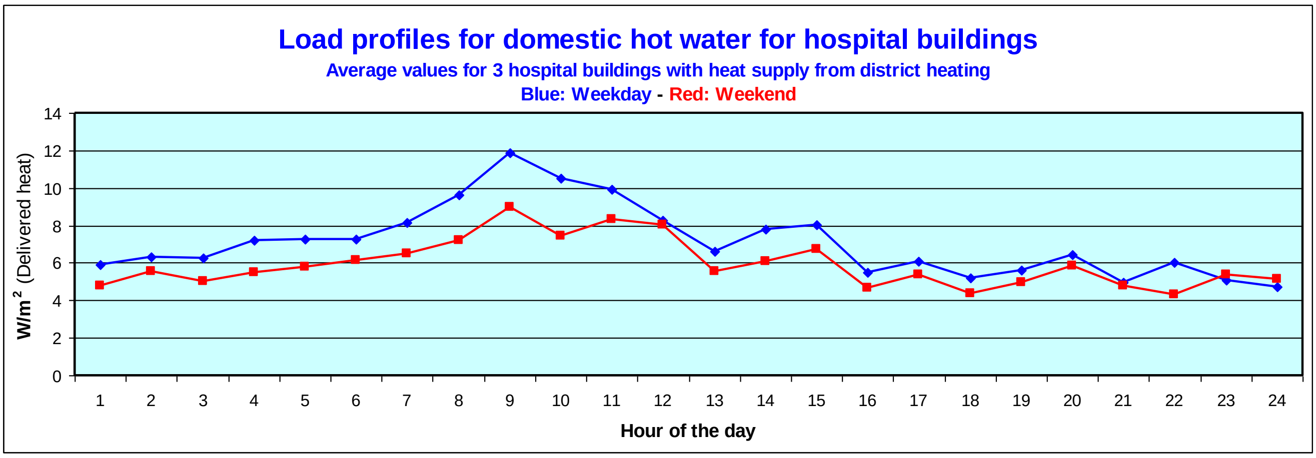

Figure 5

In Figure 5 we see heat load profiles for domestic hot water throughout the day by average hourly values for hospital buildings.

The peaks on the profiles clearly reveal the routines of the activities in a hospital building. The routines on weekends seem to be pretty much the same as on weekdays but with slightly reduced activity.

Figure 6 shows heat load profiles throughout the day by average hourly heat values for hotel and restaurant buildings. We see that the activity on weekdays starts at about 7 a.m. with a great peak at 8. a.m. The peak is most likely due to the bath and shower activity from the hotel guests that has to be taken within a narrow timeframe. The morning peak on weekends is delayed

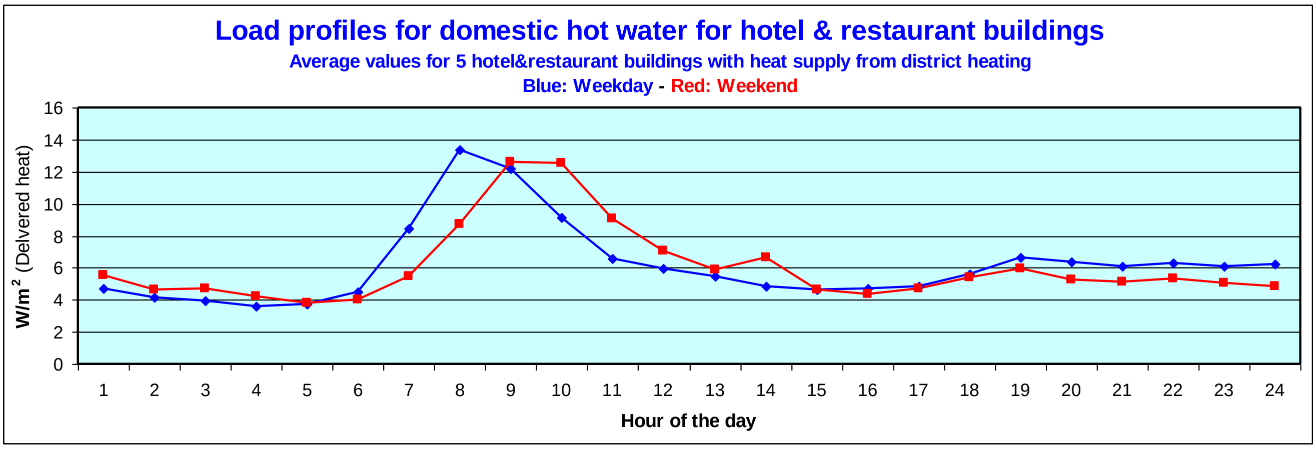

Figure 6

1-2 hours since the guests normally just have to reach the breakfast that normally ends at 10 a.m. on weekends.

EFFICIENCY OF THE DOMESTIC HOT WATER SYSTEM IN THE BUILDINGS

Directive 2010/31/EU on the energy performance of buildings (recast) is focusing on system efficiencies from the end use of energy and all the way back to the energy source. According to the EN 15316-series, we have to determine the system efficiency of the domestic hot water system to be able to calculate the delivered heat energy to the building. By using primary energy factors (PEF) we can then calculate the primary energy use of the actual end use of energy.

Table 1

	Estimated average heat loss from the domestic hot water system in the building (W/m^2)	Average total delivered heat load to the domestic hot water system in the building (W/m^2)		Estimated system efficiency of the domestic hot water system in the building (Heat loss/delivered heat)	
		Weekdays	Weekends	Weekdays	Weekends
"Apartments" 95 m^2	~ 5	8.1	7.8	~ 0.40	~ 0.35
Office buildings	~ 2	3.7	3.0	~ 0.45	~ 0.35
Educational buildings	~ 3	4.6	3.4	~ 0.35	~ 0.10
Hospital buildings	~ 4	7.1	5.9	~ 0.45	~ 0.30
Hotels and restaurants	~ 4	6.2	6.1	~ 0.35	~ 0.35

In Table 1 we are showing estimated values for the system efficiencies of the domestic hot water system in the actual buildings. We see that the system efficiency is fairly low for all the actual buildings. This is as expected since there has been very little focus on this issue until lately. Most likely the actual domestic hot water system has no insulation of the pipes in the actual buildings. By normal average insulation of the pipes we might expect system efficiency in the range of 60% for domestic hot water systems by calculating according to the EN 15316-series.

DISCUSSION

The results shown seem to prove that the statistical method used in this work is well suited to reveal the heat load profiles for delivered heat to a building from a district heating system. The statistical treatment of the measured hourly values seems also to reduce the influence of possible outliers, since these might be assumed to deviate from the averages sometimes above and sometimes below the average value. By aggregating such heat load profiles for the actual buildings in a planned district heating area, we automatically can calculate the actual time dependent heat load in the whole district heating system from the buildings through the nodes in the distribution system and all the way to the heat production plants.

OUTLOOK

The developed method for processing measured hourly heat values in district heating systems has great potential to make useful presentations of all the information you normally want from the data.

CONCLUSIONS

The following conclusions might be drawn from the results shown:

(1) The developed statistical method to treat measured hourly values of delivered heat to buildings from a district heating system has proved its capability to produce trustworthy values for load profiles for the use of domestic hot water to buildings.

(2) The results can easily be used directly for planning of district heating distribution systems and the capacity of the heat production plants in a district heating system.

(3) The results from the load profiles can be used to calculate the system efficiency of the domestic hot water systems in the buildings.

(4) The results give a strong indication that there is a great potential to improve the system efficiencies of the domestic hot water system in the actual buildings.

ACKNOWLEDGEMENT

Many thanks go to the co-author of this paper, Linda Pedersen Haugerud, for her valuable PhD-work that gave all the information needed to make this paper.

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CONNECTION OF THE TWO LARGEST DISTRICT HEATING NETWORKS OF GENEVA FOR A MORE EFFICIENT AND RENEWABLE OVERALL ENERGY SYSTEM: MONITORING, ANALYSIS AND SIMULATION OF DIFFERENT SCENARIOS BASED ON ACTUAL DATA

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ABSTRACT

This paper focuses on the monitoring and the analysis of the recent connection between the two largest district heating networks in Geneva, Switzerland. Each network has its own owner, operator and type of supply. Before the connection, one was supplied by gas boilers and the other by the municipal waste incineration combined heat and power (CHP) plant. The connection aims at improving heat recovery from the CHP. In this paper, the overall district heating system is analyzed by a systemic approach where both supply and demand side for thermal energy is studied, as well as its impact on the electrical energy production. Based on actual hourly data, an analysis of the resource availability, heat and power production and load profile is made. An input-output model of the system is developed in order to evaluate the heat recovery potential and elaborate scenarios regarding future district heating extensions and buildings refurbishment. Considering the present heat demand profile and waste availability, heat recovery from the waste incineration plant could increase from 142 to 233 GWh_{th} thanks to the connection. Network extensions could increase it to near 300 GWh_{th} even if a share of the heat demand is reduced by energy saving measures.

1 INTRODUCTION

This study is part of a project whose goal is to assess the role of district heating towards a more efficient and renewable energy system [1]. This role is well discussed and many studies show that thermal networks are key elements for the future energy system, allowing more efficiency, more renewable energy and more flexibility [2]-[3]. However, several technical and economic challenges need to be overcome in order to develop an efficient technology able to help achieving the main climate and energy goals [4]. Among many of these challenges, a key point is the opposition/synergy between district heating extensions and heat demand reduction [5]-[6].

District heating systems is a key energy infrastructure that enable to link resources to heat consumers, which is not always possible in an individual way. Another advantage is the flexibility regarding heat supply and particularly the possibility to combine different fuels in order to maximize the integration of renewable and waste heat. In this way, this paper focuses on the benefits of the connection between a thermal network supplied only by fossil-based boilers and another one supplied almost only by renewable/waste heat. The fundamental issue related to the connection of that kind of thermal networks is the possibility to increase the use of renewable/waste heat by sharing and consequently increasing base loads, while fossil-based boilers are supplying peak loads.

This issue is studied with a case-study in Geneva, where the two largest thermal networks have been connected in order to recover more waste heat from the waste-incineration CHP plant. The monitoring of both networks before the connection provided the input data necessary for the modelling of the connection. Results of the model are then compared to actual monitoring of the system after the connection. Finally, the model is used to assess the energy balance of the system with future district heating demand change, especially due to networks extensions and buildings refurbishment. The methodology developed in this paper can be generalized and used for other case-studies.

2 CONTEXT AND CASE STUDY

In Geneva, district heating system represents only 7-8% of the total heat demand, which is currently mainly covered by individual fuel-oil and gas boilers although the heat consumption is mainly concentrated in a restricted area [7]. This low penetration rate may be explained by the fact that electricity production from CHP has never been promoted due to the specific Swiss energy context characterized by a low carbon power production mix: national electricity production being mainly generated by nuclear (36%) and hydropower (59%) [8].

The first thermal network in Geneva (CADSIG, figure 1 blue line) was built in the 60's. Until 2013, it was only supplied by centralized gas boilers (160 MW_{th}). A second network (CADIOM, figure 1 green line) was built in 2002 with the aim of recovering waste heat from the municipal waste-to-energy CHP plant (60 MW_{th} and 30 MW_{el}). In 2013, both systems were connected to improve waste heat recovery and to offer new future development perspectives. A heat exchange station was built with three heat exchangers (3x25MW$_{th}$). Through this connection, heat can be exchanged in two ways: either to transfer waste heat from CADIOM into CADSIG, when there is more waste heat production than the total district heating demand, or to transfer heat produced by gas boilers from CADSIG to CADIOM, especially during peak load or when there is a lack of waste, instead of previous fuel-oil peak load boilers.

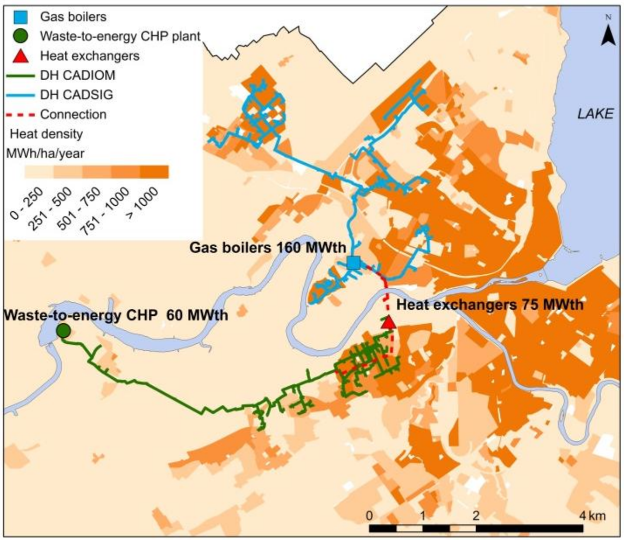

Figure 1: District heating system and heat density in Geneva

3 METHODOLOGY

3.1 General methodology

At first, the overall system before the connection was deeply analysed over one year with hourly measured data provided by the main stakeholders concerning heat and power production, heat transport and heat demand. Measured data is given from about 100 sensors (heat meters, flow meters, thermometers…). The evaluation of the energy system in real use conditions provided inputs for an input-output model which has been used to assess the heat recovery potential and more generally to establish the energy balance of the district heating system considering the networks connection (figure 2). Model results were then compared to measured data after the connection. In a second step the model was used to elaborate a sensitivity analysis considering prospective heat demand reduction and/or network extensions.

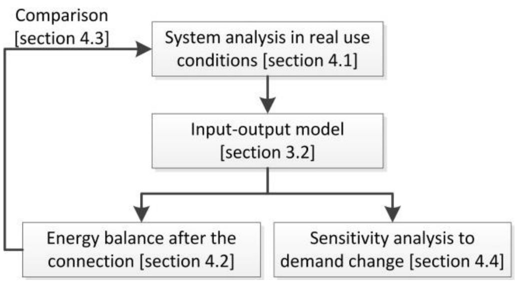

Figure 2: General methodology

3.2 Input-output model

The input-output model is based on an hourly time-step. The inputs are the district heating demand, the quantity and temporal distribution of waste incinerated, the boilers and CHP capacities and their efficiencies, and the relation between heat production and electrical production at the CHP plant.

The distribution of waste heat production throughout the year is estimated from the analysis of the waste incineration dynamics during the previous years which take into account slight variations due to the quantity of waste arrivals and incinerator revisions planning.

The hourly regulation of district heating supply gives priority to waste heat recovery. The hourly comparison between the waste heat generated at the CHP plant (q_w) and the hourly district heating demand (q_{dh}) allows estimating the quantity of waste heat that can be recovered into the district heating system ($q_{w,rec}$) according to the following equation:

$$q_{w,rec} = \min(q_w; q_{dh}) \tag{1}$$

The hourly district heating demand (q_{dh}), which consists in the sum of both network's demand, is divided into three components: space heating demand (q_{sh}), domestic hot water demand (q_{dhw}) and heat losses from pipes (q_l). Annual heat losses are calculated by the difference between district heating input (heat supply) and output (total heat consumed by the substations). In the model, heat losses are assumed to be constant throughout the year in absolute terms. Considering domestic hot water demand, it's assumed that it corresponds to the district heating demand during summer minus the heat losses from pipes. This demand is also assumed to be constant over the year. Finally, the hourly space heating share can be identified by difference according to the following expression:

$$q_{dh} = q_{sh} + q_{dhw} + q_l \tag{2}$$

Regarding the sensitivity analysis to future heat demand change induced by network extensions, linear heat density is considered to be constant, as the relative heat losses from pipes. Therefore, the extension in terms of pipe length is proportional to the increase of annual district heating demand, with the same relative hourly profile.

In case of heat savings (refurbishment of buildings), the hourly distribution of district heating demand is adapted by reducing the space heating demand share according to different type of energy savings scenarios, and by keeping similar heat losses and domestic hot water demand. Therefore, relative heat losses from pipes become higher and linear heat density decreases.

4 RESULTS AND DISCUSSION

4.1 Actual data analysis before the connection

Demand side

The overall district heating demand represents 370 GWh_{th}/year (CADIOM 150 GWh_{th} and CADSIG 220 GWh_{th}), with a maximum peak demand of 120 MW_{th}. The equivalent full load hours is of about 3'000h (see load curve in figure 3). The comparison between annual heat production and heat consumption of all the substations shows that annual heat losses from pipes represent 8%. This relatively low value is explained by the high linear heat density, 6-7 MWh_{th}/m. The domestic hot water and space heating demand represents respectively 25% and 67% of the total annual district heating demand.

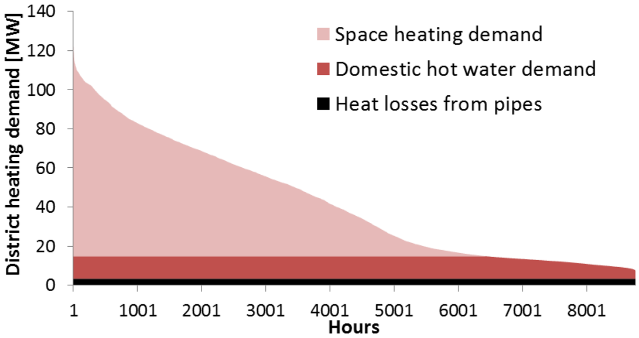

Figure 3: Load curve of aggregated district heating systems

The building stock supplied by the district heating system consists in more than 200 substations, mainly residential multi-storey buildings. The distribution of the substations according to their specific heat consumption (kWh/m^2/year) reveals that the majority of the substations consume between 110 and 150 kWh/m^2/year (figure 4). It involves a substantial potential for buildings refurbishment. In fact, buildings with specific heat consumption greater than 130 kWh/m^2/year will probably be renovated in coming years.

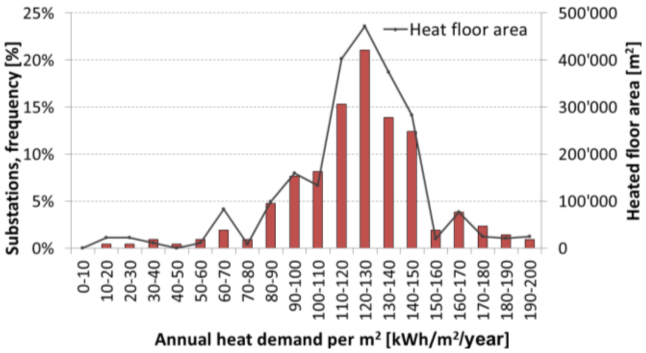

Figure 4: Substations specific consumptions distribution

A GIS-based analysis of Geneva's heat demand density (using the heat demand atlas based on annual buildings' consumption survey) attests that there is still an important extension potential into areas with high heat demand density [9]. 80% of the heat consumption is located into areas characterized by a heat density greater than 500 MWh_{th} per hectare, see figure 5.

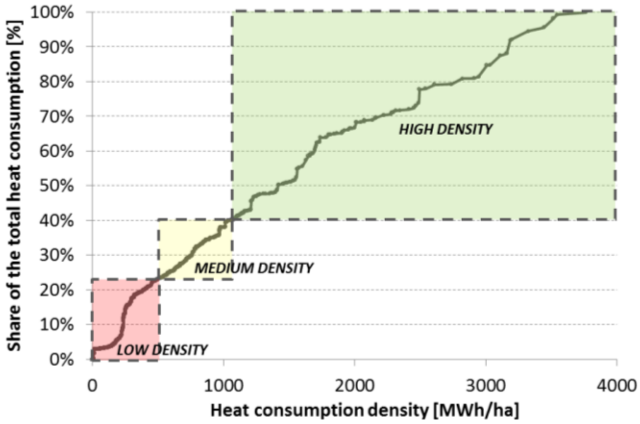

Figure 5: Heat consumption density in Geneva

Production side

The district heat demand is supplied by gas boilers (160 MW_{th}) with high efficiency (η=94%) and by the CHP waste-to-energy plant (30 MW_{el}). The waste incineration capacity is of 34 tons of solid waste per hour which represent around 100 MWh/h, considering an energy content of 3 MWh/t [10]. Electrical production is influenced by the heat recovery. The electrical efficiency of the CHP (extraction-condensing turbines) is 23.5% when no steam is extracted for the district heating supply. Data analysis shows that for each 1 MW_{th} recovered into the thermal network, the electrical production is reduced by 0.2 MW_{el}, more steam being extracted from the turbine (figure 6). The maximum heat capacity for the district heating after the power production is set to 45 MW [11].

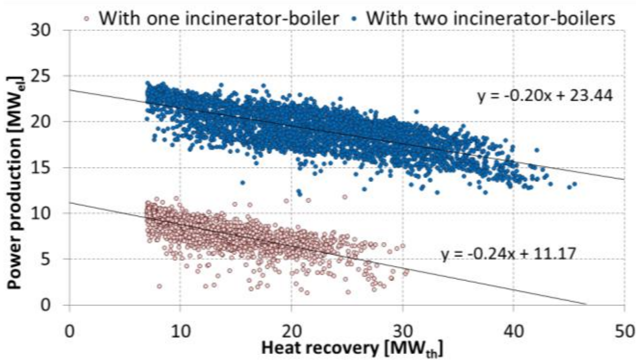

Figure 6: Hourly heat and power production relation at the incineration plant

Considering the resource, the annual amount of waste incinerated is about 220'000 tons which represents 660 GWh [12]. Waste availability throughout the year depends on the operation of only one or two incinerator-boilers, due to a lack of waste or boiler revision during some periods of the year.

4.2 Model results

Before the connection, a large amount of heat produced by the waste-to-energy CHP plant was wasted into a river, especially during summer. At the same time, gas boilers were supplying CADSIG network. The connection simulation demonstrates that the waste heat recovery could increase from 142 to 233 GWh_{th} and therefore save 91 GWh_{th} that would have been produced by fossil-based boilers which correspond to 88 GWh gas and 9 GWh oil (figures 7 and 8), equivalent to about 20 $ktCO_2$ [13]. Otherwise, electrical production is expected to decrease from 128 to 110 GWh_{el} due to steam extraction from the turbine.

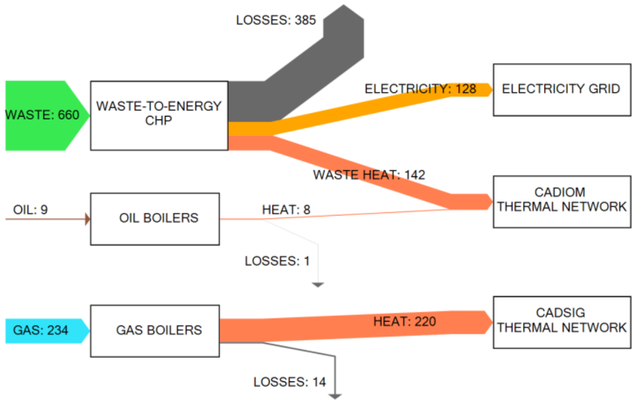

Figure 7: District heating system energy balance without connection, GWh/year

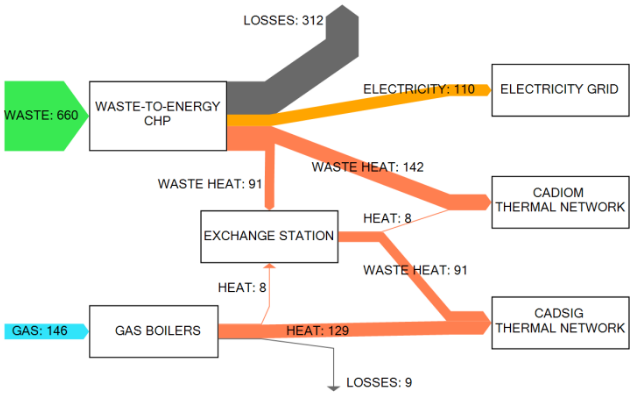

Figure 8: District heating system energy balance with connection, GWh/year

Looking at seasonal dynamic, one can notice that in summer, the overall district heating demand could be supplied only by waste heat (figure 9). In autumn and spring, the share of waste heat into the mix would depend on waste availability. In winter, gas boilers are still necessary in order to meet the demand. Even with the connection, some waste heat could still be recovered, especially during summer. With the present CHP plant efficiencies and quantity of waste, the theoretical maximal heat recovery amounts to 317 GWh_{th} (the area under the red line, figure 9). The dark green surface (figure 9, bottom) corresponds to the energy that would have been supplied by gas before the connection, while the hatched surface in dark blue (figure 9, bottom) represents the substitution of oil by gas.

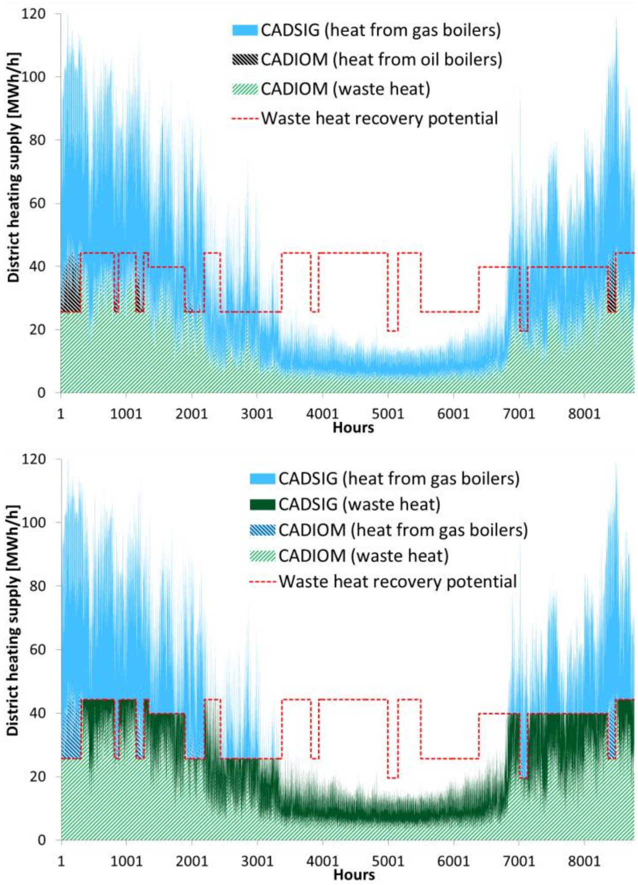

Figure 9: Heat supply before (top) and after the connection (bottom), model results

4.3 Comparison with actual data analysis after the connection

The comparison between the model and the reality shows some differences (table 1). During 2013-2014 season (4th June 2013 to 3rd June 2014), the total district heating demand represented 397 GWh_{th}. Thanks to the connection, 222 GWh_{th} were recovered from the waste incineration plant. From these, 145 GWh_{th} were consumed by the network directly connected to the CHP plant (CADIOM) which corresponds well to the model results (142 GWh_{th}). The remaining 77 GWh_{th} were transferred into the other network (CADSIG) which corresponds to a direct fossil fuels substitution. This amount of heat transferred is less than the 91 GWh_{th} predicted by the model. The difference can be explained by the fact that some technical problems occurred during some weeks at the exchange station. Moreover, during summer, the gas boilers were continuously operating because of degassing necessities (air in the pipes). During winter nights, the heat recovery was not always optimized.

Table 1: Comparison of DH demand and heat supply, model vs measures

DH heat supply with connection	Model (GWh/yr)	Measures (GWh/yr)
CADSIG (gas boilers)	129	165
CADSIG (waste)	91	77
CADIOM (gas boilers)	8	10
CADIOM (waste)	142	145
Total heat from waste	233	222
Total heat from gas boilers	137	175
Total district heating demand	370	397

The next figures show three typical weeks: in winter (figure 10), in autumn (figure 11) and in summer (figure 12). In winter, the transfer of waste heat is occurring only when the incineration plant is operating at full capacity. When it is not the case, waste heat is not enough and heat from the gas boilers is imported into CADIOM network. During spring and autumn, a lot of waste heat is transferred into CADSIG. During the day, especially in the morning's peak load, gas boilers are still operating, whereas it is not the case during the night. Moreover, the potential during the night is greater than the demand. In such weeks, thermal storage could be profitable. Finally, in summer, the overall demand is almost supplied entirely by waste heat. These three graphics show the seasonal, daily and hourly variations of the demand, with peak loads in the mornings and evenings, more pronounced during week days.

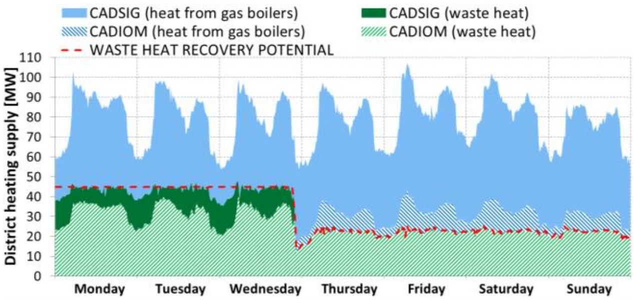

Figure 10: Heat supply profile in winter
(20th Jan. 2014 to 26th Jan. 2014)

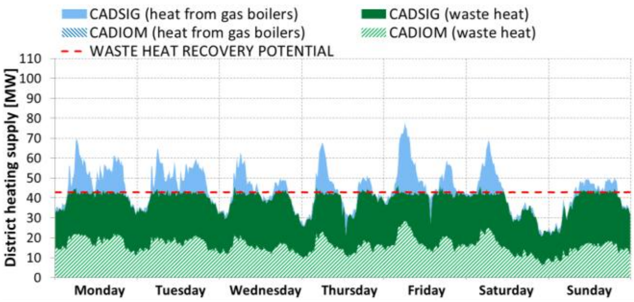

Figure 11: Heat supply profile in autumn
(14th Oct. 2013 to 20th Oct. 2013)

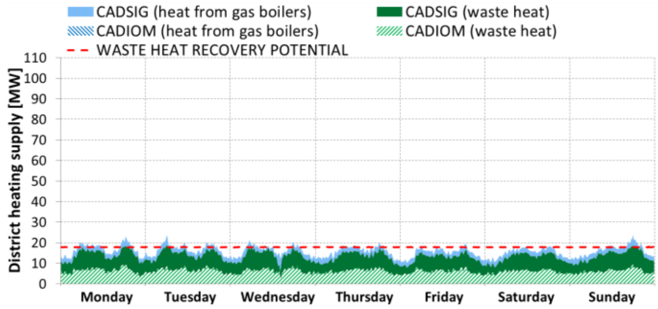

Figure 12: Heat supply profile in summer
(2nd Sept. 2013 to 8th Sept. 2013)

4.4 Sensitivity analysis to demand change

The first aspect of the district heating demand change refers to its quantity, which is mainly related to the network extension level. The sensitivity analysis considering network extension consists in simulating the system with a district heating demand varying between 0% (no DH system) and 300% (3 times the present demand), the current district heating demand corresponding to 100%.

The second aspect refers to the demand profile, which could be modified in case of building refurbishments. In energy savings scenarios, the space heating demand has been divided by 1.5, 2 and 3. As relative heat losses from pipes are higher and linear heat density decreases with energy savings, a network extension of 200%, with or without energy saving measures, has the same network length (kilometers) but not the same heat demand (see example in table 2).

Table 2: Example of heat demand with extension and energy savings

Extension level (%)	*100%*	*100%*	*200%*	*200%*
SH reduction (%)	*–*	*-50%*	*–*	*-50%*
SH (GWh)	247	124	494	247
DHW (GWh)	93	93	186	186
Pipes losses (GWh)	30	30	60	60
Total district heating demand (GWh)	370	247	740	493
Linear heat density (GWh/km)	6.7	4.5	6.7	4.5
Length (km)	55	55	110	110

By increasing the demand, a network extension would allow to recover even more waste heat, especially during summer. However, the annual fraction of waste heat into the district heating system will decrease, the waste heat recovery potential being already reached in winter thanks to the connection. The consequence is that extension must always be more and more important in order to recover the marginal thermal kilowatt-hour from the incineration plant (figure 13).

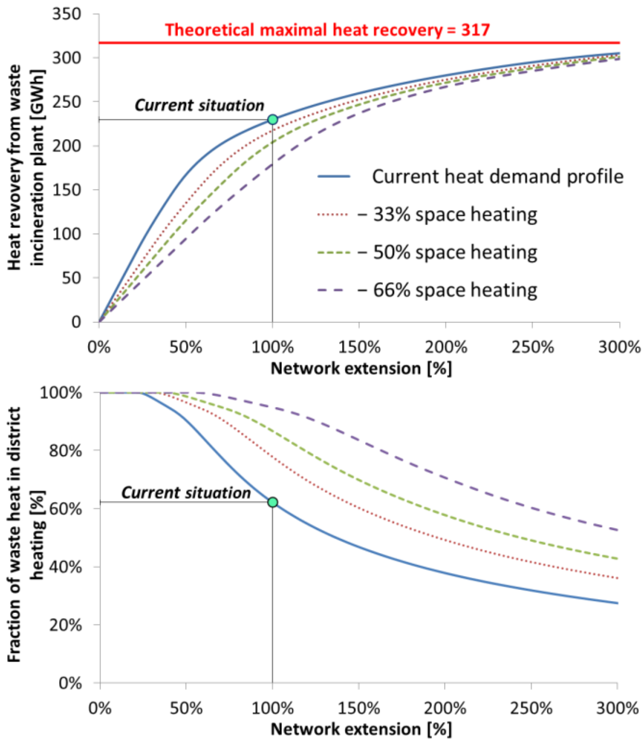

Figure 13: Waste heat recovery and mix of the DH system with network extension (%) and energy savings (%)

If energy saving measures are realized without a network extension, then the heat recovery will decrease and more heat will be wasted into the environment. This effect will mainly occur during spring and autumn, but also during winter depending on the type of energy saving measures. Of course, at the scale of the district heating system, it means that the fraction of waste heat is increasing. However, at the scale of a city, more CO_2 emissions could be avoided if these energy saving measures were realized in buildings not connected to the district heating system and supplied by individual fossil-based boilers. That is why, without network extension, energy saving measures in connected buildings are not cost-optimized and relevant solutions.

The combination of both network extension and buildings refurbishment could be interesting from an energy point of view. Energy savings would reduce the winter peak load while the extension would allow a higher demand during summer and therefore increase the heat recovery. However, after a 150%-200% network extension, the heat recovery gained by increasing the demand would become low. In fact, all the waste heat recovery potential during winter, spring and autumn would be reached. That means that a high share of other resources would be required during these periods. If it's still heat from gas boilers, it becomes irrelevant, but other resources may be integrated in the future such as geothermal or biomass. On the other side, heat demand reduction would induce a linear heat density decrease and therefore higher heat losses from pipes in percentage of the heat production.

5 CONCLUSIONS

The analysis of the district heating system in Geneva demonstrates that the connection of the two largest thermal networks contributes to avoiding fossil fuels and CO_2 emissions by the recovery of more waste heat. Moreover, this connection could allow developing the district heating system in the city and therefore contribute to integrate even more waste heat. Indeed, there is still a large extension potential for district heating systems into dense areas.

Energy savings in buildings is a key point towards a more sustainable energy system, but it is smarter to first renovate buildings that are not connected to this district heating system, especially if there are no network extensions planned. Therefore, energy planning at a territorial level is necessary in order to define zones where renovation has the priority and others where district heating development is promoted.

The combination of energy savings and network extensions seems an interesting solution from an energy and environmental point of view, however the economic viability of the district heating system still need to be evaluated, because of decreasing linear heat density. Actually, a key challenge will be to find an optimized economic and energy solution combining both development of district heating systems and energy saving measures.

FUTURE WORK

This work is part of an ongoing project and future analysis will be done to assess the potential for other energy resources such as biomass and geothermal energy. Another key point that will be explored is the role of thermal storage and CHP. Finally, a cost analysis between thermal network extension and buildings refurbishment scenarios must be done to assess future pathways towards a climate friendly energy system considering environmental and economic dimensions.

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A NUMERICAL MODEL FOR DETERMINING HOURLY HEATING AND DHW LOADS IN DISTRICT HEATING SYSTEMS

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ABSTRACT

This paper presents a method to determine the space heating (SH) and the domestic hot water (DHW) hourly loads for several building types as well as for the whole district heating network. A building type could be a unitary structure or an aggregate of buildings.

Loads are calculated on hourly basis for the whole or a part of the year. Based on an input of energy consumption over a period of time, hourly heating loads are evaluated referred to the outside temperatures, the building set point temperatures and the night and weekend setbacks.

Thermal inertia of buildings is also taken into account as it impacts their dynamic behaviors. DHW loads are assessed by using some relevant DHW consumption profiles for several building types and different weekdays. An appropriate tool has been developed for this purpose that determines the heating and DHW hourly loads. The tool has been validated for several unitary buildings as well as for an entire network in France. Mean average percentage error between the calculated and the measured values are within ± 15%.

NOMENCLATURE

DHW	Domestic Hot Water
DH	Degree hours
E	Energy [kWH]
ETS	Energy Transfer Station
$G_{Building}$	Building thermal capacity [kW°C^{-1}]
HL	Heating Load [kW]
MAPE	Mean Average Percentage Error
SH	Space Heating

INTRODUCTION

Energy companies need to have reliable optimization practices in order to optimize the design operation of their district-heating systems. Before the selection of heat generators capacity and erection of the heat plant, the heat demand needs first to be determined. Assessing these loads is the starting point in designing all the hydraulic system.

The outdoor temperature, the building set point temperature, building types and the night and weekend setbacks, have the greatest influence on the heat demand. Several approaches have been proposed for heat-load assessment, but due to lack in measured data and due to the uncertainties that are present in weather forecasts, many methods will fail in practice. In such situations, a simpler model may give as good results as an advanced one.

The aim of this work is to present the method used for estimating heat demand for individual buildings as for the entire network. A tool has been developed for this issue that estimates on hourly basis the load profiles for space heating (SH) and domestic hot water for several building types including residential, tertiary, commercial and medical. Energy measurements are available through monthly heat meter reading for billing purposes. The simplified scheme in figure 1 shows the model inputs and outputs.

METHODOLOGY

An exhaustive heat load calculation for buildings requires going through the individual rooms and zones by describing in details walls, glazing, occupancy… This thorough method is crucial for designing the heating distribution system inside the building. However, when dealing at the network level, it will be senseless and timewasting to describe hundreds and thousands of buildings in details.

A method for calculating heat load for buildings, space heating on macro level is an estimate of the rate at which the building losses heat. Space heating and domestic hot water have some distinctively different properties, so there are separate standards on DHW and space heat generation.

It should be noticed that a building means a unitary building or an aggregate of several buildings having common characteristics like inertia, activity type, DHW type. So if the network consists of identical buildings, all of them could be aggregated in one item. A diversity factor could be set to smooth the peak loads build-up.

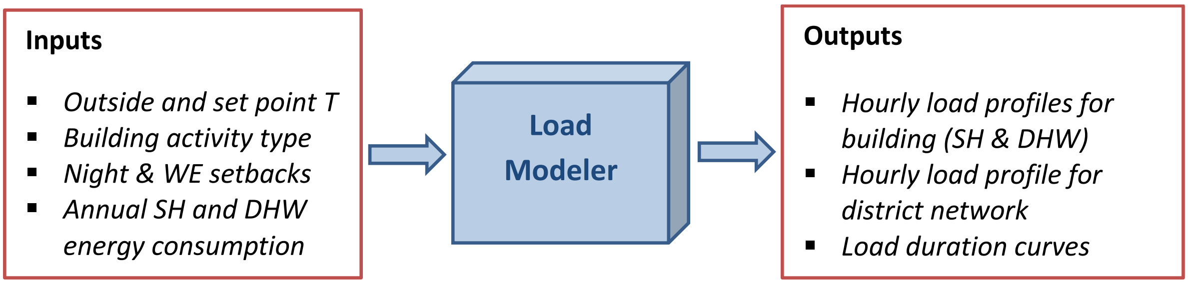

Fig. 1 - Simplified scheme showing model inputs and outputs

Heating Load Calculation

Based on heating energy consumption over a period of time or the whole heating season, the building hourly heating capacity is distributed proportionally to the temperature difference between the set point and the external temperatures by the following formula:

$$HL = G_{building} * \Delta T$$

Where: $G_{building} = E / DH$

- HL: heating load
- $G_{building}$: Building thermal capacity
- ΔT: is the difference between the outside and set point temperatures considering the setbacks.
- E : Energy consumed over the period
- DH: degree hours for a building over the considered period of time.

DH is calculated taking into account the following parameters:

- Building set point temperature,
- Night and weekend setbacks
- Building inertia
- Hourly external temperatures

DHW Load Calculation

According to the CEN standards, the energy consumption for domestic hot water (DHW) production is calculated using a three-step approach: 1) building DHW needs, 2) distribution and 3) generation. The correct estimation of the domestic hot water needs is essential. This results in volume and time of hot water needs throughout the year (the gross hot water demand) and tapping patterns. Tapping patterns are important for the calculation of the hourly distribution.

Several types of buildings are used, and each of them has its own water consumption profile for the day of the week as well as for the week ends.

The DHW production in a building could be instantaneous, accumulated and semi-instantaneous types.

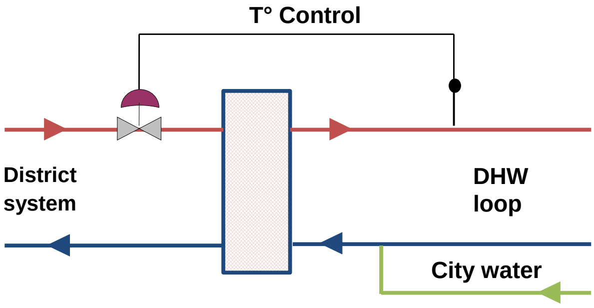

Fig. 2 - Instantaneous DHW water system

In an instantaneous DHW production (cf. figure 2), the heat exchanger has to deliver the instantaneous loads at user demand. The control valve will adjust the heat capacity supplied to the heat exchanger. The heat exchanger and the energy transfer station (ETS) components have to be seized for the maximum tapping demand. This system shows a great variation in demand profile all over the day.

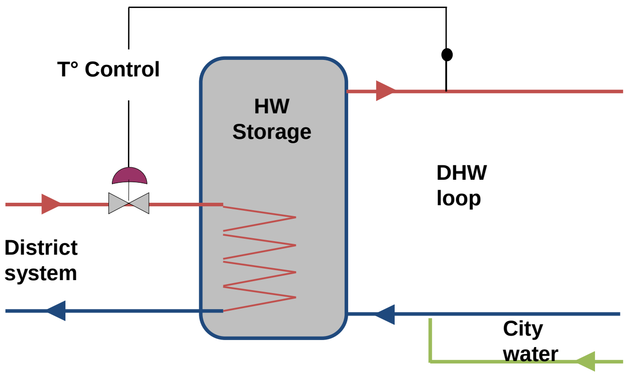

Fig. 3 – Accumulated DHW system

An accumulated DHW system (cf. figure 3) consists of a hot water storage tank, a heat exchanger and a control valve. The system will be loaded during off-peaks hours (usually during the night) and will deliver its capacity during the on-peak hours (usually during the day).

There is no direct linking between the ETS heat exchanger and the delivery points. The main advantage of this scheme is that the heat exchanger and ETS components will be down sized compared to instantaneous DHW production type. Nevertheless there is a need to a large hot water accumulator able to withstand the whole daily demand.

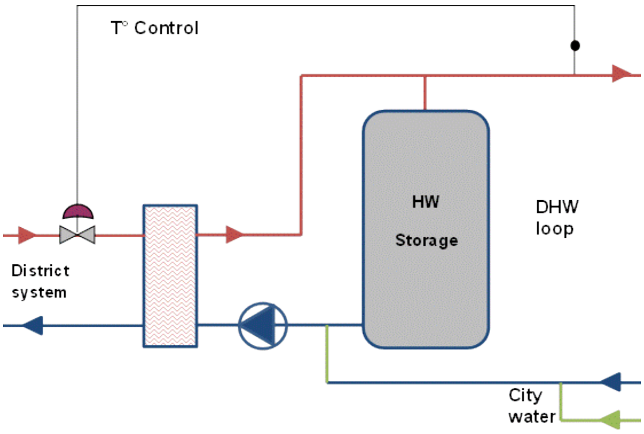

Fig. 4 – Semi-instantaneous DHW system

A semi-instantaneous DHW system (cf. figure 4) will amend the peaks, so the minimum and medium loads are delivered directly by the heat exchanger. It consists of a hot water storage tank, a heat exchanger and a control valve. When the demand exceeds a specified threshold, the storage intervenes to deliver the complementary needs.

The advantages of this scheme is that the heat exchanger and ETS components will be down sized compared to instantaneous production, nevertheless there is a need to a hot water accumulator. The hot water accumulator capacity is less important than the one used in the accumulated DHW type.

Based on the water volume consumption, the DHW energy consumption over a period of time, the building activity and DHW type, the energy can be distributed on hourly basis following the pre requisites profiles for the different buildings or building aggregate, and then for the entire network.

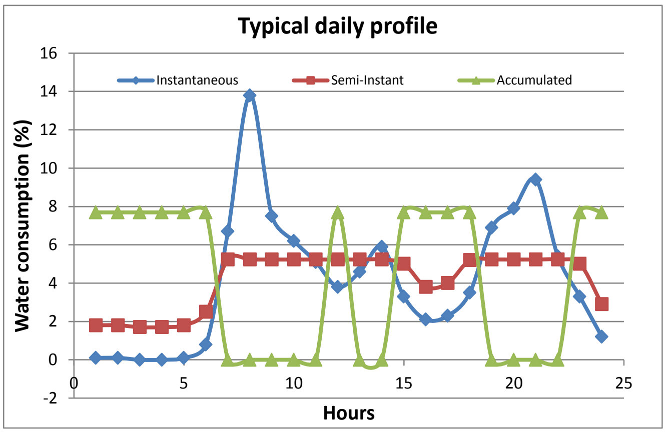

Fig. 5 - Daily water tapping patterns for the three DHW production types [6]

DHW hourly energy consumption is based on a water tapping demand pre-defined by building activity type and DHW system production type. Figure 5 shows daily water tapping patterns for the three DHW production types described before.

The calculation methodology is sketched in the flowchart of figure 6, where the user has first to introduce the different buildings or aggregate of buildings. For SH calculations, details about buildings have to be set as, type, energy consumption, set point temperature, night and WE setbacks, thermal inertia, heating season.

Outside temperatures are introduced hourly for the considered period. The tool determines then the thermal capacity of each building and then proceeds to distribute the heating capacity over the heating season.

For DHW calculations, details about building type and DHW production type have to be set. DHW energy and water volume consumptions are introduced by the user. Referred to city water temperatures and the water tapping patterns, the tool distributes the DHW energy consumption over the defined period.

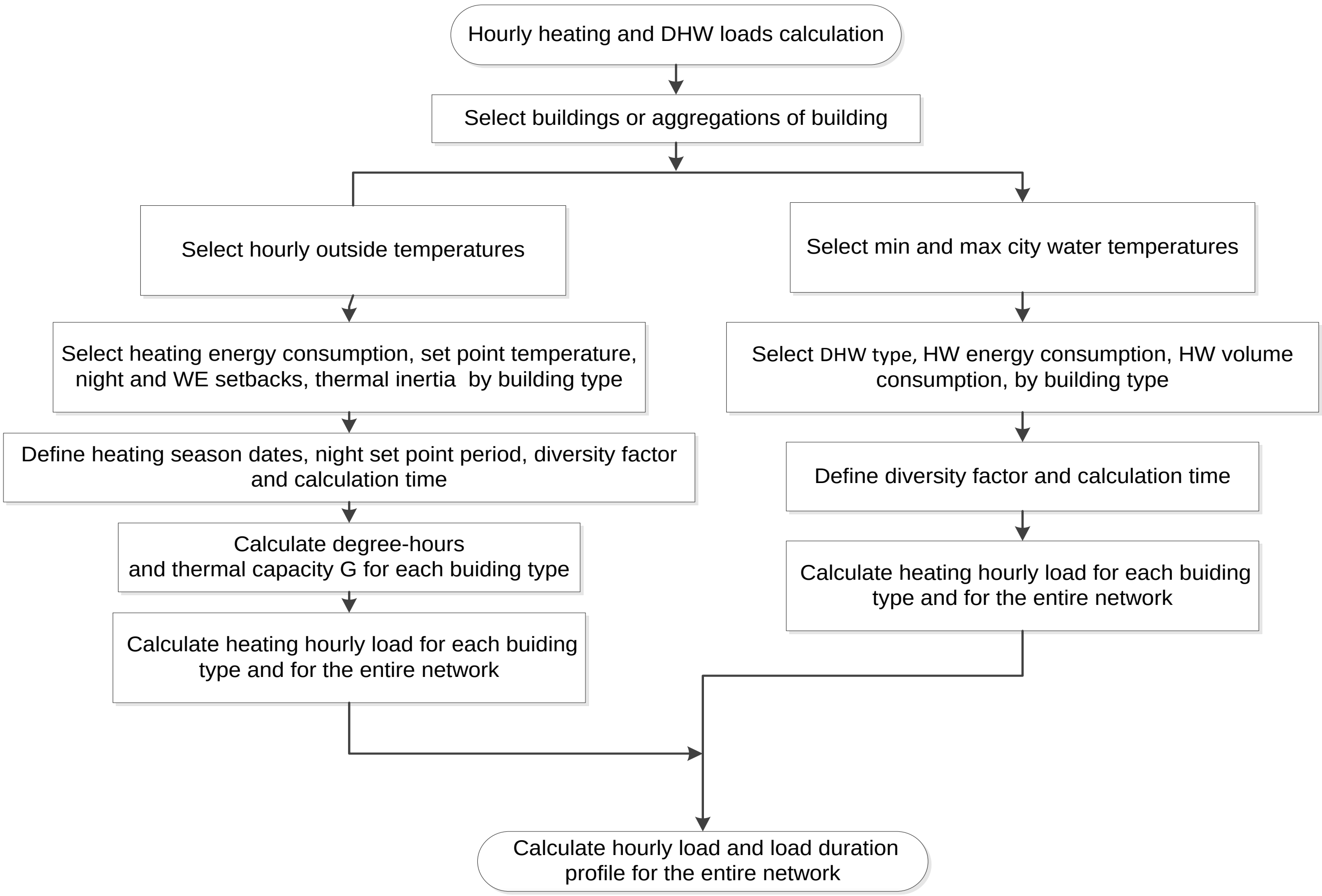

Fig. 6 - Flowchart showing sequences to calculate the hourly load

RESULTS

In order to evaluate the accuracy of the tool, a comparison was made between the model and two types of data. In the first case study A, data is hourly space heating values corresponding to a unitary building during the heating season. While in the second case B, data is hourly heating load (SH + DHW) for an entire district network gathering several building types during a complete year.

- **Case study A**

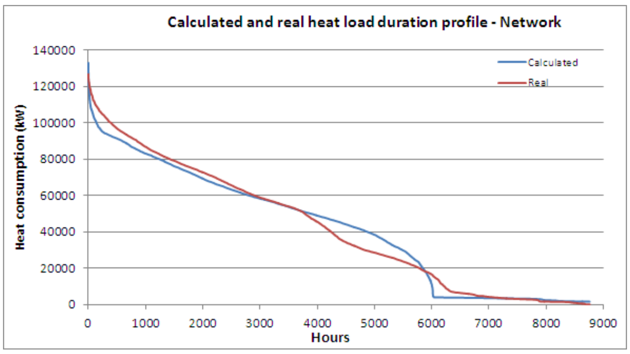

Fig 7 - Calculated and real heat load duration profiles for a typical building in heating mode on

Figure 7 shows a comparison for load duration profiles between the calculated and the real measurements for the unitary building. The model shows a good matching for the heat load duration curves.

Figure 8 compares real values against the calculated values by the tool over 500 hours. The difference between the results is quite acceptable where the model follows real trends with an accuracy of ± 15%.

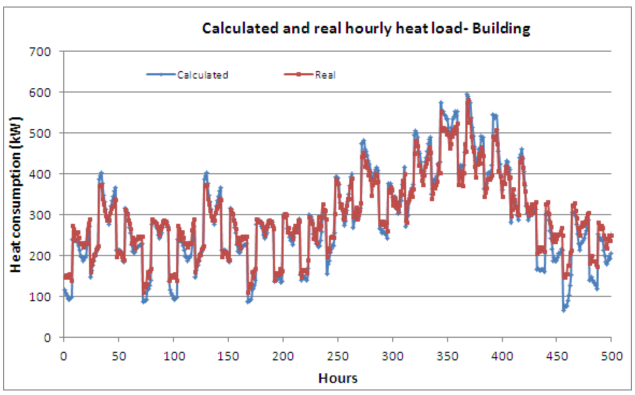

Fig 8 - Calculated and real hourly heat loads for a typical building in heating mode only

- **Case study B**

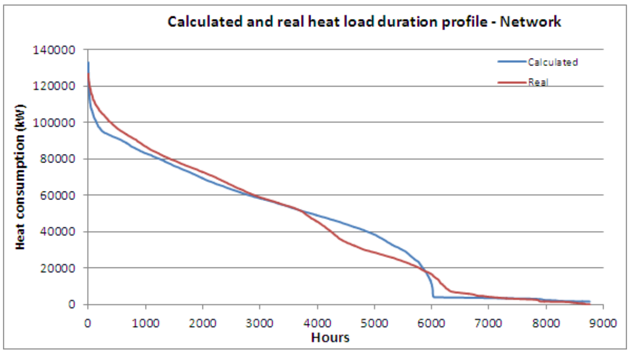

Fig 9 - Calculated and real heat load duration profiles for an entire district system including heating and DHW

Figure 9 shows a comparison between the calculated and the real measurements load duration profiles for the entire district heating network. The difference between the results and the simulation is again quite acceptable where the model shows a good matching for the heat load duration curve.

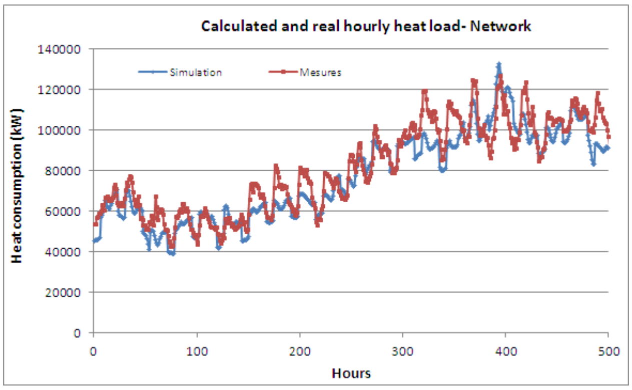

Fig 10 - Calculated and real hourly heat loads for an entire district system including heating and DHW

Figure 10 compares real values against the calculated values by the tool over 500 hours. The difference between the results is quite acceptable where the model follows real trends.

CONCLUSION

This paper presents a methodology for determining the heat load (SH + DHW) for buildings as well as for an entire network. A tool has been developed and has been tested on two real life datasets. The model arrives at very good results and the results become even better when dealing with space heating only. This is coherent because of the randomly tapping patterns for DHW that could not be 100% predicted.

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THE NEW ASHRAE DISTRICT HEATING AND DISTRICT COOLING GUIDES

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ABSTRACT

This paper will describe the development of two new guides, the ASHRAE District Heating Guide [1] and the ASHRAE District Cooling Guide [2]. The need for these publications will first be presented and then the process of developing the guides under the auspices of ASHRAE's District Heating and Cooling Technical committee will be described. Outlines for the guides will be provided along with details of coverage in a few selected areas. Several key topics will be covered in detail so the reader obtains a better understanding of the content.

INTRODUCTION/PURPOSE

ASHRAE's Technical Committee 6.2 (TC6.2) is the cognizant body within the association responsible for the specific field of interest of District Heating and Cooling (DHC). TC6.2 has long recognized the need for comprehensive DHC design guidance for the industry professionals. While material on DHC design is contained in the ASHRAE HVAC Systems and Equipment Volume [3], constraints on length of the DHC chapter have precluded the inclusion of the level of detail and comprehensive coverage needed. There exist a few additional publications of use to the designers of DHC systems such as the dated IDEA District Heating Handbook [4] and the recently published IDEA District Cooling Best Practices Guide [5]. While a number of publications are available in languages other than English, these are of little use to the design community at large. The District Heating Handbook [6] is a useful reference but is primarily focused on the mechanical design of buried "bonded" type piping systems.

Recognizing the need for comprehensive DHC design guidance TC6.2 originally conceived a project scope to develop such a guide in February 1997. However the specialized nature of the DHC practice made it difficult to convince those within ASHRAE responsible for oversight of the research program of such a need for a wider audience. Thus several versions of work statements were authored to address concerns but the project languished unapproved. In the fall of 2006 the ASHRAE President was visiting the Middle East and Chapter members expressed the desire for such a district cooling guide to be developed. This provided the impetus to TC6.2 to once again revise the work statement and resubmit it to the ASHRAE approval authorities. The revised scope was approved, and went to competitive bid in the fall of 2007. The project was awarded to a team assembled by the principal author of this paper in January 2008, with work to begin in April 2008. Soon after the original award was made a request was made to ASHRAE for a separate guide to be prepared for District Cooling only on an expedited schedule, co-funding for this coming from Empower, a district cooling provider in the UAE. A supplemental proposal was prepared for the DC design guide in February 2008 and in November 2008 that proposal was accepted.

ASHRAE research projects such as this one are monitored by a committee of individuals normally drawn from the membership of the cognizant technical committee, in this Case TC6.2, and any project cosponsors. This project was no exception with a project monitoring subcommittee of six individuals; the chairman of that committee is the second author on this paper who also contributed to the authorship of the guides. The project team was truly multinational with members from the US having much international experience as well as authors from Egypt and Denmark; there were 7 authors on the DCG and 10 for the DHG.

Before discussing some of the details of the ASHRAE Guides [1], [2] it is important to note that currently another comprehensive DHC reference is now available, the District Heating and Cooling textbook [7], however this reference was not published until 2013 when both the ASHRAE Guides were published and we were unaware of its development until after the ASHRAE Guides were completed. Our review of this document leads us to conclude that the coverage of this text is quite complementary to the ASHRAE Guides rather than duplicative.

Below the overall outlines for the two ASHRAE guides are presented.

OUTLINE OF THE DISTRICT COOLING GUIDE

- Chapter 1: Introduction
- Chapter 2: System Planning
- Chapter 3: Central Plant
- Chapter 4: Distribution Systems
- Chapter 5: End User Interface
- Chapter 6: Thermal Storage
- Chapter 7: Instrumentation and Controls
- Chapter 8: Operation and Maintenance
- Chapter 9: System Enhancements
- Appendix A: Case Studies

- Appendix B: Terminology for District Cooling

OUTLINE OF THE DISTRICT HEATING DESIGN GUIDE

- Chapter 1: Introduction
- Chapter 2: Planning and System Selection
- Chapter 3: Central Plant Design for Steam and Hot Water
- Chapter 4: Distribution System Design
- Chapter 5: Consumer Interconnection
- Chapter 6: Heat Transfer Calculations for Piping Systems
- Chapter 7: Thermal Storage
- Chapter 8: Operation and Maintenance
- Chapter 9: Case Studies
- Chapter 10: Terminology for District Heating

STATE OF THE ART

From this point out we will focus on the coverage of the ASHRAE District Heating and District Cooling Guides in more detail. It's obviously not possible to provide details of the full coverage of these documents within the confines of a symposium paper. Thus we will discuss in depth only a few areas where the guides provide either new coverage, or coverage at a level of detail not previously available in English language design guidance.

Four areas of coverage from the guides will be highlighted. The first area where we discuss detailed coverage will be the calculation of heat losses (gains for the case of district cooling piping). Specifically we will focus on the assumption of soil temperature used in these calculations and how that impacts the results. Calculation of the impacts that depth and climate have on soil temperatures is fairly well documented and has been presented in detail in [3] as well as the new ASHRAE guides [1], [2]. The impacts of surface type (e.g. pavement, grass, etc) on subsurface soil temperature are less well documented. Below we will present a method of quantifying the impact that surface type has on subsurface temperatures. This method is detailed in each of the ASHRAE guides [1], [2].

The second area of coverage will be System Planning and a tool for proper analysis of connecting a building to a DHC system or having a de-centralized approach.

Several important topics of Central Plant design will be emphasized in the third area while the last area focuses on the End User Interface.

DISTRIBUTION HEAT LOSS AND GAIN

The surface type (e.g. asphalt, concrete, grass) can have a large impact on the heat balance at the ground's surface and the resulting soil temperatures below. The type of surface impacts the heat transfer from radiation, convection, and precipitation. The impacts are well known, McCabe et al. [8] observed significant temperature variations due to the type of surfaces and predicted significant impacts for district cooling systems. While we are not aware of any detailed study beyond the work of McCabe et al. [8] on the impacts of surface type on soil temperatures surrounding district heating and cooling systems specifically, there has been significant study of the impacts of surface type on soil freezing and thawing. For this application, a method of adjusting the air temperature to find an effective surface temperature has been developed. This method is referred to as the n-factor method, with n-factors having been determined empirically by a number of investigators. Because the impacts of solar radiation in particular are so important, n-factors have been developed for the summer (thawing) and winter (freezing) seasons, and these factors vary appreciably with surface and climate types. For more discussion of n-factors the reader is referred to Lunardini [9], [10], who explains the theory and tabulates the values for the n-factor. Freitag and McFadden [11] also supply tabulated values of n-factors.

The reader is cautioned that when using n-factors one must recognize that they are not only specific to the surface but they are also site-specific and thus one should only extrapolate with caution and understanding. With that caveat as a first approximation, lacking other data, the n-factor method can be used to estimate soil temperatures beneath various surfaces. An example of the impact is provided below. This example will not only illustrate the use of the n-factor method to approximate the impacts of surface type but also it will illustrate the use of a few of the equations presented in the design guides. Consider the most general case of determining soil temperatures as a function of both time and depth using Equation 1 below.

$$T_{s,z} = T_{ms} + A_s e^{-z\sqrt{\frac{\pi}{\alpha\tau}}} \sin\left(\frac{2\pi\left(t - t_{lag}\right)}{\tau} - z\sqrt{\frac{\pi}{\alpha\tau}}\right) \quad (1)$$

where:

$T_{s,z} =$ temperature, °C.

$z =$ depth, m.

$\tau =$ annual period length, 365 days.

$\alpha =$ thermal diffusivity of the soil, m^2/day.

$T_{ms} =$ mean annual surface temperature, °C.

$A_s =$ surface temperature amplitude, °C.

$t =$ Julian date, days.

$t_{lag} =$ phase lag of soil surface temp., days.

For the purposes of this example we'll assume a climate typical of coastal Massachusetts:

$T_{ms} = 9.5\ °C$

$A_s = 11.4\ °C$

$t_{lag} = 115.9$ days

For soil we'll use a sandy soil with a moisture content of 10% at a dry density of 1600 kg/m^3, which yields the following thermal properties when using the thermal properties equations included in the guides [1], [2]:

$k_s = 1.58$ W/m-°C

$c_s = 1.15$ kJ/kg-°C

$\alpha = 0.074\ \mathrm{m^2/day}$

These thermal properties and climatic constant values may be used with Equation 1 to evaluate the soil temperature for any depth z (m) and time t (Julian day). A series of calculations have been made using the result; they are presented in Figure 1.

These calculations are based on the assumption that the ground surface temperature is equal to air temperature. Equations to adjust for a convective coefficient at the ground surface are contained in the guides [1], [2].

To illustrate the use of the n-factor concept, Figure 2 has been prepared in a manner similar to Figure 1. The same climate and soil have been assumed as for the calculations of Figure 1. A surface of concrete pavement has been assumed and the n-factors have been estimated based on the data provided by Lunardini [10] as 0.66 during the freezing season and 1.7 during the thawing season. The calculation is somewhat complex to detail here, but to summarize it proceeds by first calculating surface temperatures using the air temperatures calculated by Equation 1 at zero burial depth and the assumed n-factors. Subsequently, a sinusoidal curve is fitted to these surface temperatures using the method detailed in Appendix B of [1]. The constants from that sinusoidal curve fit are then used in Equation 1 as before, noting that no adjustment is made to depths for the convective coefficient at the surface, as this impact has been included in the n-factor. The use of n-factors for this purpose is a significant extrapolation of the technique discussed previously in the guides [1], [2] for calculating soil temperatures using Equation 1 alone. Thus, these results should be taken as very approximate. That having been said, by comparing Figures 1 and 2 we can see that at 0.91 m of depth the highest temperature reached in the summer under the concrete pavement is predicted to be about 13°C greater than in our calculation that ignored any surface type impacts and assumed the air temperature and surface temperature were equal.

It is interesting to compare the results of this approximation method with the measurements of McCabe et al. [8], who found peak summer temperatures under pavement of approximately 28°C at a 0.91 m depth. Using the n-factor method described previously with climatic constants calculated with the method of Appendix B of [1] for the Ithaca, New York, area where the measurements of McCabe et al. [8] were made, the peak ground temperature under a concrete pavement at a depth of 0.91 m is predicted to be 29°C. This is considered reasonable agreement given the approximate nature of the method outlined here as well as the difficulty in making measurements of soil temperatures. Clearly, as McCabe et al. [8] point out, consideration should be given to surface impacts on subsurface soil temperatures when making calculations to determine appropriate insulation thickness. In addition, other impacts such as those on the materials within chilled-water, hot-water, and steam distribution systems should be considered.

Accurate undisturbed soil temperatures are much more of a concern in district cooling system design than for district heating design, since for district cooling systems the temperatures of the carrier fluid are much closer to the temperatures of the undisturbed soil. Thus, errors of similar magnitude in undisturbed soil temperature estimation will result in much larger errors in estimated heat gain for a district cooling system than for heat losses from a district heating system. Consider, for example, the peak heat gains from a 4.4°C chilled-water supply pipe buried at 0.91 m in the coastal Massachusetts climate used in the example above. Peak temperature at that depth is estimated at 18°C when the surface heat transfer impacts are excluded and 31°C when the estimated impacts of a concrete surface pavement are included. The heat gains for the 31°C undisturbed soil temperature are 1.96 times greater {(31 – 4.4)/(18 – 4.4)} than those for the 18°C soil temperature. As an example of how important this difference is, imagine the lower ground temperature had been used and the economic insulation thickness (discussed in ref. [1], [2]) had been determined with the assumption of the lower ground temperature; in such a case it is likely that the resulting insulation thickness would not be valid for the higher ground temperature and more insulation would be indicated. A similar calculation for a low-temperature hot-water supply pipe operating at 120°C shows that the heat loss would only be reduced by 12% under the same assumptions. For a chilled water system it is also important to note that because the heat gains will be much greater in the summer months when demand for cooling is the greatest, delivered water temperature to consumers will be higher than expected when the impacts of surface type are ignored. This could result in difficulty meeting the consumers load, especially the dehumidification

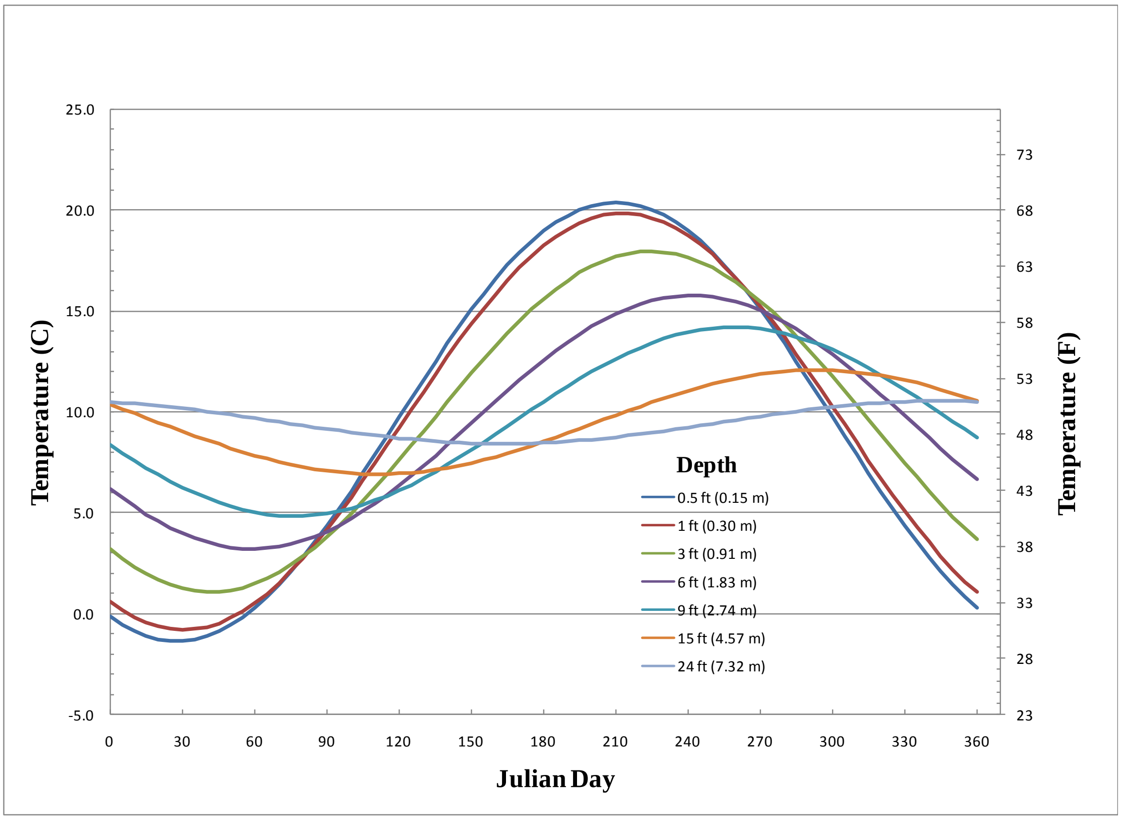

Fig. 1: Soil temperatures calculated with Equation 1 for a coastal Massachusetts climate.

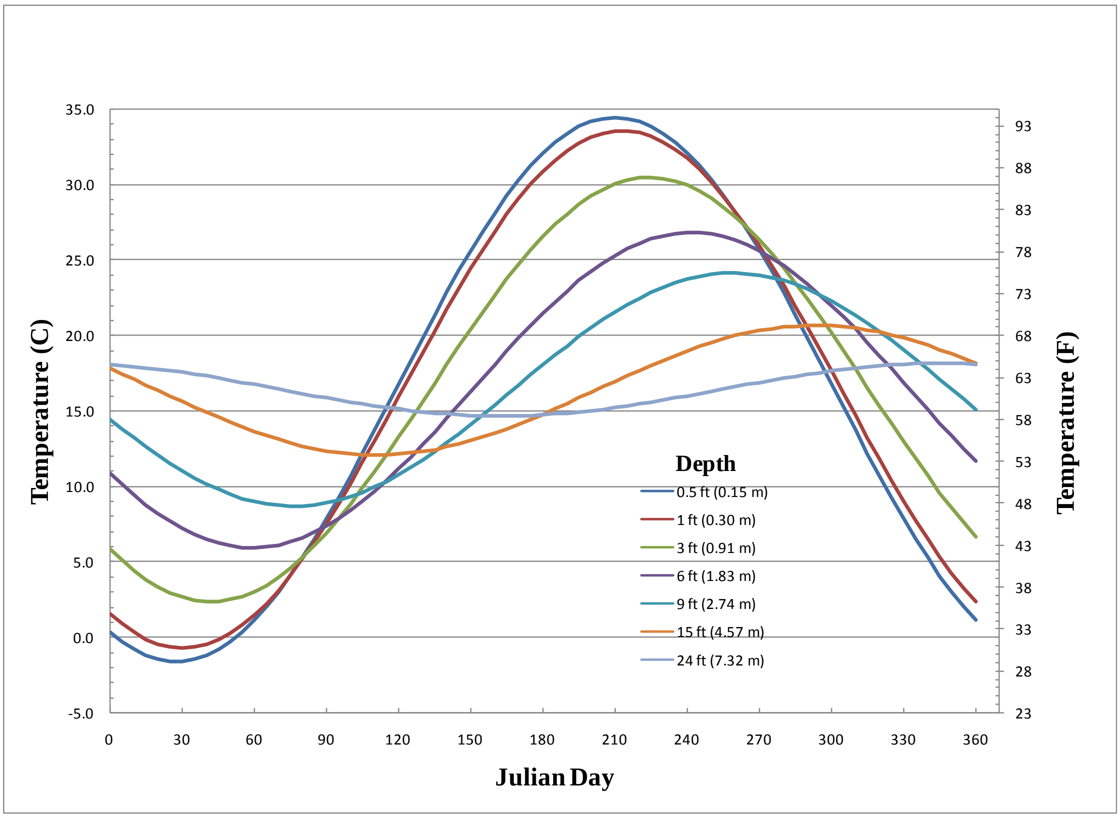

Fig. 2: Soil temperatures calculated with Equation 1 for a coastal Massachusetts climate and the use of n-factors to adjust for a concrete pavement surface.

aspect thereof. This impact would be especially acute in a system where the pipes have been sized for a future load that is not present upon initial operation of the district cooling system.

SYSTEM PLANNING

The end of the planning chapter of each of the guides [1] [2] includes a section for economic analysis and user rates which can also be found in the ASHRAE HVAC Systems and Equipment Handbook Chapter 12 [3]. The objective was to identify all items that should be included in a detailed analysis on whether to connect to a district energy system or provide a decentralized solution for a potential customer. Only an equitable accounting methodology will identify all the costs, benefits and value of connecting to district energy systems.

District energy has both quantitative and qualitative benefits and an emphasis should be made to find a qualitative value to the quantitative benefits to generate a life cycle value analysis (LCVA) that is un-biased. Table 1 below summarizes the main inputs to a LCVA. Some items are easy to quantify and others are not and are more subjective topics, but all items should be addressed when scrutinizing the interconnection agreement.

It is important to note that a DHC customer receives all the facets and benefits of the DHC system in a simple monthly bill that invoices for only the energy used and method to compensate the DHC provider on the cost of the ETS connection, while the decentralized approach must identify and allocate funds for all components of generating chilled water, hot water or steam for the comfort of the building occupants.

Figure 3 below summarizes the appropriation of costs of a typical 25 year life cycle cost analysis for a potential DHC customer having their own cooling plant Over the 25 year time frame of the LCC analysis it is interesting to note how the energy and utility costs outweigh the initial capital cost and financing costs highlighting the importance of using energy efficient equipment.

The example given is from an actual business case analysis. Over the 25 year time frame of the analysis it is interesting to note how the energy and utility costs outweigh the initial capital cost and financing costs highlighting the importance of using energy efficient equipment. The most difficult part of analysing the life cycle value proposal between a DHC provider and a customer is placing a quantitative value to the qualitative benefits. A partial list of the qualitative benefits is:

- Reuse of the space vacated by the cooling equipment since some of the mechanical and electrical space can be rented out for uses other than storage. Uses such as office space, or a clean roof area that could be used for more sustainable purposes such as a roof garden, pool, etc.
- No plumes from cooling towers or boiler stacks
- Increased thermal cooling source reliability
- Less greenhouse gas emissions and a lower carbon footprint
- Freeing up maintenance staff to perform duties other than central plant operations

CENTRAL PLANT

While this chapter in the DCG [2] was written primarily with Middle East projects and climate in mind, the intent was that the text would be universally appropriate for all international applications. Largely the differences in plants are a manner of scale which often translates into the number of chillers and cooling towers. Chiller basics and chilled water pumping fundamentals are covered as well as some maintenance costs to assist in LCC analyses covered in the System Planning section. Similarly different methods of chiller condenser heat rejection are also highlighted.

There are multiple layout options and system configurations available to the DHC plant designer today. It is recommended that variable speed prime drivers be used on chillers and pumps to provide a efficient operation that leads to lower district energy rates. Major equipment should be selected using early procurement packages which give the designers the opportunity of not only specifically designing around the successful manufacturer, but also analysing the bids to obtain the best performance available for the cost. One of the important components of a chiller plant is selecting the method of heat rejection. This selection is dependent upon local ambient conditions, availability of water, etc. It cannot be overemphasized that if any component of the plant is to be oversized, upsizing the heat rejection side is one way to ensure system performance at peak design conditions. This is also a lower cost per ton than most other performance enhancing solutions.

Not all heat rejection technologies are feasible for use on a global scale. For example, it is common for Scandinavian countries to use large centrifugal chillers as heat pumps to deliver chilled water and hot water depending on the season. This application is extremely efficient, but cannot be used in the United States for new projects due to environmental regulatory restrictions on using bodies of water and using them for a heat sink. Therefore, it is up to the system designer to use the appropriate method and configuration of the plant components.

Table 1: Summary of Economic Analysis Factors

Capital Costs	
Construction costs of the building plant vs. energy transfer station equipment	Includes the materials and labor for chillers, boilers, piping, pumps, heat exchangers, valving, instrumentation, controls, cost of electric service, cost of additional structures due to equipment weight on roof of building, etc.
Value of increased mechanical and electrical space that would house the plant equipment	Includes value of penthouse, basement, roof, and vertical chases for flues, condenser-water piping, etc.
Value of any equipment screening	Many times municipalities require screening for any equipment mounted on grade or on the roof
Cost of financing	Amount of project that is financed at the loan interest rate of the duration of the loan
Construction permits and fees	Typically a percentage of construction
Life of major equipment overhauls and replacement costs	This could include the replacement or overhauls of chillers, cooling towers, boilers, etc., over the life of the analysis/contract duration. If the district-energy contract is for 20 years and a piece of equipment must be replaced or overhauled (i.e., cooling tower replaced after 15 years or chiller-condenser-water tube replacement) this cost must be accounted for
Contract vs. installed capacity	The district-energy capacity will most likely be less than the planned in-building installed capacity, as dictated by the consultant due to many reasons, but mostly over sizing and diversity. Typically, the estimated peak loads can be reduced to 70%
Cost of redundant equipment for emergency or standby capacity	Similar to above, N+1 redundancy requirements would be accommodated and added to the first cost
Energy and Utility Costs	
Electric rate	From usage of each option from energy model or other estimate
Natural gas rate	From usage of each option from energy model or other estimate
Water and sewer charges for steam, chilled, and condenser-water systems	From usage of each option from energy model or other estimate.Water is increasingly becoming an important resource, hence makeup water and equipment blowdown/sewer discharge amount are estimated. It is not uncommon for this utility to have a different escalation rate
Operations and Maintenance Costs	
Labor and benefits of operations staff assigned to central plant activities	This would include any staff that is assigned to the duties of maintaining and operating the central plant including supervisors and overtime due to unplanned outages
Replacement or refilling of refrigerants	If refrigerant is scheduled for phasing out, chillers must be retrofitted to accept new refrigerant plus any topping off of refrigerants (or replacement)
Spare parts and supplies	Chiller and boiler and auxiliary equipment require replacement of parts for normal maintenance procedures including gears, oil, tubes, etc.
Cost of chemical treatment for steam, chilled, condenser, and hot-water systems	Includes scale and corrosion inhibitors, biocides, oxygen scavengers, etc., and these costs could be considerable
Cost of contracted maintenance	Some owners outsource specific tasks to service companies such as chiller or boiler maintenance and overhauls
Energy and Resource Usage	
Peak heating and cooling thermal loads	Used to apply the energy demand rate and the sizing of the plant equipment (chillers, boilers, pumps, electrical service, water service, etc.)
Annual heating and cooling usage	Used to apply the energy consumption rate of the utilities to the equipment meeting the thermal loads
Annual water and sewer usage	Quantify makeup water usage and blowdown discharge pertinent to the cooling towers and boilers
Other Costs	
Architectural and engineering design services	Specifically for new or retrofit applications
Fees and licenses	Air and water permits, high-pressure steam operator licenses, city franchise fees for running piping in street, etc.
Insurance of equipment	Typically a percentage of construction costs
Water and sewer charges for steam, chilled, and condenser-water systems	From usage of each option from energy model or other estimate. Water is increasingly becoming an important resource, hence makeup water and equipment blowdown/sewer discharge amounts are estimated. It is not uncommon for this utility to have a different escalation rate

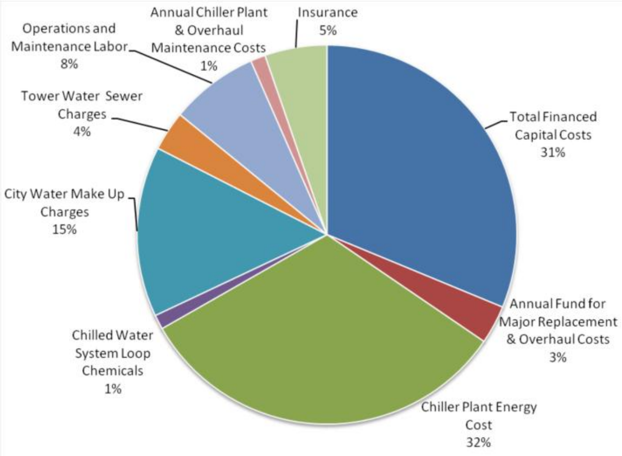

Figure 3: Cost breakdown for on-site generation of chilled water.

With the efficiency of building scale heating cooling equipment increasing every year, it is harder to justify connecting to a DHC system on pure energy cost savings. Therefore the DHC system designer must factor in all the system components (plant, distribution system and ETS) in order to optimize the operations of the system. The plant also must be adequately sized and expandable for future growth, deliver adequate redundancy requirements and be easily maintainable in order to provide uninterruptible service for many years to come. The DHG guides offer some basic fundamental assistance for system designers to be successful.

END USER INTERFACE

The interconnection between the DHC distribution system and the customer is known by many names – Energy Transfer Stations (ETS), building interconnections, etc. Improving overall system temperature differential (ΔT) is essential to efficient operation back at the DHC plant, therefore the performance of the End User Interface is critical to the success of the DHC operation. The DHC system designer must work closely with the customer's building design engineer to ensure that the foundation for high ΔT is laid early on in the project by proper selection of the heat transfer coils and control valves.

Direct and indirect types of connection are described in this section of the guides [1] [2] as well as their applicability. Furthermore, many customers suffer from low ΔT syndrome in their hydronic systems. Reasons behind low ΔT Syndrome are discussed. While a low ΔT condition does not emanate from the central plant or ETS connection it impacts the performance of both. Low ΔT is specifically related to the customer's terminal units and how they are selected and controlled. Several suggestions are offered on how to increase the chilled water ΔT by eliminating bypasses and using high performance control valves at terminal units.

Since one of the important functions of the ETS is to be the "cash register" of the system, proper components need to be provided to ensure accurate metering of energy used. Typically this is done via industrial temperature, pressure and flow instrumentation and it is recommended that the most affordable and accurate devices be used to mitigate any arguments with the customers regarding energy billings.

Furthermore, a control valve on the return pipe back to the DHC plant can be used on water based systems to further increase system ΔT by recirculating and blending the customer's water if it comes back too cool on a chilled water system or too hot on a hot water system. The operation of this valve can impact thermal comfort and the performance of the terminal units; therefore, close attention must be paid to the sequence of operation based on multiple control input parameters.

Ideally the control valve in the return piping would not be provided, but that assumes the building performs as per design conditions, but adding the control valve is the only means available of increasing system ΔT at the customer.

A final parameter to consider when connecting existing or new buildings to a DHC system is water quality. Special attention should be paid to direct connections for both heating and cooling pertaining to water treatment and cathodic protection. Many times the optimum connection point to a hydronic system is in the lower levels of the building. Once the system is de-energized for a period of time, e.g., connection to a district energy system, any particulates or sediments that were in suspension will settle to the lowest level and clog any pump strainers or control valve strainers. The interconnection should have construction flushing by-passes installed so the connection can be properly cleaned. This is especially true for indirect connections since a plate or brazed heat exchanger may act unintentionally as a great filter for the hydronic system.

All customer piping systems shall be cleaned and flushed thoroughly prior to opening the district energy water system to any potential contamination. Similarly, when connecting to a much older building, cathodic protection flanges should be used to isolate the two piping systems since the older system is slightly negative as compared to the new piping system and electrons will flow from one piping system to another potentially creating ionic corrosion and possible failure.

A successful ETS connection leads to an optimized and efficient DHC plant operation. The more efficient the plant becomes, the lower the DHC rates can be. The DHC designer and building designer must work closely during the design and commissioning phases to make the connection a success.

CONCLUSIONS

An ASHRAE research project has resulted in the development of two new publications, a District Heating Guide and a District Cooling Guide. These Guides offer coverage beyond their principal purpose of design guidance by also including planning, operations and maintenance, and case studies. The development of these guides was a process spanning over five years and included contributions from 13 individual authors. We believe the guides provide state-of-the-art information applicable to district heating and cooling systems worldwide and will assist in the development of future systems. The more information and tools that are available to system designers, the more successful the implementation of DHC will be.

ACKNOWLEDGEMENT

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THE SCHEMATIC STUDIES ON DISTRIBUTED VARIABLE-FREQUENCY DISTRICT HEATING SYSTEM

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Abstract: The distributed variable-frequency district heating system is not only to set circulating pump in the heat source, but also to set booster pumps in the heating pipeline network. All pumps adopt frequency conversion control. The application of distributed variable speed pumps in the district heating (DH) network has been considered as a technology improvement that has a potential of saving energy, compared to the conventional central circulating pump DH system. The distributed variable-frequency speed pumps district heating system has a variety of forms. Six typical schemes are theoretical analyzed in the paper. Drawing and analysis of pressure diagram are achieved by a simulation project case. On the analysis and research, how to use the distributed variable-frequency speed pumps district heating technology is put forward to the specific project. The recommendations are provided the reference to the people who are engaged in the design of district heating and researchers.

Keywords: District heating, Distributed variable-frequency speed pumps, Energy-saving, Scheme comparison, Scheme application

1 INSTRUCTION

District heating (DH) systems are an inseparable part of the infrastructure in many countries, such as China, Russia, Denmark, Finland, Sweden and Switzerland. They are also an important element of the economy. Today more attention is being paid to energy savings and efficiency improvements. District heating (DH), considered as the most efficient method for building space heating, has been dramatically developed over the past decades. There have been many studies that aim at optimizing the overall performance of the DH system [1–6]. Traditionally, DH networks in China are built as branched networks whose circulating pump is designed in the heat source (Fig. 1). The grid consists of numerous branched connections of two pipe branches. The main pipes are dimensioned according to the heating power and ventilation and the smaller street and house (or service) pipes are sized according to the hot water flow. In both cases the heating demand depends on the outdoor temperature. The mass flow rate in the pipelines is dictated by the energy consumption of different consumers. The DH supply temperature of water from heating plants is fixed according to the outdoor temperature. Water flows at local consumer points are throttled by control valves. The benefits of the traditional district heating network are that the structure is simple and it is easy to construct. But some drawbacks exist in this topology. The control system is slow, which reduces the energy efficiency of the system. In addition to this, the pipe lengths between the heating plant and different consumers vary, which creates some special needs for the network. The water flow has a tendency to flow through the shortest routes, where the pipes have the lowest flow resistance, and this is why the valves of the closest consumers are throttled most in the network when compared to those of the other consumers. This causes large local pressure differences and losses and it complicates the use of the network. Additionally, the main pump in the network is dimensioned according to the pressure difference needed for the most distant consumer. Nowadays, efforts connected to energy savings demand the search for new technical scientific expertise in the field of heating techniques [7–9]. The focus of research is on better and more efficient use of primary energy [10].

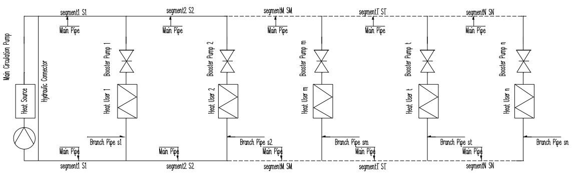

Fig. 1 Traditional type district heating network

The drawbacks of the traditional network have been noticed by many scholars for a long time. In order to increase the efficiency of distribution system, they pointed out some improvement. Somchai Paarporn put forward to the idea of setting the variable speed pump at each user to replace the regulated valve by analysis on the energy loss of the traditional resistance throttle system. The effect of energy saving is calculated through the instance in his article [11]. Green, et al pointed out what to achieve the purpose of energy saving by using the frequency conversion pump or 3 speed pumps to replace network flow control valve [12]. What the Jiang Yi pointing out that using the frequency conversion pump to replace network flow control valve, can save 1/3 system operation energy consumption[13].

2 ENERGY ANALYSIS ON TRADITIONAL PIPE NETWORK SYSTEM

In traditional district heating system (Figure1), to develop an overall dynamic model, energy balance principle was applied to each component of the DHS, and the corresponding equations were derived. For this purpose, some basic assumptions were made. These are:

a) The water temperatures inside each supply and return pipe segments (nodes) were assumed to remain uniform.

b) Similarly, each aggregated building's (zone's) air temperature was considered to remain uniform.

c) The temperature of the exterior wall of each zone was uniform over its entire surface area.

d) Water leakage from the system and the change in indoor air humidity were neglected.

e) Work carried out by the system and the kinetic energy terms in the energy equation were neglected.

f) The change in elevation of water column in the pipes was neglected because of the closed loop nature of the system

In order to facilitate the analysis and calculation, the following assumptions are also performed. Each flow of the user, spacing (including the pitch of a user with a heat source), owned pressure of the user and ratio friction of trunk mains are equal. The resistance of valve fully open is ignored.

Based on the principle of conservation of energy, equation (1) is written as

$$E = E_r + E_p + E_v + E_y \qquad (1)$$

E--The output power of pump (Energy of the system), kW

E_r-- Energy consumption of heat source, kW

E_p--Energy consumption of trunk mains, kW

E_v--Energy consumption of the sum of all the control valve, kW

E_y--Energy consumption of the sum of all the users (energy consumption of a user refers to energy consumption of the branch where the control valve is not included), kW

According to the above assumptions

$$E_p = \sum_{j=1}^{n} jGH_p = \frac{1}{2}n(n+1)GH_p \qquad (2)$$

H_p--The sum of all the pressure loss to a pair of supply and return pipe segment, (mH_2O)

Every H_p of the pipe segment is equal

G --The flow of each user (m^3/h)

It is known that energy consumption on the control valve of the n-th user is zero. Consequently, the energy consumption on the control valve of the (n-1)-th user is GH_p (the energy consumption of in other ways to increase the resistance caused by energy consumption of are included in the control valve. The essence of both is the same. It is to adjust the flow resistance to achieve the distribution and it is the same hereinafter). In the meantime, the energy consumption on the control valve of the (n-2)-th user is $2GH_p$ and the (n-k)-th user is kGH_p. Energy consumption on the control valve of the first user is $(n-1)GH_p$ .So the energy consumption of the sum of all the control valves are as follow

$$E_v = \sum_{j=1}^{n-1} jGH_p = \frac{1}{2}n(n-1)GH_p \qquad (3)$$

The energy consumption of the network is called E_w.It is not included the energy consumption of heat source and the user. Therefore

$$E_w = E_p + E_v = \frac{1}{2}n(n+1)GH_p + \frac{1}{2}n(n-1)GH_p = n^2 GH_p \qquad (4)$$

Energy consumption of the sum of all the control valves in proportion to the network is

$$\alpha_v = \frac{E_v}{E_w} = \frac{\frac{1}{2}n(n-1)GH_p}{n^2 GH_p} = \frac{n-1}{2n} \qquad (5)$$

The conclusion is obtained that the more users, the more α_v is close to 50%.

Energy consumption of heat source $E_r = GH_r$,

H_r--The pressure loss of heat source, mH_2O.

Energy consumption of a user is GH_y . H_y is the pressure loss of user. So the energy consumption of the sum of all users is $E_y = nGH_y$.

Energy consumption of the sum of all the control valves in proportion to the output power of pump (Energy of the system) is

$$\beta_v = \frac{E_v}{E_r + E_p + E_v + E_y} = \frac{(n-1)H_p}{2(H_r + H_y + nH_p)} \qquad (6)$$

$$\frac{\partial \beta_v}{\partial n} = \frac{1}{2}\frac{H_p(H_r + H_y + H_p)}{(H_r + H_y + nH_p)^2} > 0 \qquad (7)$$

It is concluded that β_v with the increase of n and H_p. On the contrary, when H_r and H_y are increased, β_v is reduced.

To traditional district heating system， The output power of pump is

$$N_1 = \frac{GH_n}{367\eta_1} \quad (8)$$

G—Total flow of system， m^3/h

H_n-- The resistance loss of the most adverse loop pipe network，m

η_1—Pump operating efficiency

The end user needs to add a booster pump in case the main circulation pump is layout to the second most adverse loop pipe network. So the output power of pump is

$$N_2 = \frac{GH_{n-1}}{367\eta_2} + \frac{G_n(H_n - H_{n-1})}{367\eta_n} \quad (9)$$

G_n—The flow of the most adverse loop pipe network, m^3/h

H_{n-1}—The resistance loss of second most adverse loop pipe network，m

η_2—pump operating efficiency

η_n—booster pump operating efficiency

A method of energy with respect to the conventional method is

$$\Delta N = \frac{N_1 - N_2}{N_1} = 1 - \frac{\eta_n H_{n-1}}{\eta_1 H_n} - \frac{G_n(H_n - H_{n-1})\eta_2}{\eta_n G H_{n-1}} \quad (10)$$

Different pump models, design efficiency and operational efficiency is different, however it can be ignored as a program of assessment and energy analysis.

$$\Delta N = (1 - \frac{G_n}{G})(1 - \frac{H_{n-1}}{H_n}) \quad (11)$$

It is concluded that the booster pump added to install in DHS, is energy-efficient. The higher saving rate is, the larger ratio of the resistance loss of second most adverse loop pipe network to the resistance loss of the most adverse loop pipe network is. While the higher saving rate is, the smaller ratio of the flow of the most adverse loop pipe network to the total flow of system is.

When the selection of main circulation pump is only satisfied with the i-th loop pipe network, the users of the (i+1)-th, (i+2)-th ，…，n-th are needed to add a booster pump. So, saving rate is

$$\Delta N^* = \sum_{j=i+1}^{n} (1 - \frac{G_j}{G})(1 - \frac{H_i}{H_j}) \quad (12)$$

In other words, the size of the saving rate is related to the rate which is the resistance loss of a loop pipe network added a booster pump to the i-th loop pipe network and which are the flow of the loop pipe network to total flow of the system. It is fully shown that energy-saving rate of the DN system whose pipelines are increased booster pumps can be improved.

3 DISTRIBUTED VARIABLE-FREQUENCY SPEED PUMPS DISTRICT HEATING NETWORK

3.1 Six schemes of heating network

Because of the drawbacks of the traditional network, the study has been directed to the other type of district heating topology, where such a large number of valves would not be needed. This topology is called distributed variable-frequency speed pumps district heating system. It is especially suitable for mass flow control where is not only to set circulating pump in the heat source, but also to set booster pumps in the heating pipeline network. These inverter-controlled centrifugal pumps are driven by the heat demand and desired return temperature. This connection is suitable for different applications in addition to the district heating network, such as under floor heating and radiator heating systems.

District heating network is a kind of fluid network, similar to the electric network, it follows the Kirchhoff's current, voltage law, Its branch flow, pressure drop and the pipeline resistance characteristic coefficient can be drown analogy with branch current, voltage and resistance of the electric. Consider a model of the heating pipe network, m for its branch number, n + 1 for its node number. And we can get its associated matrix A and basic circuit matrix B_f where A is an n ×m order matrix, B_f is an (m-n) ×m order matrix. According to the logical network diagram and the Kirchhoff's law, the equation can be written as follows;

$$A * G = Q \quad (13)$$

Where A is the connection matrix of the heat-supply network; G is the flow column vector of each pipe in the heat-supply network, $[G_1, G_2, ...G_m]$; Q is the node net out flow, which is n-dimension constant column vector, and we assume the inflow direction the positive and the outflow negative, $Q=[q1, q2,..,qn]^T$ From the Kirchhoff's voltage law, the equation can be written as

$$B_f * \Delta H = 0 \quad (14)$$

Where B_f is the basic circuit matrix of the heat-supply network; H is the differential pressure column vector of each pipe in the heat-supply network,$[\triangle H_1, \triangle H_{2,,,,,}\triangle H_m]^T$

Partition the basic loop pressure balance equation ($B_f * \Delta H = 0$), and get $\Delta H = [\Delta H_l, \Delta H_t]$, $B_f = [B_{fl}, B_{ft}] = [I, B_{ft}]$

In the formula, ΔH_l corresponds to the column matrix of the pressure loss of the remainder of the tree; ΔH_t corresponds to the column matrix of the pressure loss of the branches; B_{fl} corresponds to the column matrix of remainder of the tree, an m-n order unit matrix; B_{ft} corresponds to the column matrix of the branches, an (m-n)× n order matrix.

So, $B_f^* \ \triangle H = [B_{fl}, B_{ft}]\ [\triangle H_l,\ \triangle H_t]^T = [I, B_{ft}]\ [\triangle H_l, \triangle H_t]^T = \triangle H_l + B_{ft}\ \triangle H_t = 0$

And we get： $\Delta H_l = -B_{ft}\Delta H_t$ (15)

Presume $\Delta H = \Delta P - H$

Where ΔP is the resistance of each branch, an m order column matrix; H is the lift provided by power plant of each branch, an m order column matrix

$[\Delta H = \Delta P - H]_l = -B_{ft}\ [\Delta H = \Delta P - H]_t$ (16)

By formula (16), In order to make pipeline run under the lowest energy consumption, circulating pump installed in only thermal station branch or only in for supply and return trunk line. According to the above analysis, six basic schemes can get the following:

The first scheme: The pumps are set to the pipe of heat source and on each user branch (Fig. 2)

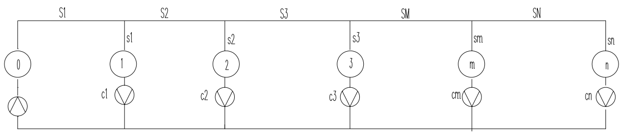

Fig. 2 The first scheme of district heating network

The second scheme: The pumps are only set to the each user branch pipe (Fig. 3)

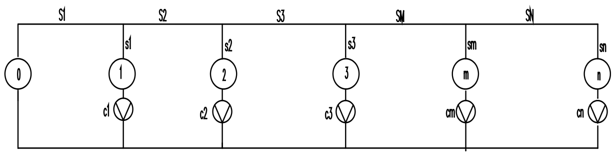

Fig. 3 The second scheme of district heating network

The third scheme: The pumps are set to the pipe of heat source and for supply and return trunk line (Fig. 4)

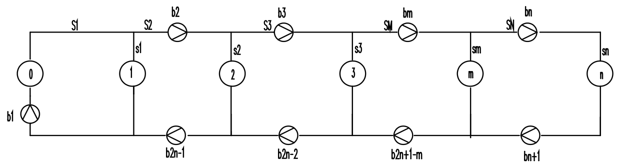

Fig. 4 The third scheme of district heating network

The fourth scheme: The pumps are set to the pipe of heat source and for supply trunk line (Fig.5)

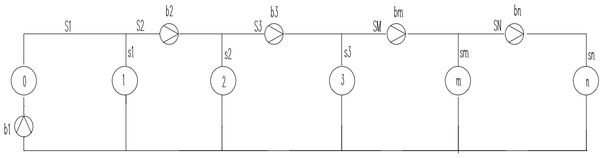

Fig. 5 The fourth scheme of district heating network

The fifth scheme: The pumps are not only set to the pipe of heat source and for supply and return trunk line, but also on each user branch (Fig. 6)

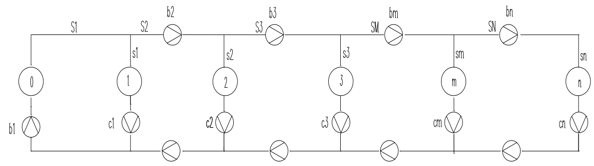

Fig. 6 The fifth scheme of district heating network

The sixth scheme: The pumps are not only set to the pipe of heat source and for supply and trunk line, but also on each user branch (Fig. 7)

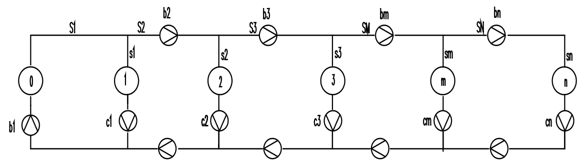

Fig. 7 The sixth scheme of district heating network

3.2 Analysis and Comparison

First of all, the number of trunk mains resistance factor of each pipe section are assumed to S1, S2, S3 ... SN and branch pipes resistance factor to thermal stations are s1, s2, s3 ... sn. For convenience of study the change rule of solution, $S_1=S_2=S_3= \dots =S_N$ and $s_1=s_2=s_3= \dots =s_n$ are assumed. The flow of each user is equal. The water pressure diagrams of six schemes are drawn. (Fig. 8-13)

For scheme one

The independent network circulating pump is abolished in the scheme .The heat source circulation pump is only bear the water cycle of the heat source. However the transport functions of heating network and pressure head on user-owned were undertaken by booster pump of user. Comparing to traditional solutions, the program plan is to let heat medium in the pipe "smoking water goes", but traditional solution is to heat medium in the pipe, "propelled". In the pressure diagram, the biggest difference is that traditional scheme of water supply pressure (supply pressure line) is greater than the return pressure (return pressure line), however the program return pressure (return pressure line) is greater than the supply pressure (supply pressure line). But the pressure of the booster pump head increases with heating radius and the number of users.

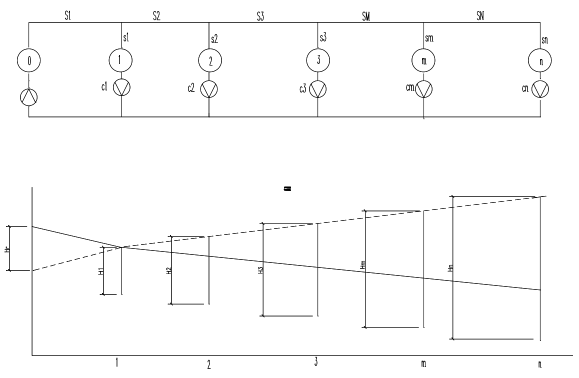

Fig. 8 The pressure diagram of the first scheme

For scheme 2

Comparison with scheme 1, it does not exist differential pressure point. In theory, the heat may not be located at the circulation pumps, it is fully pressurized pump from the external network, circulation pump, booster pumps and heat users instead. To do so, heat lost control of the basic means of heating system. It is not conducive to the safe operation of the system. In addition to program one of its features, it is not conducive to the regulation of the heat source system, there are risks to the safety of heat cycle.

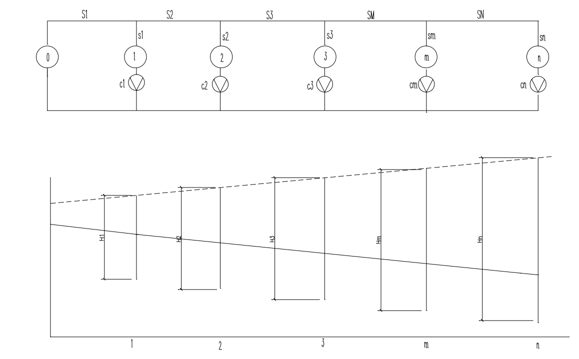

Fig. 9 The pressure diagram of the second scheme

For scheme 3, 5

The pump is set to the pipe of heat source and for supply and return trunk line and each pump head pressure on the trunk mains pressure drop equal. Pressure pump flow and the trunk line conveying flow are equal too. If not every trunk line are fitted with pressure pump, power consumption will inevitably produce invalid. The program system has the advantage of setting down, low operating pressure. However, the initial investment is large and operation and management is not easy.

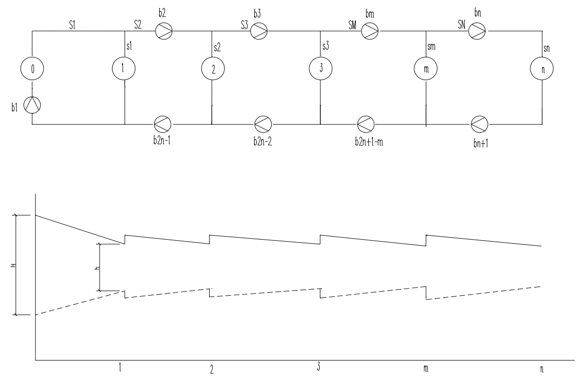

Fig. 10 The pressure diagram of the third scheme

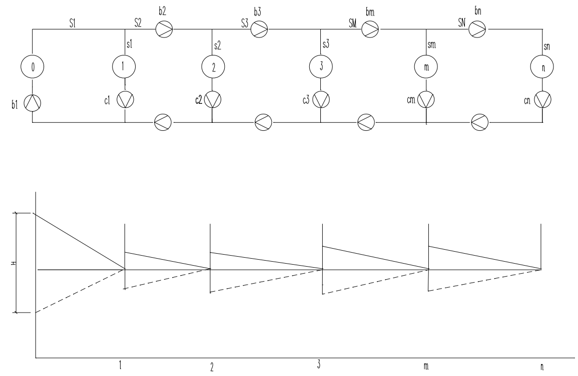

Fig. 11 The pressure diagram of the fifth scheme

For scheme 4, 6

Since there is no return water trunk pump, so return pressure line is a continuous upward. With the increasing radius heating system operating pressure is increasing. To have installed booster pump on the supply water network each trunk, the initial investment is large too and operation and management is not easy.

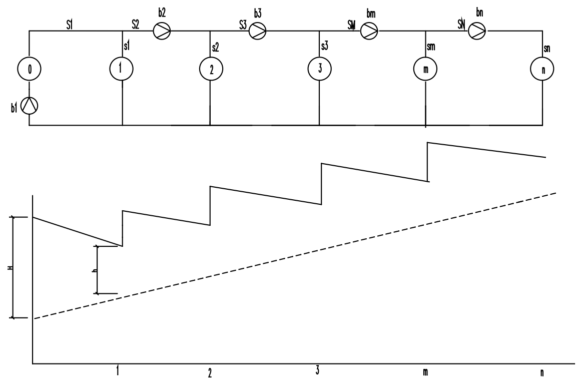

Fig. 12 The pressure diagram of the fourth scheme

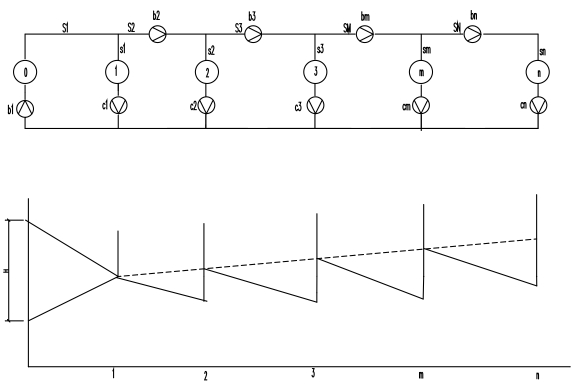

Fig. 13 The pressure diagram of the sixth scheme

4 THE SCHEME OF RECOMMENDATION

There have been a number of configurations of DH system with the distributed variable-frequency speed pumps district heating system. Compared to the six forms, the first scheme is recommended. It has the following characteristics: (1) there is a hydraulic connector between the outlet and inlet of the heat source. That makes it convenient to control the system and allow the heat source to be operated safely, especially when the heat source includes more than one boiler. The hydraulic connector is also working as a constant pressure point of the DH system. (2) Each of the heating substations has a variable speed pump that is used to pump either the supply water or the return water. (3) The operating condition of the DH system is controlled by the circulating pumps rather than by control valves in the conventional central circulating pump DH system.

Due to the hydraulic connector that is a pipe that connects the supply-water pipe and return-water pipe, the heat source loop is hydraulically independent. Under full-load operation, the flow rate in the hydraulic connector is nearly 0; while under part-load operation, the hydraulic connector is working as a bypass pipe. A variable speed pump is installed at each substation and used to provide the required hydraulic head for each loop. As there is a pump at each substation, no central circulation pump and control valves are required (Fig. 2a). Hence, the power loss related to throttling is avoided

Correspondingly, the variation of the hydraulic head with locations is illustrated in Fig. 8. It is clear that for the distributed variable-frequency district heating system, the pressure in the supply-water pipe is lower than that in the return-water pipe, which is contrary to the pressure profile in the conventional central circulating pump DH system., because for the distributed variable-frequency district heating system, the pump is used to pump return water. Since the flow rate in each branch is adjusted by variable speed pump, the supplied head can match the needed head by regulating the rotational speed of the pumps and there is no rich head to be throttled. It is also clear that, for the conventional central circulating pump DH system, there will be some rich head need to be throttled in most branches except the furthest one from the boiler and thus, throttling effect cannot be avoided.

5 CONCLUSION

Distributed frequency heating is an advanced form of design idea which the circulating pump is to separate these three functions into a heat circulating pump, circulation pump and heat circulation pump users. The application of the distributed variable-frequency speed pumps DH system has been considered as a technology improvement that has a potential of saving energy, compared to the conventional central circulating pump DH system. By analysis and comparison of heating six kinds of schemes on distributed frequency, using of the scheme 1 can be reduced the number of booster pump, and easy installation. Several other characteristics of the specific schemes can be selected according to the practical engineering.

ACKNOWLEDGMENTS

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SESSION 8

Customer relations, market issues, pricing and costs

JOINT COST ALLOCATION AND COGENERATION

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ABSTRACT

With the joint production of two goods, one subject to competition and the other being a natural monopoly, the threat of cost based price regulation should lead the rational producer to allocate as much costs as possible to the product under scrutiny. We investigate whether Swedish district heating companies allocate joint costs accordingly as well as the importance of these choices in terms of reported segment profitability. The study is conducted through telephone interviews with Swedish companies with combined heat and power (CHP) production, and by analyzing effects on segment profitability from different allocation policies in a DH firms. Our main findings are that most CHP producers do not allocate costs for purposes of reporting or decision making, but that they, implicitly or explicitly, consider electricity a by-product which is used to subsidize heat customers. The case study also suggests that the choice of allocation method has a substantial impact on reported business segment profitability.

BACKGROUND

The potential benefits from allocating costs between products that are jointly produced have been the topic of much research. If products are traded at competitive markets the reason for engaging an allocation exercises are not entirely clear. However, in non-competitive markets the issue of allocation becomes more important. Monopoly pricing is typically mitigated by law makers with some form of regulation, and historically the price that the regulated monopolist is allowed to charge often derives from the company's costs (c.f. European Court case 27/76). If the product under scrutiny is jointly produced with another product one must determine how much of the joint costs that should be allocated to each product. In such cases the principles of allocation have direct value consequences for supervised companies.

In this paper we study joint cost allocation schemes by analyzing Swedish energy companies where at least part of the energy is produced in combined heat and power (CHP) plants, i.e. the joint production of electricity and district heating (DH) . By increasing total plant efficiency CHP offers substantial contributions to energy security as well as mitigating climate change compared to when producing DH and electricity in separate utilities. In conventional power plants total efficiency amounts to 25-45 percent whereas CHP production raises that number to 70-95 percent [13]. Replacing central heating with district heating systems also makes possible the usage complicated fuels, better waste management and improvements to the local environment. These features have made the advancement of CHP a political priority. In Europe this is manifested in the European CHP directive (COM 2004/8/EC), where member states are urged to promote efficient cogeneration. In the United States the current administration has set up a goal of 40 GW new CHP capacity until 2020, which corresponds to a 50 percent increase in total American CHP capacity [10]. In Sweden the share of total electricity production that stems from CHP is comparatively low, this because the Swedish electricity system in large relies on hydro and nuclear power.

In recent years the market for DH has been widely debated. In Sweden, which has one of the most developed DH markets in the world (measured as the DH's share of the market for heating), it has been claimed that district heating systems are to be considered natural monopolies where producers allegedly use their market power for overpricing. The Swedish Competition Authority recently investigated two cases concerning possible overpricing in the municipalities of Stockholm and Uppsala [24], but these investigations were written off in late 2010 as it was deemed that any further investigation would not result in any clear conclusions. In the new District Heating Act the relation between DH companies and their customers is addressed insofar that a special District Heating Board is created with the purpose to act as mediator in case of conflicts over terms. However, this body has no coercive competence and has been criticized by customer representatives for not being a satisfactory safeguard. This conclusion is supported by the Competition Authority [24] and the Swedish Energy Markets Inspectorate [12] where both want a price regulation put in place. Further, a cost plus regulation of Swedish DH prices is also advocated by the International Energy Agency [20].

If DH prices are to be determined based on costs one must establish how to determine costs, in particular in relation to joint production. A substantial part of the total energy production in many DH firms takes place in CHP plants, and with mark-up pricing joint costs should somehow be allocated between the products heating and electricity. Assuming rational agents one would expect that firms in industries subject to public debate or regulatory threat, like Swedish CHP producers, allocate as much costs as possible to the product invoking concerns. Such allocation would make the DH business segment appear less profitable and potentially help to avoid becoming the target for criticism for overpricing or, if regulation is enacted, push the possible price limit upwards. Conversely, consumers of the same product would prefer the size of costs addressed to DH to be as small as possible since that would strengthen their argumentative power in a price conflict. A competition authority would be in the middle, having the ungrateful task of finding the policy that would be most aligned with economic efficiency. In addition, the environmental benefits associated with CHP production provide arguments for not putting in place regulation which discourages investments in CHP plants.

In the context of the Swedish DH sector, given the threat of regulation that these companies face one could expect them to allocate as much costs as possible to the DH business segment and as little as possible to the electricity segment, and thereby lifting an upper price cap. On the other hand, Swedish DH companies are in most cases municipally owned and were in the past not even firms, but municipal administrative units. This indicates that these firms do not come from a culture of profit seeking. Instead, municipally administered services in general are by law provided on a cost-coverage basis. It is important, however, to note that municipal energy companies are exempt from the requirement of prime production cost pricing. To the contrary, there is a phrasing in the law that these firms should conduct business on commercial basis. But that does not rule out that the historical administrative culture is lingering to some degree, or that politicians want to keep energy prices down in order to avoid upset voters. Even so, it is not clear why anyone should want to put avoidable pricing constraints on themselves. Even without for-profit motives, a CHP producer would gain some slack if more costs are attributed to the DH business segment.

This background suggests that how firms allocate joint costs has consequences for firm profitability, energy security, environmental performance and consumer welfare. Knowledge on these issues is therefore important, and any regulation or debate on companies' allocation choices should be rooted in an understanding of how CHP producing firms allocate joint costs today, and what implications they may have for firm performance. Consequently, the purpose of this paper is to increase our knowledge on how cogenerating companies allocate joint costs and how cost allocation policies influence company operations. This is met by answering two questions. First, a solid understanding is warranted for to what degree companies allocate costs today, how it is done, and for what purposes. Thus, our first research question is:

How and for what purposes do Swedish DH companies with CHP production divide joint costs between heat and electricity?

Second, we need to understand how different joint cost allocation principles affect perceived segment profitability. It could well be the case that effects of allocation choices are insignificant. If so, it would not make sense to engage in costly search for alternative allocation principles. So, we finally ask:

To what degree does the choice of joint cost allocation principle influences segment profitability in a CHP producing company?

This study leaves several contributions. First, we are able to obtain information on how a large set of companies within the same industry actually allocate joint costs, and for what purposes. This in itself is interesting as access to firm often is a main problem for researchers. Second, cost allocation choices are commonly viewed as a firm internal affair, of little interest for external actors. This study illustrates that such choices indeed may be of importance for interests outside the company. Third, joint cost allocation in itself has attained little academic interest as the link to the firm's value creation has been vague. We highlight the role those choices might have for product pricing, something that indeed is of importance for value creation and thereby deserves further examination.

We find that for purposes of decision making the vast majority of CHP producing companies do not allocate costs, and that the CHP production is regarded an indivisible business operation. However, we also find that most firms, implicitly or explicitly, allocate costs in relation to pricing. This is typically done so that heating consumers are fully benefiting from the electricity sales. Tax legislation also drives allocation, but it is not important when it comes to investment decisions or short-term production decisions. We also find that the choice of allocation method may have a substantial impact on reported segment profitability.

The remaining of the paper is organized as follows. The next section covers literature where possible purposes of joint cost allocation are discussed, tentative allocation principles identified and previous research on joint cost allocation in CHP production is presented.

LITERATURE

The literature at date provides with some tentative explanations or purposes to why companies allocate joint costs. These are grouped into what we coin purposes for: financial reporting, internal decision making, pricing, environmental reporting and taxation. Further, the literature also suggests numerous ways to allocate joint costs. Below, we introduce this literature and relate it to the case of cogeneration.

Allocation purposes

Joint cost allocation could provide input in internal decision making. For instance, It has been argued that allocation of joint costs have an auxiliary function for managers in deciding whether a joint-product should undergo further processing beyond the split-off point [27]; although this has been debated ([18], [25], [28], [26]). In any case, this argument is of little relevance for this study, as there is no further processing beyond the split-off point. However, allocation choices could affect investment appraisals and operative decisions if estimated costs are somehow incorporated in these decisions. For example, allocation choice could influence the perceived attractiveness of adding an additional customer to the DH system if the estimated DH costs are used in the cost-/benefit analysis. If so, with mark-up pricing, a higher proportion of CHP costs allocated to electricity increases the likelihood that additional investments are done in adding new DH customers.

Joint costs could be allocated for purposes of financial, though the reasons to why are not entirely straightforward. Historically, the prime reporting purpose has been inventory stock valuation ([2], [27]), and by prolongation profit measurement [6]. However, an external investor's primary concern is the value of the firm at large. Certainly, information on business segments normally is a valuable component in the analysis of overall firm performance [19]. But with joint production it is more complicated as any assignment of costs to the separate products must be based on some arbitrary principle [42]. This arbitrariness conveys the risk of making segment reporting a driver of obfuscation rather than clarification. Therefore, it is not self-evident that value is added through such reporting practices. In fact, for this very reason Thomas (ibid.) wants us to leave allocation reporting altogether. This is also applicable to cogeneration. What ought to be of interest from an strict investor perspective is how firm value can be augmented by combining the production of heating and electricity, well aware of the fact that the combination per se creates value. Concerning inventory valuation in particular, in CHP production there is no inventory as both DH and electricity are consumed at the same time as they are produced.

Joint cost allocation has also been put forward as being useful in pricing policy [6] where mark-up pricing is used. It is not perfectly clear why this should be important to firms when they are price takers, or even when they are monopolists. What should be of interest is to maximize total profits. However, the fact that most Swedish DH companies are municipality owned increases the probability of a cost-plus pricing practice. According to Swedish law (Swedish code of statutes 1991:900), fees charged by municipal administrations (e.g. fees for water and sewage, waste management and child daycare) may not exceed the cost price. This would potentially influence the pricing policy of a DH company owned by a municipality as well, despite the fact that DH companies should, by law since 1996 (Swedish Code of Statutes 2008:263), be run on a commercial basis. With the municipal heritage it is reasonable to believe that although district prices in such companies are no longer cost prices, they could very well be cost based.

In environmental impact analysis allocation has become an issue of significance. As environmental awareness increases companies are under growing pressure to measure, quantify and lower their environmental impact [29]. For this purpose, methodologies have been developed to make possible comparisons between products and services in terms of their respective ecological (and social) consequences. The environmental damage that a company causes is an external cost [9] as it is not fully born by the company itself, and therefore not fully reflected in firm value. But if the environmental impact of a (jointly produced) product is to be communicated the choice of allocation method becomes important, and where the ISO 14041 standard provides with some basic principles [5]. The customer wants only to know the environmental impact of his/her particular purchase and then allocation becomes unavoidable. This part is highly relevant for cogeneration. The energy industry is one of the main drivers of air pollution and large amounts of natural resources are plowed into energy production. In this context, the allocation of pollutants from CHP plant (a joint external cost) has great influence in the perceived attractiveness of for instance electricity sold when customers compare it to other power sources.

Last, but not least, taxation should be an obvious driver of allocation choices. If the effective tax rate of a company is somehow affected by allocation principles there is also an incentive to pick the allocation scheme which minimizes tax payments. This is apparent in previous research for instance in relation to charity organizations where tax exemptions are relatively commonplace, and where the size of those exemptions are partly driven by joint cost allocation choices [23]. The intersection of cogeneration and taxation has been analyzed in several studies. For instance, [32] study the competiveness of CHP under different tax regimes, and analyze the contract zone (the set of possible cost allocation schemes that allow the CHP to compete against technologies where heat and electricity are produced separately) for three different CHP technologies. The researchers find that most CHP technologies are profitable even without taxes, and that energy taxes generally increase the contract zone. In their study on marginal costs in DH production [39] note heat is heavier taxed than electricity at the production stage. To the degree a producer can chose allocation method he would, under such a tax scheme, opt for assigning as much fuel costs to electricity as possible. However, the researchers also note that in the Swedish tax system allocation has been done proportional to heat and electricity production and that this allocation method attributes a relatively large share of total costs to the DH production due to the assumption of equal efficiency between heat and electricity.

Under a regulatory threat the intersection of financial reporting and pricing makes joint cost allocation a driver of firm value. Decreasing cost industries are often natural monopolies, and to ensure socially optimal outcomes pricing in such industries is often subject to some form of regulatory scrutiny. Often such regulation is cost-based. The determination and reporting of costs for business segments then becomes necessary, and allocation of joint costs will have consequences for companies' value creation. As already described in the introduction price regulation in the DH industry is in Sweden debated and regulation is advocated by many, including the Energy Markets Inspectorate and the Competition Authority.

Allocation methods

In an early article on the topic, [2] distinguishes between accounting for by-products and accounting for joint products. When accounting for by-products he proposes three alternatives. First, one could allocate all costs to the primary product and then use the sales from the by-product to reduce overhead expenses otherwise put on the manufacturing process. Second, one could treat the net income (sales minus selling expenses) from the by-product as a deduction to the total cost of the principal product. The third proposal is almost identical to the second, but in this case also includes costs for further processing after the split-off point when calculating the net income of the by-product. In the case of joint cost allocation, allocations by (1) volume/weight, (2) sales/value or (3) basically any arbitrary rule are identified. The alternatives in [2] are the ones commonly found in textbooks in management accounting [11]. Of course, the arbitrariness in all of these approaches (already in determining whether it should be considered a by-product or joint product, where [2] makes reference to a ten percent rule), and he himself also concludes that the allocation problem per se is insolvable. This conclusion is in coherence with the call of [42] to abolish allocation reporting.

The distinction between main product and by-product in [2] is echoed in a Swedish governmental investigation on separation of DH and electricity markets [38], which argues that from a business perspective DH is to be considered a main product and electricity a by-product. To regard DH as a main product and electricity as by-product, and therefore to allocate all costs to the DH operations and subtract electricity revenues as a "negative cost" is equivalent as to say that no part of the company's profits are to be attributed to the electricity production. This would push a possible price cap on heating downwards as DH costs are subsidized by power sales. Whether this investigation in turn reflects an already established practice in the DH industry or some other influence (e.g. literature) remains an open question. The usage of such a rule would on the one hand contradict the rationality assumption as electricity would subsidize district heating. On the other hand, it could be perfectly rational for politicians to let electricity subsidize heating.

The allocations for joint production proposed by [2] are also used in relation to CHP. In particular, the energy method stipulates that joint costs in CHP are allocated proportionally to the energy content in the DH production and the electricity production respectively. For example, this method is used by Statistics Sweden [40] when allocating fuel use between DH and electricity. A modified version of this method is the exergy method [44], in which the quality of bifurcated flows are taken into consideration. With exergy accounting a larger fraction of joint costs are allocated to electricity compared with when using energy accounting. A comparative analysis of energy- and exergy accounting is found in [31]. Allocation proportional to sales, or economic value, between electricity and DH is rare, but has been touched upon by [15] in relation to CHP plants based on waste incineration.

Despite the call for reporting free from cost allocation [42] researchers continue to study allocation. Moriarity [30] states that he does not want to argue any theoretical justification for his proposed model; instead he *"assumes that accountants will continue to be required to allocate cost for reporting purposes"* and that his proposition is *"justified to the extent that the results of* [his model does] *not possess the disadvantages of the allocation techniques of employed in current practice"*. In Moriarity's alternative production model [30], joint costs are allocated proportionally to what the individual product's cost share would be in a portfolio where all products are instead obtained independently. One disadvantage with Moriarity's model is pointed out by [16], however, as they show that the model may result in suboptimal coalitions. But in response to this critique [14] shows that the alternative production model can be outside the core only when there are three or more cost centers as well as non-increasing marginal costs.

Moriarity's model has gained importance in relation to CHP production (though reference is not made to him). This is essentially the same principle as the one used for preparation of Environmental Product Declarations

(EPD) for electricity and heating when jointly produced [21]. This principle is also mirrored in the CHP Directive (EC2004/8) when it is determined whether a CHP plant is to be considered highly efficient. In Sweden, this principle is also the foundation for the recently agreed upon method for allocating environmental impact of CHP plants between electricity and heating [35]. Moreover, the critique of [16] is not very relevant in the case of cogeneration. Here, we look at the joint production of two products, district heating and electricity. However, in a nearby future we will see an increased production complexity as many DH companies are considering investing in bioenergy combines, in which some bioenergy product (e.g. ethanol, biogas or pellets) is coproduced with district heating and electricity [3].

Lastly, it could be argued that if a company adds a new product to its operations, and where the new product is jointly produced with an existent product the cost that should be assigned to the new product this the incremental cost from adding the new product to the portfolio. In this view it should not be the case that the new product subsidies the old product. In a cogeneration perspective this could be important. In Sweden CHP producers have historically regarded themselves DH suppliers first and foremost. Only at a later stage was electricity added to the production. Therefore, to break out electricity from this perspective one only excludes the identifiable incremental costs for electricity production, and electricity revenues are not included in the DH business segment. Of the approaches presented here, this is the one that probably favors the producer the most, almost all cost are assigned the DH segment but no part of the electricity revenues.

In addition to the abovementioned allocation schemes various game theoretic models are suggested for the allocation of joint costs ([36], [37], [34], [14], [16], [22], [7], [8], [33], [17], [4], [43]). The one that perhaps has gained the most academic attention is the usage of Shapley values [36] as applied to cost allocation [37]. Here, each division pays a charge equal to the expected marginal cost (expected as the order of entering is unknown) that arises when entering. Although these game theoretic approaches provide with valuable insights into the potential problems of joint cost allocations, they are probably of minor importance in our empirical quest to understand how Swedish CHP producers allocate costs and why they do so. Would it not have been for studies such as [7] or [1], one would have guessed that these models never left the academic den and been exposed to the light of reality. Nevertheless, I still find it implausible that we would find such methods when looking into the companies in our study; the prime reason for that would be that they probably do not know about them, nor would they find it easy to motivate the computational effort required had they known about them. But yet again, this needs to be corroborated empirically, and it could be the case that we will have reason to return to these approaches.

RESEARCH DESIGN

Our research design consists of two parts. First, we investigate how energy companies allocate joint costs through an extensive interview study. Second, by making an in-depth case study on a CHP producing company we analyze to what degree the choice of allocation method matters for reported segment profitability.

Interviews

All the companies in our study are located in Sweden, and produce district heating and electricity in CHP plants. These companies were identified in cooperation with the Swedish District Heating Association as they have already collected statistics on electricity and district heating production in member companies. The association provided with contact details for the persons responsible for CHP operations in the firms. We sent out an e-mail to these persons with the industry association as consignor, where we asked them to participate in interviews and notified that we were to telephone them. The positions of the respondents vary. In some companies the respondent is the managing director, in others it is the head of operations or someone that is specifically responsible for the CHP plant in the company. Common for all these persons was that their names have been put there by the companies themselves as persons to contact regarding issues on cogeneration. In some cases we were, in response to our e-mail, immediately redirected to other employees, and this was also the case sometimes when we telephoned. For instance, for some companies we ended up talking with the financial manager of the company, and for a few companies we conducted two interviews with different persons as our questions covered areas that sometimes were organizationally separated. Hence, our interviews have not been directed to persons with a specific title. Instead, considerable effort has been spent in finding the person who is best apt to answer our questions.

In total, we interviewed 35 persons in 33 companies, recorded the interviews, and later summarized and analyzed them. The interviews are semi-structured, i.e. we have a battery of questions that we want to cover but there is room for discussion and elaboration. Mostly, each interview lasted between about 30 and 60 minutes, but in some case it was considerable longer. Moreover, the interviews were recorded and later summarized and analyzed. This is an important measure, as we as interviewers then can analyze the interviews as non-participants. When doing so, we realized on several occasions that the respondent's answer to a question was in fact something other than we had understood while we were interviewing. It also occurred that we in the subsequent analyses realized that respondents were giving us valuable insights into what problems they experience, and that we had not taken notice of this during the interview as we were eager to “ask the next question”. In sum, the recording and summarizing of interviews are important tools to raise validity.

Each interview commenced with the respondent presenting him-/herself, the company and the CHP operations. This provides with an immediate understanding of the respondent’s knowledge (from the description of work tasks and how long they have been in the company), as well as the relative importance of CHP production. The presentation was then followed by the actual interview, which in our initial battery of questions revolved around how joint costs are allocated in relation to external reporting, environmental reporting, pricing, investment decisions, operative decisions, and also how they have allocated in the past and whether they plan any changes in allocation principles. When possible we ask for actual examples to illustrate the point the respondent wants to make. Each interview is ended with the question if the respondent can think of any aspect of joint cost allocation that has not been covered in the interview and that could be of importance in any business matter.

The exact questions, and the framing of them, were slightly modified over the course. Earlier interviews revealed knowledge gaps of ours as well as interesting questions that we had not taken into consideration initially. These insights were therefore incorporated in later interviews. For example, in the first interviews we connected the issue of how joint costs are allocated to the reporting requirements of the Energy Market’s Inspectorate. Soon we realized that the law is written in such a way that it is easily interpreted that reporting of CHP is to be done in a certain manner (all cogeneration costs are reported and electricity revenues from cogeneration is included as well). We therefore generalized the first question so that we asked whether they allocated joint cost in any context. In a similar fashion, questions we have included in the beginning turned out to be quite unproblematic or difficult to research from a practical perspective. For example, we had prepared questions on the history of how allocation schemes are adopted. Initially, we suspected that companies might have allocated in a certain manner in the past but that these allocation schemes (with the surging debate on DH prices and call for regulation) later have been changed or that such a change was anticipated in the near future. Instead, we soon found that this issue was totally unproblematic for most respondents (“we have never discussed it, and have always done it this way”), and that it is even difficult to state when an allocation scheme was implemented, or by whom. Our development in understanding the problem matter therefore influences how we ask questions over time and perhaps also, to some degree, changes the focus of the research problem itself.

The interviews are thereafter analyzed through the lenses of for what purposes companies allocate joint costs as well as how they allocate joint costs, and what consequences that may follow from these choices. Accordingly, we try to establish how companies allocate in relation to internal decision making, financial reporting, pricing, environmental reporting and taxation. With the purpose of decision making we refer to how companies allocate joint costs in order to evaluate their economic performance over business segments, and how they compile and analyze information in relation to investment and operative decisions. We would argue that this closely reflects how company representatives also regard the nature of their own business operations. This includes the assessment of economic performance, investment decisions, and management accounting.

Case study

In order to evaluate possible effects of different joint cost allocation methods, we carry out a case study of the energy company Kalmar Energi AB (hereafter KEAB). KEAB is mutually owned by the municipality of Kalmar and the multinational utility company E.On. With net sales of SEK 221 Million in 2011, KEAB ranks 18 out of the 50 companies with CHP plants that reported their income statements for the DH business segment to the Swedish Energy Markets Inspectorate. Formerly being entirely dependent on a wood burned heat plant in the town centre, in 2009 they completed a SEK 1.2 Billion bio-fuel CHP investment. Following the inauguration in end 2009 the CHP plant stands for the bulk of the company’s heat and electricity production. In 2011 (2010) the company’s total heat production amounted to 406 (473) GWh, of which 359 (384) GWh were produced in the CHP plant together with 132 (136) GWh of electricity. KEAB also get revenues from district cooling, wood fuel services, electricity grid fees and electricity sales, as well as wind and solar power. One of the concerns that underlie this study is the risk of future underinvestment in cogeneration if allocation is too strict. That is why we consider KEAB to be a suitable study object; it is a middle size company and they have just put their CHP plant into operation – therefore, using this company as a study object may serve the needs for other companies that are similar in terms of size and new or projected CHP investments.

Our point of departure are the reports handed in to the energy market inspectorate, in which revenues and costs, as well as balance sheet items are reported for the DH business segment in particular. Accordingly, revenues and costs from district cooling, wood fuel services, electricity grid fees and electricity sales, and power production outside the CHP plant are not reported. Nor are these items included in our analysis. In the reporting to the Energy Market's Inspectorate KEAB have not made any allocation of costs. All costs associated with CHP operations are included in the DH business segment and the revenues from the electricity produced in the plant are included as revenues in the same report. Our task is to artificially construct two separate business segments from this report: DH and electricity. Specifically, in close collaboration with the financial manager as well as two development engineers of KEAB we determine from the company's chart of accounts (at a fine grain level) what items should be allocated to either business segment.

Revenues are straightforward to allocate between business segments. Revenues from electricity production and green certificates are allocated to the electricity segment. Revenues from heat sales and connection fees are allocated to the DH segment. In addition, there are some minor items (e.g, services and activated work) which in our analysis are allocated to the DH business segment. Costs are re-categorized into one of the following categories: production, distribution or miscellaneous (Fig. 1). Production costs are associated with the heat plant and the CHP plant respectively, where the former are fully attributed to the DH business segment whereas CHP related costs are further divided into one of three sub-categories. First, CHP related costs could be directly attributable to an electricity business segment (e.g. turbine, generator and switchgear). Second, costs could be defined as strictly related to the DH business segment (e.g. flue gas condensation). The remaining CHP costs are allocated between the two segments. Distribution costs are costs directly associated with the distribution of district heating and thereby belong to the DH business segment. Miscellaneous costs include for instance sales costs and overheads. These costs are further divided in sub-categories in the same fashion as for CHP related costs. The units of analysis that are actually used are also codified with numerical values so that aggregation is made easy.

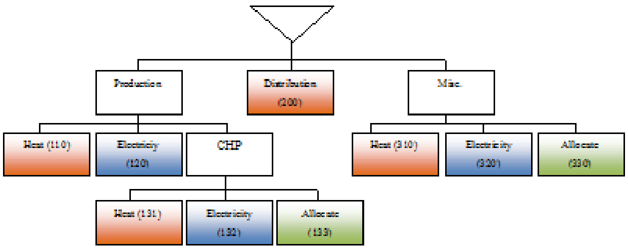

Fig. 1 Example for Symposium Template

As a reference point we first present the original form, in which no allocation is done, but where costs are re-categorized to be compatible with our analysis. This is the base case. Second, joint costs are allocated following a main product/by-product methodology. That is, all costs are allocated to the DH business segment, and revenues from electricity production are subtracted from total costs. Next, costs are allocated proportional to sales (allocation proportional to economic value), followed by an allocation where joint costs are allocated proportional to production volume (energy method). In particular, joint costs from cogeneration are allocated proportional to the CHP production, but other joint costs (sorted under "miscellaneous") are allocated proportional to the total production (i.e. the heat load is based on the CHP plant as well as the heat plant). The fifth model we analyze is the alternative production model, which is used by the DH industry today for allocating environmental impact in CHP production between electricity and DH. Lastly, we use a method of marginal production. In this model all costs, save costs that are directly attributable to the electricity segment (again, turbine, generator, etc.), are allocated to the DH business segment. But none of the electricity related revenues are included. Obviously, this latter method is the method that makes DH appears the least attractive from a profitability perspective.

RESULTS

How are joint costs allocated?

We find that there are a number of different joint cost allocation schemes in use in Swedish CHP producing companies. But this variation is not primarily seen between companies; rather the variation is found within companies. What stands out is that the way joint costs are allocated depends largely on for what purpose they are allocated, and therefore one rarely sees in a company a unified approach in relation to cost allocation. From the results we can distinguish between at least five different purposes for which joint costs are allocated (or better yet, not allocated). These purposes we denote decision making, external reporting, pricing, tax planning, and environmental reporting.

Financial reporting and decision making

For purposes of internal decision making and financial reporting the ways of allocating coincides for almost all respondents. Therefore we present our findings for these two aspects jointly (Fig. 2). We find that the most common way to allocate costs between heat and electricity is actually to not allocate them at all, in three quarters of the companies included in our study this was the case. The revenues from sales of electricity and certificates are simply inserted as revenues from the heating business operation. This is also reflected in the mandatory reporting for the DH business segment required by the Energy Market Inspectorate, in which it is stipulated that revenues from electricity production in CHP plants should be reported separately and that costs from the same plants are included in full. The majority of the respondents explicitly state that they see this as a unified production process (it is the very point with it) and that any separation between the two does not make sense. Even though the absence of allocation is the most common approach for this purpose, the alternative approaches offer interesting perspectives.

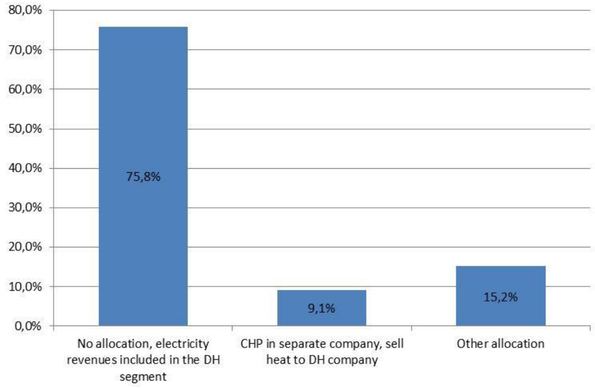

Fig. 2 Joint cost allocation for decision making

Three out of the 33 companies included in our study have chosen to separate the CHP production from the DH business segment by putting it in a production company of its own. Implicitly, the production company produces electricity and then sells heat to a distribution company that is part of the same business group. There are different reasons that motivate such an organization of operations. First, this type of organizing is partly a response to the recent debate on third party access to the DH distribution system. Analogously to the design of the electricity market, where production and distribution are separated, it has been proposed that the DH distribution system should be separated from the production so that other heat producers would be able to sell heat directly to end users. To meet this possible future state, a few companies have chosen to put production and distribution in different companies. Second, one company representative explained how one driving force has been tax planning. This company also have wind power production, and by placing the CHP production in a separate company, it was possible to utilize the electricity tax discount that is allowed if you produce wind power for own use in the DH segment. Third, an organizational separation could be motivated if there are additional complexities associated with the production. It could be that additional products (e.g. bioenergy combines or steam) are intertwined in the same production process, and/or that there are inter-organizational ties through production or ownership which calls for a separation of the two segments. The production company then becomes somewhat a nexus in tying together functions and interests.

A key question to address in this setting is how to determine the (transfer) prices which the production company charges the distribution company. The three companies in our study that have placed CHP production in a separate company have addressed this issue differently. For instance, one company has determined that the production company should meet some level of return on capital, and determine heat prices to the distribution company on a cost-plus basis. Another company has a more advanced pricing construction. Heat prices to the DH company is determined based on alternative costs. The person we interviewed in this company argues that they can estimate with high precision what it would have cost to produce the same heat load in a separate heat plant, as they have another heat plant in use in the system, and that they know what the investment outlay would have been for a heat plant which can be compared with what they spent for the CHP plant. Moreover, this same company produces a bio-product which is partly used in the internal production. This bio-fuel is priced in the same way as when it is sold to external customers, and thereby cross-subsidization is avoided.

The remaining companies do not organize their business segments in separate legal entities, but they do however allocate CHP costs for internal decision making. These companies typically base their allocation on the energy method, i.e. costs are allocated proportionally to the produced quantities of each product. But not all of these companies allocate between heat and electricity. There are also examples where it is instead a third product, steam, which is broken out from the rest of the production.

In terms of decision making more specifically, we tried to find out whether these allocation choices might have any effect on investment appraisals and operative system optimization. With a few minor exceptions, we find that they do not. In relation to investment appraisal we mainly considered investments in production capacity and the connection of new costumers. It was clear that allocation has not been an item when investing in new capacity. Instead, investment appraisals were based on whole-system analysis where all incremental economic effects are taken into consideration. In relation to connecting new customers we suspected that allocation choices would influence the cost estimates being used for investment appraisals. Depending on allocation methodology that could lead to that the additional electricity sales that follows from the increased heat load would be excluded from the analysis. If so, the value added from connecting new customers would be slightly underestimated with the risk of underinvestment. Even though there were some companies that did not take into consideration the increase in electricity sales, most companies did. Either by making a whole-system analysis (e.g. by using the MARTES tool, see [39]) or by adding estimated additional electricity sales to the cost-/benefit analysis. Moreover, the majority of the companies that did not take into account any effects from further electricity sales did so for a good reason. The effects were often non-existent or small, due to capacity constraints. These constraints often follow from the fact that the CHP plants are base-load production units or that they are waste incinerated, which implies that they are already working at full capacity.

Regarding the relation between joint cost allocation and operative decisions the separation between the two was complete. It was apparent how nearly all respondents were optimizing their systems in the short-term in a microeconomics text-book fashion. All that matters in the daily operations are how marginal revenues and marginal costs affect the system as a whole. The heat load is a constraint that has to be met and, to the degree it makes sense to alter the electricity output, prices on electricity and green certificates are set against marginal production cost (mainly current fuel prices). That means that in utilities with waste incineration where you are getting paid for the fuel you use it is always the best option to produce as much electricity as possible. The same parameters also determine what production units that will be put in operation. In a way one could perhaps say that there is an allocation method that is used indirectly, namely the main product/by-product approach. By deducting the revenues from electricity sales for a specific plant you can obtain a marginal heat production cost which can be compared with other plants within the system in order to determine what order plant should be used, but the same result could be achieved by other means so we are somewhat hesitant we should call it a joint cost allocation in the sense that we have treated the term in this paper.

Pricing

For pricing purposes an overwhelming majority of DH companies use cost based pricing (Fig. 3), only two of the firms (six percent) we interviewed does not use cost based pricing. This mean that estimated costs are first determined and then DH prices are set in order to cover these costs and meet some rate of return – but not more even if that would have added firm value. From profit maximizing competitive firms such behavior is unexpected. Instead, all else equal, one would expect that firms would charge as much as possible taking into consideration its competitors. The reason that we do not find this for the firms in our sample is simple. These are not profit maximizing firms. Rather, these are municipality owned firms acting under a multiple objective regime mandated by politicians, rather than under a single objective value maximization criterion. Returns are not maximized, they are satisfied. Instead, municipal DH firms are expected to meet additional goals such as contributing to the fulfillment of municipal environmental goals and to provide with cheap energy. The latter objective, in particular, is key for understanding the adoption of cost based pricing instead of charging market prices.

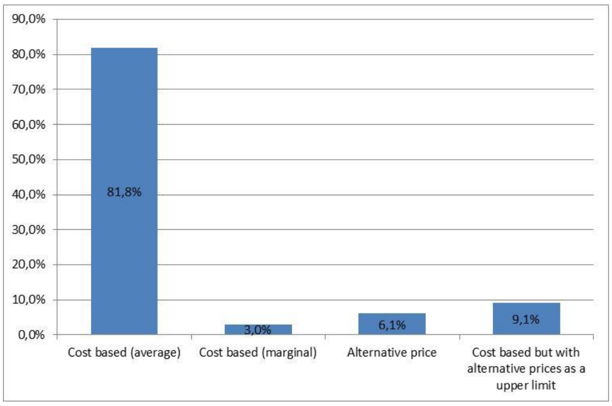

Fig. 3 Pricing of DH in CHP producing firms

Regarding cost allocation in relation to pricing, DH customers typically get the full benefit from electricity production. This is ensured either through a main product/by-product approach or indirectly through the budgetary process. The two approaches are equivalent in outcome. Both approaches imply that average costs are used for determining price per energy unit. Only one respondent states that they use marginal cost pricing. Therefore, not only does the mark-up pricing serve DH customers, they are also subsidized by the revenues that follow from the electricity production.

In relation to cost allocation in firms with mark-up pricing it is noteworthy that the companies that have gone the furthest in mimicking competitive forces in search for firm efficiency, and that have the most elaborated policy schemes for tax optimization, asset valuation and transfer pricing, also pass over the benefits from the electricity sales to the heat customers. Even in the business groups that have singled out production and distribution into separate companies, and argue that CHP is first and foremost an electricity utility where DH is a residual product which is sold at "market" rates to its sibling company, fully subsidize heat customers.

The other way to go about is to use alternative pricing instead of cost based pricing. With this approach, DH pricing is not contingent on production costs. Instead, the customers' feasible alternatives (typically heat pumps) determine how much that can be charged. Therefore, setting DH prices is about being only slightly cheaper than competitors. Only two firms state that they use alternative prices, and that prices are entirely unrelated to the costs of the firm. Unsurprisingly, the two firms that adopt this pricing strategy are the companies without municipal ownership. Obviously, decoupling costs and pricing makes cost allocation redundant, so for these firms no allocation is made for pricing purposes.

Note however that in addition almost a tenth (three firms) of the companies make a point that they do look at alternative prices. But in these cases the alternative prices form the upper price limit. That means that pricing is cost based in principle, but if average costs are higher than the prices of alternative heat sources these firms will not reach cost coverage. For these firms this was not a theoretical issue, to various degrees they experienced, or had experienced, difficulties in covering costs while at the same time adapting to upper price constraints. In essence, they eroded firm value.

Environmental reporting

Historically, the firms we have interviewed have to various degrees engaged in environmental reporting, from the minimum requirements stipulated by law to more elaborated and voluntary disclosure of the firm's environmental impact. Recently, however, the Swedish District Heating Organization on the one hand, and a number of customer organizations as well as the Swedish Energy Association on the other hand, have agreed upon principles for reporting the environmental impact of DH. In these agreements the environmental values of CHP plants are determined based on the agreed upon alternative production methodology. In practice, data on fuels and energy production is now sent to the Swedish District Heating Association and then environmental values are calculated centrally and made publicly available at their webpage. In this reporting the allocation of environmental impact (pollutants and natural resource usage) in cogeneration is included and disclosed.

It is also clear from the interviews that the link between how environmental impact is disclosed in relation to CHP production and how costs are allocated in other contexts (financial reporting, decision making, pricing) is non-existent. In fact, in several cases the persons we interviewed (in charge of e.g. operations or finance) were not aware of how the firm reported the environmental impact of their CHP production. I most cases, however, the respondents were aware of the principles for environmental reporting but still no one had also considered to use the alternative production method (or the method they have used previously when applicable) to allocate joint costs.

We find that the lack of coherence between allocation in environmental reporting and allocation for other purposes is due to two main reasons. First, it has simply not been an issue. This could be because they did not know about the allocation principles in the environmental reporting framework, or simply because they had not considered the possibility that environmental impact could be considered a cost (though external) and that the same method could be used for also allocating other costs. Second, they disagree. Some of the respondents we interview expressed disappointment over the agreed upon principles for allocating environmental impact in CHP plants. Partly this is due to different views on what the marginal environmental effects should be, but there is also an explicit concern that these principles will be used in a future harmonization of reporting standards across societal sectors. In one word, if this would become the standard allocation principle also for taxation purposes this would negatively affect some CHP companies. The fact that the industry association has agreed upon the alternative production method in relation to environmental reporting could be regarded a legitimization of the allocation method itself which would increase the probability that it will be used for other purposes. If you accept this principle when allocating pollution, why should you not also accept it when it comes to cost calculation for tax purposes?

Taxation

Taxation is probably the prime reason to why cost allocation matters today, as the choice of allocation method drives the effective tax rate. Most importantly, fossil fuel taxes are levied on heat production but not on electricity production. Instead, consumers pay consumption tax on electricity. Therefore, the allocation of costs in cogeneration between heat and electricity has real value consequences. The companies with fossil fuel based production that we interview typically allocate costs in accordance with the energy model. That is, joint costs are allocated proportionally to energy produced. In this model 1 MWh oh heat is considered as equivalent to 1 MWh of electricity and where no consideration to exergy is taken.

However, there are signs that CHP producers increasingly argue that CHP plants should be seen as electricity utilities first and foremost, and that DH is a residual product. With this view the bulk of the costs should be allocated to the electricity business segment and only incremental costs to the DH business segment. One respondent goes further and questions taxation on DH production altogether:

> *"Why should we be taxed for making use of excess energy, while at the same time nuclear power operators cool of excess heat into the ocean for free?"*

(Interview with a DH director)

What this respondent claims is that their CHP plant is a power plant, and moreover with greater efficiency than the nuclear power plants, and that they are getting financially punished for reducing overall environmental impact . On the margin there is a tax incentive not to make use of residual energy which obviously goes against goals on increased energy efficiency.

This later approach, to regard CHP plants as electricity utilities has also led some companies to already adopt allocation principles that treat heat as a residual product, and where only incremental costs are allocated to the heat – this in order to minimize fuel taxes. One respondent describes how another company has been successful in making this argument vis-à-vis the Swedish Tax Authority, whereas they themselves have been denied the opportunity to use the same allocation method. This shows two things. First, CHP producers paying production taxes are likely to argue more forcefully that they should be regarded as power plants. Second, there seems to be a certain degree of arbitrariness in the decisions of the tax authority, which means that companies are treated differently on an issue that has direct value consequences.

Other taxes influence allocation choices as well. For instance, one company has chosen to organize their cogeneration in a separate company, partly because that allows them to make tax deductions for their wind power production. In Sweden an electricity consumer can deduct the electricity tax for electricity that he produces himself in windmills. This is one partial explanation to why we see that the total wind power capacity has a much more dispersed market structure than what is traditionally found in the electricity market. From this perspective it makes sense for a Swedish CHP producer that also has wind power in the portfolio to place the cogeneration in a separate company and the windmills in the DH company, as the tax deduction can be done for heat production but not for electricity production. Other consequences from taxes and economic policy instruments that are affected by allocation choices include for example the treatment of auxiliary power and also the number of emissions rights that are granted within the EU-ETS.

Summary

It is clear from our interviews that there is a fairly great variation in how joint costs are allocated. This variation, however, is not primarily found between firms. Instead we find the variation within firms. What is clear is that what is determining how costs are allocated is for what purpose the allocation is done. Actually, there is little variation between firms, as most of them tend to allocate in similar ways when taking into consideration for what purpose they allocate.

Having identified what allocation schemes that are used, and for what purposes they are used we can illustrate how schemes and purposes are related by placing them in a simple matrix (Table 1). The allocation schemes used are no allocation, a main/by-product allocation, alternative production allocation and a marginal production allocation. The purposes for which we allocate we call decision making, financial reporting, pricing, environmental reporting and taxation.

We find that, with some exceptions, that for purposes of decision making and financial reporting joint costs are typically not allocated at all. Executives do see this as an integrated business operation where separation between the two does not make much sense. For pricing purposes, on the other hand, the picture is different. Here, a strong tradition of identifying oneself as DH companies, in combination with a vivid political ambition to hold down local energy prices, has led to an allocation philosophy where DH is seen as a main product and electricity a by-product, and where the revenues from the latter is used to subsidize heating customers. This is in stark contrast to the view that DH companies in general use their market power to gain monopoly profits. Only two companies of the ones we interviewed use market (or alternative) pricing, and therefore they do not allocate costs for this purpose. For purposes of environmental reporting there is now an industry standard, and the alternative production method is used. For taxation purposes, finally, one typically uses the energy method but we also see that there is a tendency to the increased usage of a marginal production approach, i.e. that only the incremental costs are allocated to the heat business segment.

An result that might follow from this multitude of purposes and allocation schemes is that it might create some interesting internal conflicts, especially if there will be a political ambition to harmonize the principles of allocation as well as to put DH pricing under some form of cost based regulatory regime. Then CHP producers could face a situation where they want to allocate as much costs to the electricity segment as possible for tax purposes, as much costs as possible to the heating segment due to regulatory constraints, and where they themselves have provided legitimacy for an alternative production method in relation to environmental reporting.

Table 1 Allocation of joint costs and intended purpose.

Purpose	No allocation	Main product/ By-product	Alternative production	Energy method	Marginal production
Decision making	X				
Financial reporting	X				
Pricing	(X)	X			
Environmental reporting			X		
Taxation				X	X

However, the regulatory threat from an allocation perspective has substantially diminished in Sweden. A coming price regulation will most likely be decoupled from the cost structure of the company as it will encompass the changes in DH prices, and not the profits of the companies. But the possible conflict between tax minimization and maximizing the scope for raising prices should still be of interest for CHP producers in other parts of the world if ever cost-plus price regulation in the DH market would be considered.

To what degree does the allocation choice influence segment profitability in a CHP producing company?

From our case study we analyze the consequences for reported business segment profitability that follows from the choice of allocation method. Accordingly, in Table 2 we show the results for what the reported segment probability would have been for the years 2010 and 2011 contingent on what method you should apply. In the first column we report the base case, which means that no allocation is done at all. This is also in the way that KEAB actually reports their operations to the Energy Market's Inspectorate. In 2011 KEAB had total revenues of MSEK 334, of which MSEK 115 derived from electricity production. The same year total costs amounted to MSEK 273 leaving an EBIT of MSEK 61 and a profit margin of 18 percent.

In the second column the results are given for the case in which we instead allocate costs according to a main product/by-product method, i.e. all costs are allocated to the DH segment whereas electricity revenues instead are treated as a negative cost. It follows trivially that as you reduce revenues and costs with the same amount EBIT will remain unchanged while the profit margin (i.e. EBIT over sales) will increase as the denominator is deflated. With this method KEAB would have shown in 2011 an EBIT of MSEK 61 and a profit margin of 28 percent – an increase by ten percentage points.

Next we show, in the third column, we show the consequences from allocating joint costs proportionally to sales (the economic value), the only method included in this analysis that no one seems to use among the companies we interview. With this method would have been perceives as doing much worse. The 2011 EBIT would have halted at MSEK 24 and the profit margin at 11 percent – a decrease by more than 40 percent compared to the base case. Allocating in proportion to production (column four) would yield even worse results – an EBIT of only six percent and a profit margin of less than three percent.

In the fifth column we present the results from using the alternative production method. Here the allocation factor is given by the environmental reporting disclosed at the webpage of the Swedish District Heating Association. In 2011 the electricity share with this allocation method was 55 percent and in 2010 it was 48 percent. With this method the calculated EBIT (MSEK 65) and profit margin (30 percent) are higher than for any other method analyzed herein. That is, under a cost-based price regulation, and for this company, the alternative production method would render the strictest pricing constraints.

I the last column we present the results from when applying a marginal production method to our case. In this case, practically all costs are assigned to the DH business segment, only the incremental costs directly associated with the electricity production are allocated to the electricity segment. Nor does the DH segment benefit from the electricity revenues. Obviously, this is the model that makes the DH segment look the worst. In our case it lead to negative results with an EBIR amounting to MSEK -57 and a profit margin of -25 percent.

Table 2 Reported segment profitability as a result of allocation choice (MSEK)

	Base case		Main-/By-product		Prop. to revenues		Prop. to production		Alternative prod.		Marginal prod.	
	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010
REVENUES	**334 507**	**353 184**	**219 064**	**235 488**	**219 064**	**235 488**	**219 064**	**235 488**	**219 064**	**235 488**	**219 064**	**235 488**
Heat (incl connection fees)	214 869	233 504	214 869	233 504	214 869	233 504	214 869	233 504	214 869	233 504	214 869	233 504
Electricity (incl green certificates)	115 443	117 696										
Other (incl. activated work)	4 195	1 984	4 195	1 984	4 195	1 984	4 195	1 984	4 195	1 984	4 195	1 984
COSTS	**-273 485**	**-294 578**	**-158 042**	**-176 882**	**-195 796**	**-196 722**	**-213 254**	**-211 912**	**-154 685**	**-165 631**	**-273 114**	**-294 240**
FUEL	**-130 905**	**-149 605**	**-130 905**	**-149 605**	**-92 778**	**-110 501**	**-101 204**	**-118 915**	**-70 142**	**-93 280**	**-130 905**	**-149 605**
Heat	-20 427	-32 261	-20 427	-32 261	-20 427	-32 261	-20 427	-32 261	-20 427	-32 261	-20 427	-32 261
CHP	-110 478	-117 344	-110 478	-117 344	-72 350	-78 240	-80 777	-86 654	-49 715	-61 019	-110 478	-117 344
EXPENSES	**-134 457**	**-138 602**	**-134 457**	**-138 602**	**-96 055**	**-80 206**	**-104 830**	**-86 906**	**-78 268**	**-66 494**	**-134 086**	**-138 264**
Production	-107 309	-111 681	-107 309	-111 681	-74 335	-80 206	-81 540	-86 906	-54 979	-66 494	-106 938	-111 343
Heat	-10 045	-16 065	-10 045	-16 065	-10 045	-16 065	-10 045	-16 065	-10 045	-16 065	-10 045	-16 065
CHP	-97 264	-95 616	-97 264	-95 616								
Heat	-2 421	-1 843			-2 421	-1 843	-2 421	-1 843	-2 421	-1 843	-2 421	-1 843
Electricity	-371	-338										
To allocate	-94 472	-93 435			-61 868	-62 298	-69 074	-68 998	-42 512	-48 586	-94 472	-93 435
Distribution	-4 932	-5 459	-4 932	-5 459	-4 932	-5 459	-4 932	-5 459	-4 932	-5 459	-4 932	-5 459
Miscellaneous	-22 216	-21 462	-22 216	-21 462	-16 788	-15 991	-18 357	-17 796	-18 357	-12 751	-22 216	-21 462
Heat	-6 490	-5 045			-6 490	-5 045	-6 490	-5 045	-6 490	0	-6 490	-5 045
Electricity	0	0									0	0
To allocate	-15 726	-16 417			-10 299	-10 946	-11 868	-12 751	-11 868	-12 751	-15 726	-16 417
DEPRECIATION	**-8 123**	**-6 371**	**-8 123**	**-6 371**	**-6 963**	**-6 014**	**-7 220**	**-6 091**	**-6 275**	**-5 857**	**-8 123**	**-6 371**
Heat	-4 763	-5 301	-4 763	-5 301	-4 763	-5 301	-4 763	-5 301	-4 763	-5 301	-4 763	-5 301
CHP	-3 360	-1 070	-3 360	-1 070	-2 201	-713	-2 457	-790	-1 512	-556	-3 360	-1 070
To allocate/total costs	*81%*	*77%*										
EBIT	**61 022**	**58 606**	**61 022**	**58 606**	**23 268**	**38 766**	**5 810**	**23 575**	**64 379**	**69 856**	**-54 050**	**-58 752**
Interest revenues												
Interst expences												
EBT	**61 022**	**58 606**	**61 022**	**58 606**	**23 268**	**38 766**	**5 810**	**23 575**	**64 379**	**69 856**	**-54 050**	**-58 752**
PROFIT MARGIN	18.24%	16.59%	27.86%	24.89%	10.62%	16.46%	2.65%	10.01%	29.39%	29.66%	-24.67%	-24.95%

Of course, these results are specific for this particular company. If circumstances are changing, so will the calculated results. For instance, if it would have been a larger company with substantial production capacity besides the cogeneration, then allocation choices would have less effect as other production units are brought into the equation. On the other hand, if the CHP plant would incinerate fossil fuels instead the allocation choice becomes even more important as the company then has to pay fuel taxes. Despite this fact, and as we have argued above, it should still be relevant for CHP production in general. Most CHP firms are in the middle size group of companies with bio-fuel (or waste) incineration and are highly dependent on their CHP production. These results should therefore be of interest to other companies as well as to policy makers.

CONCLUSION

Historically, the companies that produce energy in CHP plants in Sweden have regarded themselves district heating companies first and foremost. To a large degree this self-image influences how they act, strategically and operationally, as well as how they report their activity. The electricity production has been an activity that has been added as a supporting activity to the main business model of district heating. For instance, many companies use electricity revenues as a means to hold back prices to DH customers. In this mindset the main problem has been to explain to customers why heat prices must be raised when electricity prices plunge. Many companies explicitly consider the DH to be their main product and electricity to be a by-product. In practice this means that no profits are allocated to the electricity production and all profits to the DH business segment (typically electricity is not even a business segment).

However, there is nothing in nature that says that the DH should be considered the main product. Looking outside Sweden the opposite is the norm as heat is considered the residual. Increasingly this view is adopted in Swedish CHP producing companies as well. They are comparing themselves with other electricity producers and find it harder to motivate why they should not be considered the same. Not surprisingly, the shifting in self imaging is to some (probably the main) part driven by tax considerations, and how policy makers regard heat and electricity respectively.

This study has implications for policy makers. If anything, this study that cogeneration offers significant challenges when it comes to achieving political goal congruence. On the one hand policy makers want to protect consumer welfare and avoid overpricing; on the other hand the promotion of cogeneration is a key component in achieving a more energy efficient society, both at a national and a global level. This makes cogeneration an issue that spans over several governmental competences, and where the risk of lacking policy coherence is obvious. The measures taken in order to promote the increase of cogeneration could to some degree be impeded by measures that are designed to protect consumers. Therefore, we recommend that policy makers establish some form of apparatus where coordination between competences is facilitated.

To the degree joint cost allocation will become an issue in such a coordination effort; one should recognize that the allocation of costs is done differently with respect to different purposes. Any harmonization of allocation principles should be preceded by the contemplation of the potential adverse consequences that follow for individual companies. It could even be the case that a harmonization of allocation principles is not desirable at all.

This study also has implications for CHP producing companies. For instance, we find that there are several local initiatives that could be of general interest and that there is some scope for intra-industry benchmarking. There seems to be a leeway for alternative allocation schemes in order to reduce tax payments. To the degree it is not already taken into consideration companies should explore this field further. Moreover, it could possibly be of interest for more companies to reorganize so that production is legally separated from distribution (or CHP separated from DH) by placing them in separate companies. It could be that this way of organizing conveys some tax advantages as well as facilitates transfer pricing. This could also be of growing importance as production systems become more complex with the adding of additional energy products. Of course, the reorganization could also convey more transaction costs as the management of the total operations would become more difficult. Nevertheless, it is our impression that those that have organizationally separated CHP and DH into different companies are somewhat more able to navigate in this terrain.

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DIFFERENCES IN PRICING AND MARKET STRATEGY BETWEEN PUBLIC AND PRIVATE DISTRICT-HEATING COMPANIES

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ABSTRACT

The deregulation of the Swedish electricity market in 1996 made it possible to operate district heating commercially. This attracted private corporations to the district heating market. A competitive and integrated district heating market is expected to lead to equal prices. The market integration is limited due to problems in heat transfer between systems. District heating systems are local and therefore often seen as natural monopolies. In this study the differences in price levels, price strategy and business goals between municipal, private and state district heating companies is investigated. District heating price statistics and owner type data was used along with results from a questionnaire that was answered by representatives for 109 Swedish district heating companies. The results show that, despite the fact that district heating is supposed to be commercial, a vast majority of district heating companies apply self-cost pricing and not market pricing. The municipal companies also prioritise political goals before financial. Variations in prices between municipal systems are larger than between private and state owned systems. The conclusion is that over 15 years after commercialisation of district heating there are indications that a large share of the district heating sector is not functioning as a market.

INTRODUCTION

District heating is an infrastructural system designed to distribute hot water in an underground pipe network from a central heat producing facility to different heat users, mainly for space heating in buildings and domestic hot water. The benefits of district heating is its flexibility in fuel use and possibility to utilize energy from resources that would otherwise be hard to make use of, such as domestic waste and left over branches and tops from the forest industry. District heating also enables the possibility to use waste heat from industrial processes and to combine heat and power generation in an efficient way.

During the last 30 years frequent market deregulations have characterised the economic development in the industrial sectors of the western economies. Large infrastructural systems such as electric power systems, railway systems and mobile telephone networks have been deregulated and significantly changed in their operational structure. Less market rules and an increased number of market actors is generally considered to increase system efficiency and business profitability. The period after the World War II until the early 1970's was a golden age for the western civilizations with rapidly increased economic growth and increased prosperity. However, during the 1970's the economic growth was decreased and new challenges emerged, such as increased unemployment, high economic inflation and stagnating industrial production.

During this post-war period many of the large infrastructural systems had been functioning as natural monopolies, which were either owned and operated by states or strictly regulated. These natural monopolies were questioned in the 1970s and new theories regarding fully informed markets were developed and applied to previous non-market systems. According to these theories, deregulation increase market competition and thus enhance more efficient markets in three aspects [1]:

- Changes in market structures in form of company mergers and acquisitions
- Lower customer prices
- Better incentives for development of new technology.

Another theoretical aspect on market deregulation that is relevant to relate to in this analysis of the Swedish district heating market is found in theories on market integration and the classical approach of Marshall [2]. An integrated market is characterized by that market prices tend to be equal. The district heating market is not integrated as a whole since heat cannot be moved from one system to another system, unless the systems are connected to each other through distribution pipes which is rarely the case in the Swedish district heating sector in large. So, the district heating sector is not to be considered one single market, but rather many local markets. But, the actors on the district heating markets could share the goal that the pricing of district heating should be according to market pricing principals, and that this should be in competition with other building heating options, such as heat pumps or domestic boilers. If so, the expectations would be that district heating prices among Swedish district heating systems be equal, even though the systems are local markets. The reasoning is based on the assumption that electricity prices for heat pumps and fuel prices for boilers are not varying between different areas of Sweden.

So, if the Swedish district heating sector shares the vision of a market where district heating competes with other heating systems, the district heating prices should be equal. If, however, the prices are not equal this should indicate that other pricing strategies are applied, such as self-cost pricing, and that the district heating sector is not functioning as a market.

District heating history in Sweden started in the late 1940's. Initially the largest cities adopted the idea of district heating as an efficient way to secure power production capacity by either building, or prepare for, CHP plants. Energy supply of electricity and gas had previously in Sweden had a strong tradition in being managed by the Swedish municipalities, which are characterised by their extended self-governing authority [3, 4]. During the 1980's the establishments of new district heating systems were many. However, the Swedish nuclear power expansion in the 1970's led to a surplus of electricity and this limited the interest in building new CHP plants [3, 5]. Instead was the district heating development during this period driven by an urge to reduce the oil dependency in the energy sectors, much due to the oil crises in the 1970's. The result from this was that in the 1990's nearly all Swedish municipalities and most cities had a district heating system owned and operated locally mostly by a municipality owned company.

In 1996 the Swedish power system, including electricity generation and distribution, was deregulated and transformed. From being a natural monopoly that was state owned and operated, the power system infrastructure was turned into a market, where private and non-private actors were interacting and competing in order to lower customer prices and increase the systems efficiency, both technically and financially. This deregulation of the Swedish power system also included all Swedish district heating systems. The consequence of the electricity market deregulation for district heating systems meant that the opportunity to apply market-pricing strategies instead of self-cost pricing was given. And this leading to private actors entering the sector of district heating would be a likely development.

In 2002 private district heating companies delivered about 20% of Swedish district heating [6]. Today about 35% of Swedish district heating systems are owned by private companies, or by state owned Vattenfall. 65% are still owned by municipal companies. [7] This development is clearly illustrated in Magnusson [8]. Therefore it is reasonable to argue that a market organisational restructuring of the Swedish district heating sector has taken place after 1996. Additional systems have been built by, or existing systems sold to, private companies or Vattenfall.

The overall aim of this study is to investigate the effects of Swedish district heating business deregulation on district heating pricing strategy in municipal, private and state district heating companies.

Questions:

- What are the differences in price level variation, pricing strategy and organisational goals between different district heating system owner types?
- Have the commercial ambition among municipality owned district heating companies increased since the business deregulation in 1996?

METHOD

The data used for the analysis is partly data obtained from the Swedish district heating association (SDHA) [9] and the Swedish energy market inspectorate (SEMI) [10], and partly primary data from a recent questionnaire study presented here for the first time. All analysed data is divided into three groups depending on the ownership of the district heating system/systems that data represents.

Owner type groups

The district heating system data used and presented here is divided in three owner type groups; *municipality* owned systems, *privately* owned system and *state* owned systems.

The municipality owned systems' group is the largest of the three. This is the traditional type of owner in Swedish district heating and the companies within this group is normally owner of one single system and occasionally a few smaller systems geographically close to the main urban area of the municipality.

The privately owned systems' group is the second largest. Private actors within the Swedish district heating sector are more commonly owners of more than one district heating systems spread over a large geographical area, compared to the municipal systems. These private actors are thus to a larger extent corporate groups, such as E.ON, Rindi Energi AB Norwiegian Statkraft Värme AB. Further, the largest actor in the district heating sector as a whole, Fortum värme AB, is private. Fortum is however not a corporate group since the organisation only operates in the city of Stockholm. It is interesting to note that two of the privately owned companies represented in the Swedish district heating sector are owned by other states; Fortum Värme AB (partly owned by the Finnish state) and Statkraft Värme AB (Norway).

The third group – state owned systems, in fact consists of district heating systems that all have one common owner, namely the Swedish state owned power-producing company Vattenfall. Vattenfall is however in several aspects acting as a private company and the state influence on the company appears to be limited.

Further there is some district heating systems with other types of ownerships. There are for instance a few split ownerships where municipalities own one half of the district heating operating company and the other half is owned by a private actor. These ownerships are not included here, due to the few present examples of this type of ownership.

Handling of statistical data

Statistical data from two different databases are used to analyse the price level variations between district heating systems with different types of ownership. Information regarding the type of ownership for the Swedish DH systems is available for 2009 and is obtained from SDHA. The data was collected from the SDHA member companies that, according to the organisation, constitute about 98 % of the total annual heat deliveries in Swedish district heating systems [SDHA]. In 2009 there were 140 companies registered in the SDHA statistics, each company is owner of one, or several, district heating systems.

District heating price statistics for 2011 were obtained from SEMI. Data for two different types of customers is used; one for Single family houses (SFH) with an annual heat demand of about 15000 kWh/year and one multi family residential building (MFRB) using about 100 MWh/year. The price statistics were combined with the owner types from the SDHA statistics from 2009 in order to visualise the variations in price levels between different systems, grouped according to the type of owner.

Questionnaire study

132 questionnaires were sent to representatives for 120 different Swedish district heating companies. 109 questionnaires were answered and returned which gives a response rate of 83%. The high response rate is probably explained by that each questionnaire was preceded by a phone call were the potential respondents had a chance to decline participation in the study.

The questionnaire contained eight different questions corporate grouping both future technology development of district heating and district heating market strategy. All questions had three or more given response options, but also the opportunity to, in text, motivate the response option chosen. The possibility was also given to choose more than one of the options.

Out of the 109 respondents; 53 were CEO's, 22 were titled director of district heating and 19 were titled director of district heating sales. Other titles among the respondents were; operational director, operational engineer, environmental strategist, expert on taxes and financial instruments, director of distribution and operational coordinator.

The questionnaire responses were divided into groups based on ownership in correspondence to the division made for the statistical data. Questionnaire data contain 84 responses from municipality owned systems, 17 from privately owned systems and 4 responses from representatives for the state owned Vattenfall corporate group.

In this study the results from two of the questions included in the questionnaire that corporate group district heating market strategy, are presented.

DISTRICT HEATING COMPANIES' GOALS, PRICE STRATEGIES AND PRICE LEVELS

Initially the companies' ambitions in terms of major organisational goals and pricing strategies are investigated using the questionnaire results. Thereafter the correspondence between the ambitions and actual statistics regarding price levels is analysed. This will provide information on how well the Swedish district heating sector is functioning as an integrated market, in terms of application of the market pricing strategy supposed to yield equal district heating prices in the entire sector.

Organisational goals

Questionnaire response data contains information on what the main goals are for the organisation represented by the respondent. The response options given were; return of capital, growth, environmental goals, energy supply, and other.

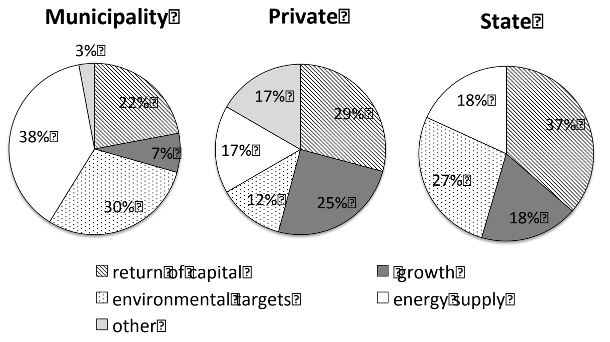

Figure 1. Questionary study results for organisational target priorities between different owner types.

The four organisational goals for which results are presented in Figure 1 can be divided into financial goals (return of capital and growth) and into political goals (environmental goals and energy supply). It is obvious that the ambitions among the municipal companies are focused to a larger extent on the political organisational goals (68%) while the corresponding shares for private and the state companies is 29% and 45%, respectively. More unexpected is that the ambitions declared by private district heating company representatives regarding the financial goals is that these goals are only prioritised to 54%. Which is similar to the 55% declared by representatives for the state organisation.

Pricing strategy

The response to the question regarding what pricing strategy is applied in the organisation is also analysed. For this question the given response alternatives were; self-cost pricing, market pricing, and other.

In Figure 2 it is obvious that municipality owned district heating companies have the ambition to apply a self cost pricing strategy to a large extent (62%) when adjusting district heating price levels, while the results for privately owned systems shows the opposite (11%).

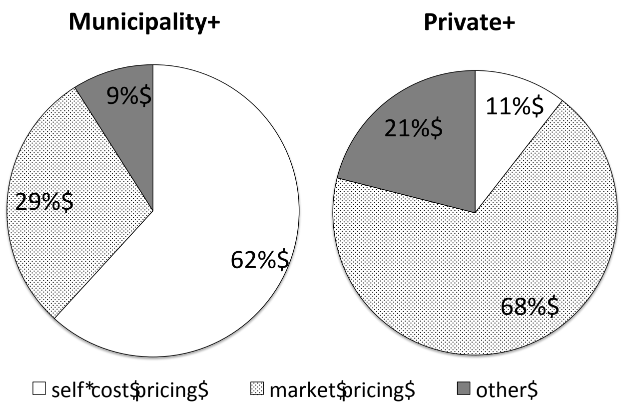

Figure 2. Questionnaire study results for difference in pricing strategy between public and private district heating companies.

The representatives for the state owned company Vattenfall all responded that they apply market pricing on district heating. In an analysis of the questionnaire response free text answers, respondents occasionally use the option "other" to describe an application of a combination of market pricing and self-cost pricing. However, the free text motivations indicates that these combining pricing strategies are in fact similar to market pricing. This is for instance seen in the text answer below

"Alternative pricing that means equal or lower than the customers alternatives"

District heating price levels

By presenting price level statistics for all Swedish district heating systems together (Figure 3), an indication is provided on if the entire district heating sector as a whole is functioning as an integrated market. Further, by correspondingly presenting price level statistics separately for the owner type groups provides information on how the market integration differs in between municipal, private and state systems.

The 2011 price level data shown in Figure 3 indicates that the Swedish district heating sector does not function as an integrated market, this due to the large price level variations among the Swedish district heating systems.

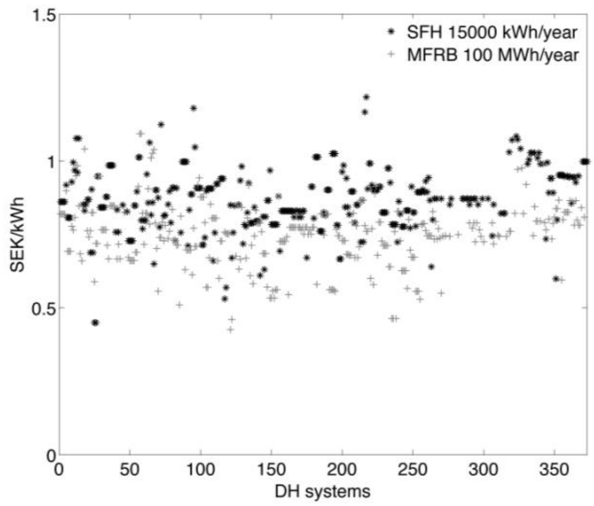

Figure 3. Prices for DH in all systems. Prices are presented for single-family houses (SFH) and for multi-family residential buildings (MFRB).

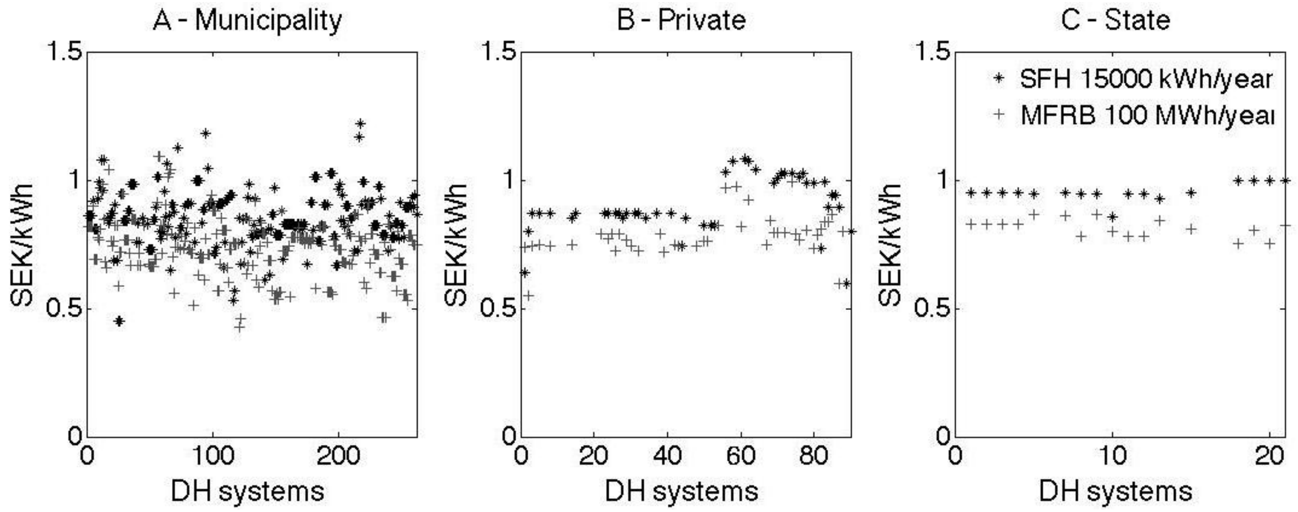

Figure 4. Prices for DH in all systems grouped according to type of owner. Prices are presented for single-family houses (SFM) using about 15 000 kWh of DH per year and for multi-family residential buildings (MFRB) using about 100 MWh of DH per year.

Figure 4 and Table 1 show the prices for district heating in 2011, presented for the three owner type groups. Prices are shown for the two different types of heat users, single-family houses (SFH) and multi-family residential buildings (MFRB). In the district heating prices there is both a difference in prices between different owner groups and between the two user categories. In Figure 4 (diagram A) it is shown that the spread of prices is significantly larger among the municipality owned systems than what is seen for the privately owned systems (diagram B) and the state owned systems (diagram C).

The data for private systems prices seem to be divided into two sections with more equal prices than for the municipal systems, but on different levels. This is however due to data being stored in company order and 52 of the systems plotted to the left in diagram B are all systems within the E.ON corporate group. These systems are equal in price levels while the other 39 privately owned district heating systems are managed by 10 different companies that apparently price district heating generally higher than E.ON, which is seen among the systems to the left in diagram B. As for the E.ON systems are the state owned systems presented in diagram C also equal in price. Also, as for the E.ON systems are the state owned systems owned by the same corporate group, i.e. Vattenfall.

Table 1. Key figures (mean, max and min values), for the DH prices shown in Figure 1.

(SEK/KWh)	**SFH (15000 kWh/year)**			**MFRB (100 MWh/year)**		
	mean	max	min	mean	max	min
Municipality	0.85	1.22	0.45	0.74	1.09	0.43
Private	0.90	1.08	0.60	0.78	0.99	0.55
State	0.95	1.0	0.86	0.81	0.87	0.75

DISCUSSION AND ANALYSIS

Statistical price level data from 2011 is here combined with owner type data from 2009. There is a possibility that companies have changed ownerships between these two years and that this might affect the analysis. The number of possible ownership changes in two years is however assumed to be small and the impact on the analysis marginal.

From the results presented here it is obvious that the municipal district heating companies apply self-cost pricing to a larger extent than the private and the state owned companies. It is also obvious that the organisational goals are more directly oriented to political goals for municipal companies, and are more financially oriented for private companies. The reason to why municipal district heating companies do not prioritise growth as an organisational goal could be connected to the tradition of strong self-governing municipalities in Sweden.

The price levels among the private and the state owned systems were observed as more equal than the price levels among the municipality owned systems. These equalities are however mainly seen for private and state owned systems within the same corporate groups. Between the groups are however prices less equal, which even more suggests that district heating is not functioning as a market. Equal prices seem to appear mainly between systems owned by the same company.

OUTLOOK

The results and the analysis show that district heating has not been suitable for a transformation into a market. The natural monopoly characteristics of district heating suggest that other coordination models for district heating should be considered. One example is the price-regulating proposal from the Ministry of enterprise, energy and communications expressed in a PM in 2012 [11].

CONCLUSIONS

The results and analysis presented here shows that, despite the ambition to transform the Swedish district heating sector from a collection of natural monopolies into one single competitive market with equal prices on district heating among different systems, is district heating systems in Sweden to a large degree still functioning as natural monopolies, especially if they are municipal companies. This since the varying price levels and the extensive use of self cost pricing among the municipality owned district heating systems indicates that district heating sales in these systems is not functioning as an integrated market.

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CHALLENGES AND OPTIONS FOR THE INTERACTION OF PRODUCERS AND CONSUMERS IN DISTRICT HEATING: A CASE STUDY IN LITHUANIA

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ABSTRACT

Policies and measures aiming to enhance the use of renewable energy sources (RES) are mainly driven by EU policy. The problem arises from the Lithuanian state policy, because it supports competition on the production side of district heating. Projections of RES utilization give unreasonable excessive role for biomass. Meanwhile, the usage of a huge potential of solar and geothermal energy is significantly insufficient. The possibilities to use solar collectors and heat pumps on the supply and demand sides in district heating system were analysed in small Lithuanian towns. EnergyPRO modelling software was used for calculations; comparative analysis and Levelized Cost of Energy (LCOE) were used for detailed analysis. RES development in district heating requires large investments; however the use of renewable resources in the district heating system would let to diversify the fuel mix. Subsidies for investments of solar and geothermal energy technologies would let to use them in district heating system as economically attractive alternatives. Scientific problem is to define the economic background for RES support. It is essential to analyze economic support measures for the development of RES technologies in order to make them competitive with technologies of traditional fuels and to make them relevant to actual purposes, needs and possible effects. All support schemes must form a whole of uniform and systematic economy.

INTRODUCTION

The main problem is the lack of integration of more diversified fuel sources, such as solar heating or geothermal heating in Lithuania.

Unique situation of the district heating occurs in Lithuania, when competition in the supply side of district heating is required from the state policy.

Present situation shows that there is no installed capacity of solar collectors' field or geothermal heat pumps on the district heating supply side in Lithuania. Deep geothermal sources exist in Klaipeda city in Lithuania, but this type of district heating is not competitive enough in market economy. Beginning of the use of solar collectors on the roofs of multi-apartment buildings is noticed in Lithuania. Moreover, unique apartment building of both solar collectors and heat pumps that disconnected form district heating network in Varena town was widely announced in the media. This case was chosen for deeper economic analysis by using LCoE method.

The consumption of RES was very low in Lithuania after the recovery of independence in 1990. This amounted only to 320.3 kilotons of oil equivalent (ktoe) and represented 2% of gross inland consumption of energy in 1990. Because of the implemented RES support policy, gross inland consumption of RES was increasing by 6.1% a year over the period 2000–2012. RES gross inland consumption amounted to 1164.8 ktoe (16.4% of gross inland consumption of energy) in 2012. Currently, wood and wood waste dominates in the structure of RES. In 2012, wood and wood waste covered 85.7%, biofuels – 5.4%, hydro energy – 3.1%, wind energy – 4.0%, biogas – 1.0%, agricultural waste – 0.4%, geothermal energy – 0.3% and solar energy – 0.02% of total RES consumption [1]. Over one-third of RES (402.8 ktoe) were transformed in power and heat plants for heat and electricity production in 2012.

Households are the main consumers of RES. However, during rapid economic development in Lithuanian for the period till 2009, households were tended to decrease the consumption of RES by 3 % a year. Reduction was covered by the increased consumption of natural gas and electricity. Structure of fuel mix consumed in household sector changed during the period of national economy slowdown after 2009 crisis. Consumption of wood and wood waste increased in households mainly because of dramatic increase of the natural gas price. In 2012, households consumed 560.9 ktoe of RES that is 74.3% of final RES consumption. Industry consumed 10.9% of RES, transport sector – 8.1%, trade and service – 4.6%, agriculture and fishery – 1.6%, and construction – 0.5%. Increase in RES consumption was highly related to governmental actions and increasing investment in RES sector.

The overview of financing sources and instruments in Lithuanian heating sector revealed that biomass is recognized as RES type, which has opportunities to gain the district heating market in Lithuania that is currently based on combustion of natural gas. However, a gap of information about other RES technologies to enter district heating market is noticed. Therefore more diversify RES sources such as solar collectors and heat pumps is analysed in this paper, especially comparing economy of RES on the supply and demand side of district heating.

STATE OF THE ART

The major changes appeared with introducing new energy policy goals by adoption the RES Directive [2], where district heating is recognized as promising technique for reaching overall strategic energy goals: safety of energy supply by increasing independence from imported energy resources, wider use of waste energy from industries and integration of RES into energy supply infrastructures. According to RES Directive, every member state has developed its own National Action Plan that fixes specific objectives for each member state in the use of RES for each sector, including heating. Lithuania has quite ambitious plans to increase RES in heating and cooling sector from 27 percent in 2005 to 39 percent in 2020. District heating should increase the use of RES to 50 percent. The share of RES in district heating sector was 27 percent in 2013.

The Law on Renewable Energy of the Republic of Lithuania enacted in 2011 and was mainly driven by EU Directive 2009/28/EC [2]. This law repeats goals that were set in RES Directive. It aims to ensure sustainable energy supply, promote the further use of renewable energy technologies and their development, especially in regard to the environment (climate change). The Law on Renewable Energy frames an excellent opportunity to significantly reduce costs of producing hot water in apartment buildings using RES technologies, such as solar collectors. However, the pricing of produced heat is unfavourable for independent heat producers, because district heating suppliers have to buy energy made from RES at the lowest price. Consequently hot water that is prepared using solar collectors has to be used by its owners. Finally, the main problem of the Law on Renewable energy is still lacking executive acts that limit further investments in renewable energy.

Modelling assumptions are made using various sources, available statistical data, studies, reports, papers, and websites. The paper deals with the possibility to install the solar collectors' field that is connected directly to district heating network in Varena town. Solar collectors are selected taking into account the intensity of solar radiation and fluctuation of hot water system needs in district heating. Moreover, the possibility to install geothermal heat pump on the supply side in Gargzdai town was analysed. Finally, alternatively LCoE price with different scenarios was calculated for apartment building in Varena town that installed heat pump and solar collectors already.

Debts of consumers and disconnections from the networks are important issues for district heating in Lithuania, because every disconnection increases the price and lowers the energy efficiency of the system. Main reasons for these issues are high consumption of heat energy and low income of households. Majority of multi-apartment buildings was constructed during Soviet Union times, when district heating was subsidised from the state and buildings were not energy efficient. Individual heating sources, such as natural gas boilers, were alternative for district heating before the price of district heating increased more than four times compared with 2006 year. Nowadays speculation in a media exist that heating based on natural gas is cheaper than district heating. Comparing on a heat unit basis natural gas is more expensive, nevertheless result in lower monthly heating bills as heating can be used as required rather than 24 hours per day.

Lithuania supports district heating producers with investment subsidies for biomass boilers up to 10 MW capacity, and economizers; intensity of support is not more than 50 percent. Consumers of district heating have investment subsidies for the use of RES (solar, geothermal, etc.); intensity of support is 30 percent. Support measures are given according Climate Change Special Programme requirements.

The current problem arises that support is given for the biomass boilers, but not for CHP plants of biomass in Lithuania. Support scheme does not encourage the most efficient technology in the market. Moreover, the quota tariffs for electricity from biomass CHP plants are reduced during the last year. The main idea of reduced quotas is that electricity should be traded in the market.

Lithuanian Law on Heat states that heat production is base on the competition between heat producers. The heat supplier is obliged to connect all RES heating devices of independent heat producers that were installed to replace fossil fuel plants. Priority is given for purchase of renewable heat. Heat suppliers (owned by municipality of private investors) must purchase all heat from RES produced by independent heat producers, which is cheaper than the heat produced by the heat supplier and which satisfy quality, supply security and environmental requirements, unless the supply of RES heat produced by independent heat producers exceeds the consumers' heat demand. If RES heat is produced by two or more independent producers, priority is given to the lower price. Heat suppliers must not discriminate independent heat producers when operating, maintaining, managing and developing the heat transmission network.

Lithuanian state support for the heating of multi-apartment buildings has the following characteristics:

- Individual social support is given mostly for heating old, energy-inefficient buildings, and discourages their renovation, because social payments are not associated to energy savings;
- A preferential 9% rate of value-added tax rate is applied to all amount of heat that is consumed by the households. Therefore 12 percentage points (from the standard VAT rate of 21%) support mostly gets owners of large flats (presumably

potentially richer residents) and energy-intensive buildings. This is unfair to both social solidarity and economic terms.

- The beneficiaries of the social compensation for heating often prevent energy-saving initiatives, because their payments for heating have a little dependency on the quantity of thermal energy consumption.

Social compensation for heating and VAT exemption will only increase with fuel prices and will discourage renovation of apartment buildings; therefore more rational use of the taxpayers' contributions to state budget should be taken.

METHODS/METHODOLOGY

EnergyPRO by EMD [3] modelling software has been used, which allows carrying out comprehensive and detailed analyses of energy projects. EnergyPRO is typically used for techno-economic analysis of simulating cogeneration plants and district heating systems with multiple energy producers [4], [5], [6]. Other types of projects, e.g. geothermal, solar collectors, can also be analysed and detailed within the software [7]. EnergyPRO provides the user with a detailed financial plan in a standard format, that includes presentation of the operating results for the project, monthly cash flows, and key investment figures such as Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Time [3]. The reason for choosing energyPRO is its ability to model solar thermal and geothermal production, as well as to connect district heating network.

EnergyPRO evaluates characteristics of solar collector and its inclination and orientation to the sun, accurately models hourly amount of produced heat. Revenues are evaluated as produced heat price meets an average district heating price. The formula for a solar collector is as follow:

$$Y = A\cdot\left(\left(I_{beam}\cdot K_{\theta}+\left(I_{diffuse}\right)\cdot K_{60^0}\right)\cdot\eta_0 - a_1\cdot\left(T_m - T_a\right) - a_2\cdot\left(T_m - T_a\right)^2\right) \quad (1)$$

where: Y - heat production, [W]; A - solar collector area [m^2]; I_{beam} - beam radiation on a horizontal plane, [W/m^2]; K_θ - incidence angle modifier; $I_{diffuse}$ - diffuse radiation on an inclined plane, [W/m^2]; T_m - solar collectors average temperature, [^{o}C], that is an average between the temperature of the cold water entering the collector and the hot water leaving the collector; T_a - ambient temperature, [^{o}C].

The efficiency of the solar collector is defined by three parameters: η_o - intercept (maximum) of the collector efficiency, [-]; a_1 - the first-order coefficient in collector efficiency equation, [W/(m^2 ^{o}C)]; a_2 - the second-order coefficient in collector efficiency equation, [W/(m^2 ^{o}C)]. The radiation is split into beam radiation and diffuse radiation. Since the diffuse radiation per definition has no incidence angel is used the incidence angle modifier or K_θ at 60^o.

The economic feasibility analysis of the chosen solar collectors for district heating purposes in Varena town is based on net present value (NPV), simple payback time and internal rate of return (IRR). Economy in energyPRO basically is monthly based. Payback time is defined as the month, in which you are able to pay back your loans (the month in which the money in the cash account equals remaining debts in the loans). It is, however, not the most suitable criteria for a long term investment. Due to its widespread application, though, it is used as an indicator in the calculation results. NPV calculation every monthly payment is brought back to present (start of the planning period) on a monthly basis. IRR is the discount rate that makes the net present value of all cash flows from a particular project equal to zero. The higher is project's internal rate of return, the more desirable it is to undertake the project. The IRR is found by iterations using Newton's method. EnergyPRO calculates the nominal IRR. The difference between the nominal and the real IRR is in practice equal to the average inflation in the planning period.

The use of geothermal energy in energyPRO is modelled as an electrical heat pump, because the case of the use of geothermal heat pump on the supply side in Gargzdai town was analysed. There must be defined electricity consumption and heat production when calculations are specified. Electricity consuming heat pumps increases the complexity of energy system calculations.

Levelized cost of energy (LCoE) is the price of energy which has to be set that at the chosen (stated) discount rate, which is equal to capital price, all discounted expenditures are equal to income, and the net present value equals zero.

This method is appropriate, because all main criteria can be concentrated in it, such as NPV (equal to 0) and IRR. The main advantage of this indicator is possibility of comparison to the competitive price of energy in the market. LCoE shows that the project will have, for example, 10 % IRR (that is determined), if the price of district heating (or any other producer/supplier) is not lower than the price that is calculated by the formula:

$$K_s = \frac{\sum_{i=1}^{i=n}\frac{\left(I_i + e_i - Z_i\right)}{\left(1+r_n\right)^i}}{\sum_{i=1}^{i=n}\frac{G_i}{\left(1+r_n\right)^i}} \quad (2)$$

where: I_i – capital investments; e_i – annual operational and maintenance costs; Z_i – external benefit of renewable energy (could be negative); n – years of lifetime; i – serial number of the year; G_i – yearly amount of produced and consumed energy; r_n – stated periodic discount rate (discount rate for RES can be lower than for fossil fuel).

LCoE method is suitable for the evaluation of a wide spectrum of different options. The result obtained, for example, 1 kWh levelized cost of heat can be compared to official district heating price, and the feasibility of a project can be decided. The LCoE can be calculated for any of energy development scenarios of analysed object (apartment building, city, district, etc.).

It should be noted that the main criterion is not the price of solar collectors and their installation; the price of a heat unit that is produced by solar collector and effectively consumed is more important. Moreover, there is possible and even necessary to calculate how much the produced heat unit will cost with chosen type of solar collector. The case of the use of heat pump reveals the importance of electricity price. The application of LCoE method allows estimation of technical aspects and economic projections to the levelized cost of the heat unit. Initial calculations show that the increasing prices of district heating make the use of solar collectors and heat pumps for the preparation of domestic hot water competitive in some towns. Large scale solar collectors' field is also competitive in cities with high price of district heating.

RESULTS

Modelling is being done by evaluating the heating demand in Varena city, working period of flat plate solar collectors in a year, their efficiency. Depending on the solar collectors' area, heat loss parameters the program calculated the price of hot water made by collector, the payback period of the system, NPV, IRR, etc. An average 20 year outdoor temperature and solar radiation was calculated according EnergyPRO yearly available data. The annual heating demand is about 42.3 thous. MWh. Heat storage is available in Varena district heating network in total 1070 m^3. Interest rate of 5 percent is calculated according to Lithuanian bank. Inflation is taken into account as European Central Bank's medium-term prognosis that is 2 percent. Lifetime of solar collectors is 20 years. Operating costs for solar collectors is about 1 euro per MWh [8] of produced heat, which encompasses mainly electricity consumption and maintenance.

The main scenario is analysed that solar collectors are able to cover all heating demand during the summer time in Varena town. Land area for solar collectors is available for free. Calculation tool "f-EASY (SDH)" estimated of 10000 m^2 solar collectors' area. Investments were calculated according market situation and answers from a suppliers' survey. System of solar collectors that could be connected to Varena district heating network approximately cost 7.7 million litas (about 2.23 million euro). Calculations of the use of solar collectors showed that payback time is about 14 years. The assumption of stable district heating price was taken into account. Revenues are calculated as heat amount from solar collectors multiplying by district heating price of 198.1 LTL/MWh (1 EUR = 3.4528 LTL). To sum up, even a simple indicator shows that investments are risky, because payback time is longer than 10 years.

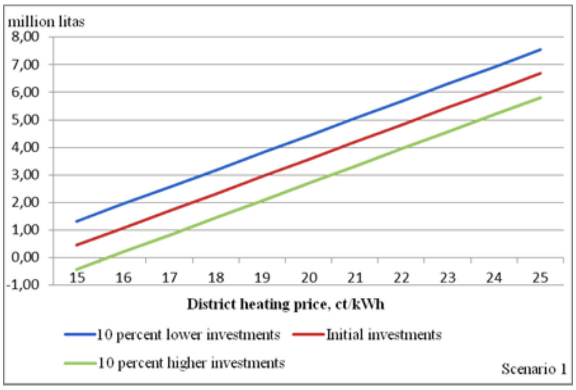

Fig. 1 Sensitivity analysis of the district heating price in Varena town (ct/kWh, excl. VAT)

Sensitivity analysis of solar collectors' NPV results in Varena town is shown in Fig. 1. The district heating price of Varena town is selected as a basis (198.1 LTL/MWh), and 20 percent increase and decrease of the district heating price was calculated. Moreover, 10 percent increase and decrease of the investments were also included into calculation. The results have showed that 20 percent decrease of district heating price gives negative NPV values for solar collectors' field.

IRR calculations have showed that investment in solar collectors is very risky, because IRR is around 8 percent. Usually property of district heating companies is already bonded for banks. Therefore the interest rate is usually higher than 8 percent.

The main conclusion is that without government support (such as existing 30 percent subsidies for investment in biomass boilers or soft loan with 3 percent interest rate) investment in solar collectors is financially unacceptable in Varena town. It should be noted, that calculations are done for the city, which has one of the lowest district heating price in Lithuania and uses mainly biomass fuel. Economically attractive investments could be just for cities with district heating price higher than the average.

Modelling is also being done for the use of geothermal heat pump on the supply side of district heating in Gargzdai town. The evaluation of the heating demand was taken from district heating company. Small closed district heating network of 7 apartment buildings was chosen for analysis. The annual heating demand is about 1,7 thous. MWh. An average 5 year outdoor temperature was calculated according EnergyPRO yearly available data. Interest rate of 5 percent is calculated according to Lithuanian bank. Inflation is taken into account as European Central Bank's medium-term prognosis that is 2 percent. Lifetime of 300 kW heat pump is 20 years. Investments about 1.1 million Litas (about 0.32 million euro) for heat pump system and vertical 100 metres boreholes are calculated according suppliers' survey.

Initial calculations have showed that without state support payback time is longer than 16 years. The assumption of fixed electricity price (400 LTL/MWh) was taken into account. Consequently, investments in heat pump for district heating company in unacceptable.

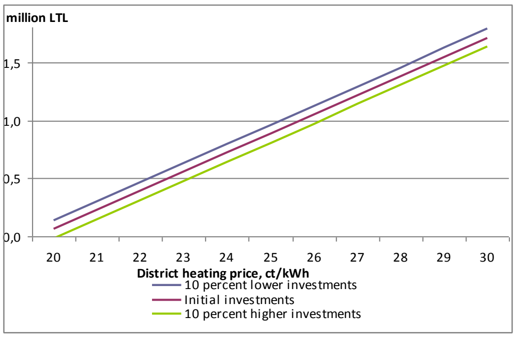

Fig. 2 Sensitivity analysis of the district heating price in Gargzdai town (ct/kWh, excl. VAT)

Sensitivity analysis of NPV results in Gargzdai town with a subsidy of 30 percent for the investment of geothermal heat pump is presented in Fig. 2. The district heating price of Gargzdai town is selected as a basis (256.4 LTL/MWh), and 20 percent increase and decrease of the district heating price was calculated. Moreover, 10 percent increase and decrease of the investments were also included into calculation. The results have showed that with 30 percent subsidy investment for heat pump on the supply side in small Gargzdai town area NPV has positive value when district heating price is decreasing by 20 percent. However, economic indicators show unacceptable investment in heat pump.

IRR calculations have revealed that investment in heat pump with a 30 percent subsidy is 21 percent. This indicator means low risk investment. On the other hand, low NPV value and payback period longer than 11 years have indicated that investment in heat pump is unacceptable. The main obstacles that causes unattractive position of heat pump is high temperatures in district heating network; therefore, the COP is lower than 3 and heat pump does not work efficiently with current electricity price.

The main question is competition between the price of self-produced RES energy on the demand side and price of RES district heating on the supply side. Therefore, comparison of LCoE is shown for solar collector and heat pump on the demand side with different support intensity (Fig. 3). Moreover, LCoE of renovation of apartment building is included because of the need to consume energy efficiently and compare the result of various support intensity.

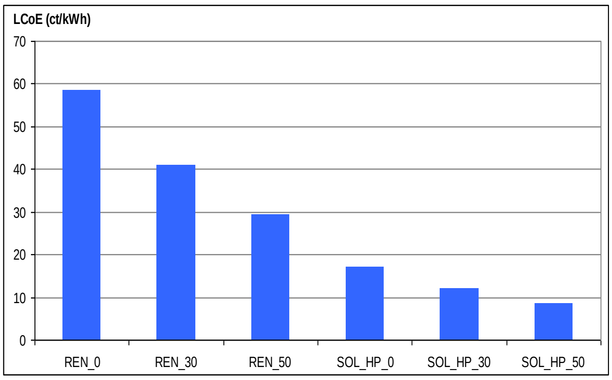

Fig. 3 LCoE analysis of the apartment building renovation without/with solar collectors and geothermal heat pump (Varena town) (ct/kWh, excl. VAT)

Multi-apartment building in Varena town that has already installed solar collectors for the preparation of hot water and heat pumps for the space heating is taken into account. This five floors multi-apartment building with 40 apartments is the only one in Lithuania that uses both types of RES technology for heating purposes already. Figure 3 shows analysis of the renovation LCoE in multi-apartment building without subsidy (REN_0), with 30 percent and 50 percent intensity of subsidy (accordingly REN_30 and REN_50). Furthermore, LCoE of solar collectors and heat pump without subsidy (SOL_HP_0), with 30 percent and 50 percent intensity of subsidy (accordingly SOL_HP_0 and SOL_HP_0) are calculated. Comparison of LCoE with various intensity of subsidy reveals that in the case of complete renovation of multi-apartment building even with fifty percent intensity savings in heating cost is higher than existing district heating price (198.1 LTL/MWh) in Varena town. Moreover, complete renovation requires large investments. This problem could be solved by limits of separate effective elements of renovation, such as renovation of heating system, replacement of windows, etc. On the other hand, RES on the demand side such as solar collectors and heat pump could compete with district heating price without any subsidy in Varena town.

LCoE for the heat pump on the supply side of district heating is also calculated and the obtained value is 283 LTL/MWh. This result is higher than current district heating price (256.4 LTL/MWh) in Gargzdai town and average price of district heating in Lithuania. Therefore, heat pump on the supply side of district heating is not competitive technology mainly because of high temperature in the heating network. On the other hand, LCoE of the solar collectors' field on the supply side of district heating obtained value is 187 LTL/MWh. This result is lower than current district heating price (198.1 LTL/MWh) in Varena town, which is one of lowest price of district heating in Lithuania. The conclusion could be that solar collectors on the supply side of district heating are competitive technology. If subsidy for this type of RES is given, the increase of solar collectors' field in Lithuania could be noticed. The similar boom of solar PV technology was during year 2012 of high feed-in tariff for electricity generation from PV installations in Lithuania. State support has an essential role to change situation from moving towards cleaner energy production and diversifying fuel mix in district heating sector both the supply and the demand sides.

DISCUSSION

Integration of renewable energy projects (such as solar collectors) into district heating systems may create external positive effect to the whole society concerning environmental and other regional development goals. Consumers' need for hot water or space heating is satisfied without burning natural gas or biomass, therefore the pollution is avoided. Moreover, import of natural gas from Russia is reduced and the forest conservation is increased.

Measures that could give greater opportunities for the use of solar and geothermal energy in the district heating system are promotion of the competition and support schemes that enable competitiveness. Energy, which is produced by consumers, can participate in the competitiveness process if this issue is treated on the state level, i. e., minimize investments and costs in the macroeconomic context. In this regard short study of the financial system and opportunities for improvement is given.

Heat producers that use RES technologies have no direct subsidy, such as feed-in tariff. However, subsidies for investment and soft loans for RES heat technologies are provided by the Lithuanian Environmental Investment Fund (LEIF). In 2012, 5.7 million EUR of subsidies were offered from LEIF to finance biomass projects. Subsidies decreased to 3.1 million EUR in last year's financing period for biomass projects.

Subsidies for the heating sector were also provided from EU Structural Funds for the period of 2007–2013. Lithuania has implemented the Promotion of Cohesion programme. Subsidies under the measure "Utilization of RES for the production of energy" were provided under mentioned programme. Beneficiaries were asking for 164 million euro during the 2012 year, but finally only 29 financial agreements for total value of 61.9 million euro was signed. The amount of subsidy varied from 29 thousand euro to 5 million euro with intensity of fifty percent. The remaining amount of financial resources must be covered by the private investors by using their own financial resources or loans. Governmental assistance is not foreseen for the implementation of the measure. Several examples of co–financed biomass related projects by various sources of financing exist; however, typical financial instruments, such as subsidy and loan, are dominated. The fourth largest city of Lithuania Siauliai in 2010 started to build combined cycle heat and power plant, fuelled by biomass. The support from EU Structural Funds was 5.2 million euro. Heating company used about quarter million euro of private financial sources for the project. Moreover, additional financial sources of 10 million euro were received from European Investment Bank as a loan. Scandinavian banks SEB bank and Swedbank provided a syndicated loan of more than 13.6 million euro.

Tax incentives for the utilization of RES in the heating sector are not provided, except excise tax that has exception for biomass.

European countries use various financial sources and different incentives mechanisms to support energy from RES. However, traditional financing sources and incentives are used in Lithuania RES sector because of the lack of knowledge, shortage of experience and unstable regulation of RES sector.

Possibilities to use innovative financial sources and incentives for the wider finance of RES sector in Lithuania are presented in this section.

JESSICA initiative is a Joint European Support for Sustainable Investment in City Areas. The initiative has been launched by the European Investment Bank, in cooperation with the Council of Europe Development Bank and the European Commission. Support is given to sustainable urban development and regeneration through financial engineering instruments such as stock capital, loans and warranties. Since the beginning of 2008 Lithuanian Ministry of Finance together with European Investment Bank analysed possibilities of JESSICA implementation in Lithuania. Decision was made that JESSICA funds will be allocated to the sector of old multi-apartment buildings, which were built before 1993. Agreement was reached that funds should be directed to the implementation of energy efficiency measures. Therefore, JESSICA Holding Fund was established. The contribution committed into JESSICA Holding Fund is 227 million euro and consisted of European Regional Development fund (127 million euro) and National funding (100 million euro) for the improvement of financing conditions for multi-apartment building, higher education schools and students' dormitories. European Investment Bank selected three banks (namely, Swedbank, SEB bank and Siauliu bank) in Lithuania, which finance projects. Banks are able to finance up to 100 percent of construction costs. Soft loans are provided for 20 years period with 3 percent fixed interest rate. JESSICA Holding Fund foresees to support various activities related to renovation and reconstruction of the building. RES technologies also could be funded by soft loans from this fund for the installation of RES in the buildings. This alternative source of finance should be used more widely in Lithuania.

JEREMIE (Joint European Resources for Micro to Medium Enterprises) Holding Fund was established at the end of 2008 in Lithuania after Ministries of Finance and Economy and European Investment Fund reached an agreement for establishment of JEREMIE Holding Fund. Total sum of 210 million euro was directed to this fund. Financing is provided to small and medium enterprises via financial intermediaries in a form of venture capital and guarantees. JEREMIE can support improved access to finance in urban areas.

Overview of different sources of finance for district heating suppliers and consumers revealed that market is ready to finance implementation of RES alternatives.

OUTLOOK

The risk of biomass and other fuel prices, and lower demand of heating after renovation of multi-apartment buildings should be taken into account in further researches.

Moreover, further researches should take deeper analysis of the macroeconomic effect that arises from the interaction between district heating producers and consumers.

Monopoly of district heating exists due to specific of the infrastructure. The detrimental trend is to solve complex tasks by one-off measures. Uniform programs are needed to relate both spheres of production and supply. Nearly all support measures are concentrated on the production side in Lithuania, while the infrastructure could be used for the consumers' efforts to reduce the volume of consumption and to produce heat and hot water by the use of solar and geothermal energy without disconnecting from district heating.

Reforms in heat sector, Renovation (Modernisation) Program of multi-apartment buildings, and implementation of Law on Renewable Energy are needed in order to make purposeful, legal scenario system; then district heating suppliers and consumers could interact, and investment decisions could be synchronized in unified investment scenario.

According to the Heat Supply and Consumption Rules in Lithuania, multi apartment building or one apartment could disconnect from district heating system and use another energy source. However, the Rules exclude the cases when consumers install heat production facilities of RES, but without disconnecting from the district heating. Outstanding question remains how to cover fixed costs of heat supplier, when such consumers use significantly less amount of heat than in case without RES facilities. Nevertheless, heating system must be maintained at appropriate technical conditions, that at any time these consumers could have supply of heating.

CONCLUSIONS

Development of RES in district heating requires large investments; however the use of renewable resources in the district heating system would let to diversify the fuel mix. Subsidies for investments of solar and geothermal energy technologies would let to use them in district heating system as economically attractive alternatives. Moreover, if ecological, economic and social benefit is comprehensive evaluated in a long term period and on that basis would be given support for consumers and suppliers who produce energy using solar or geothermal energy, the demand for advanced RES technologies would increase noticeably.

ACKNOWLEDGEMENT

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ULTRA-LOW TEMPERATURE DISTRICT HEATING AND MICRO HEAT PUMP APPLICATION – ECONOMIC ANALYSIS

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ABSTRACT

The trend in district heating (DH) is to lower the network temperatures to integrate more renewable heat sources with better economy and increase the network efficiency, by addressing the distribution challenges towards future low-energy buildings. Today there are number of DH networks operated with supply and return temperatures of 55-60/30°C. The reason for the lower limit of 55°C is due to the need of preparing 50°C domestic hot water (DHW). However considering the space heating, the supply temperatures of 35-40°C is sufficient for the floor heating systems. There is therefore still possibility to decrease the DH supply temperature and allow for more low-exergy and low-cost heat sources to be used in the DH energy mix.

To solve the issue with DHW preparation a micro booster application has been developed, a small heat pump that uses DH water as a heat source to boost the temperatures to 55°C for preparation of DHW by instantaneous heat exchanger.

In this paper an economic analysis is made to compare ultra-low temperature district heating (U-LTDH) by applying the micro booster concept and a U-LTDH network in a new area in Denmark. The analysis takes into account the cost of the network, pump operations costs and heat losses. The results show that compared to the traditional low temperature solutions the U-LTDH is cost-efficient in case the additional investment cost for the micro booster units is balanced by decreased heat losses and possibilities of using cheaper heat sources.

INTRODUCTION

Today, approximately 25-30% of the annual heat demand of family houses in Denmark is used for domestic hot water purposes – the rest for space heating. New houses built in accordance with the new building codes require much less heat and the share of heat used for domestic hot tap water is rapidly approaching 50% of the annual heat demand. Furthermore, more circulation is needed as the heat off-take from the network is diminishing. Reducing heat losses in the network is becoming increasingly important in order for district heating to be competitive with alternative heating applications. Low supply temperatures present a solution to these challenges.

However as the supply temperature is decreased the available capacity in the distribution networks decreases as well. It is therefore clear that low temperature district heating (LTDH) goes hand in hand with the increased amount of low energy buildings with low heat capacity requirement being built today.

Experience shows that in a LTDH network the distribution heat losses are only 40-55% compared to what is experienced in a traditional DH network, see [1]. However, so far the lower limit on the supply temperature has been restricted by the need of preparing DHW. By preparing the DHW instantaneous with low DHW system volume, >3 liters, a DHW temperature of 45°C can be accepted. But achieving 45°C DHW temperature requires a minimum 50°C DH supply temperature.

To remove this lower limit of supply temperature it has been proposed to utilize booster units to raise the supply temperature up to the minimum of 50°C for preparation of DHW water. This can be achieved by utilizing a booster unit. In [2] different alternative temperature booster units were investigated and compared together. In the paper it was concluded that the best booster should be based on a heat pump that splits the DH supply into two flows (micro booster), a) supply for DHW preparation and b) heat source for the heat pump. The heat pump is then used to transfer the heat from the flow b) to flow a) and hence raising its temperature to sufficient temperatures for DHW preparation. To limit the requirements to the heat pump and to the network it was further on proposed to have a storage tank where the heated DH supply water is stored for future instantaneous DHW preparation. It is also worth noting that having the storage tank on the primary side of the network the risk of Legionella contamination from the storage tank is eliminated.

In a the project “Heat Pumps for Domestic Hot Water

Preparation in Connection with Low Temperature District Heating”, see [3], funded by Technology Development and Demonstration Programme (EUDP) the applicability of the micro booster unit was accessed in 4 existing houses in Birkerød north of Copenhagen. The results from the project showed that the concept works and could actually induce significant heat loss savings in the distribution network as a large share of the yearly heating demand in existing buildings can be fulfilled by low temperature supply.

When it comes to the distribution network is has been shown in various articles and demonstration projects that it is economically feasible to go towards LTDH instead of traditional network design, see for example [1,4,5]. The value of decreasing the supply temperature further, towards 40°C or U-LTDH, which would be sufficient for year around heating, given a floor heating installation in buildings and applying booster units for DHW preparation, has not been investigated at the current stage, to the knowledge of the authors. The main influencing factors when going towards U-LTDH is that as the temperature difference between the supply and return (network capacity) decreases the larger the distribution pipes need to come, which will affect the investment costs. Of not less importance are the additional DHW unit investment cost and the local energy consumption needed to boost the supply temperature to sufficient levels to prepare DHW. To compensate for these additional costs it maybe necessarily not only to look on the heat loss savings but also towards the increased heat plant efficiency and the possibilities of introducing new low temperature heat sources that have lower cost value than traditional heat sources used in DH today.

The aim of this paper is to shed light on the cost differences of establishing a new distribution network, traditional, LTDH and U-LTDH, supplying new low energy buildings.

NETWORK DESIGN TYPE DEFINITIONS

Today there is much talk about different network types and it is therefore important to make a distinction between the different network design types.

Traditional District Heating

Traditional networks are networks with peak supply temperature of 70°C or higher.

Low Temperature District Heating

The LTDH are networks that have sufficient supply temperatures to achieve instantaneous DHW preparation with DHW temperature of minimum 45°C. In general terms LTDH have supply temperature in the range of 50-70°C.

Ultra-Low Temperature District Heating

U-LTDH are networks that have supply temperature below 50°C and use temperature booster units to boost the supply temperature to sufficient levels to allow instantaneous DHW preparation.

Cold Water District Heating

Cold water district heating networks are a new idea. To make a distinction from the U-LTDH networks the cold water DH networks have supply temperature below 30°C and require heat pumps to raise the temperature both for DHW as well as space heating.

Table 1. Expected heat consumption of the connected consumers.

Building type	Floor area [m2]	Space heating	Consumption [kWh/m2/year]	Total space heating [kWh/year]	DHW consumption [kWh]	Total heat consumption [kWh/year]
Single family building	175	Consumption (22°C)	49	8.575	3.200	**11.775**
Row house	110	Consumption (22°C)	49	5.390	3.200	**8.590**
Apartment	95	Consumption (22°C)	34	3.230	3.200	**6.430**

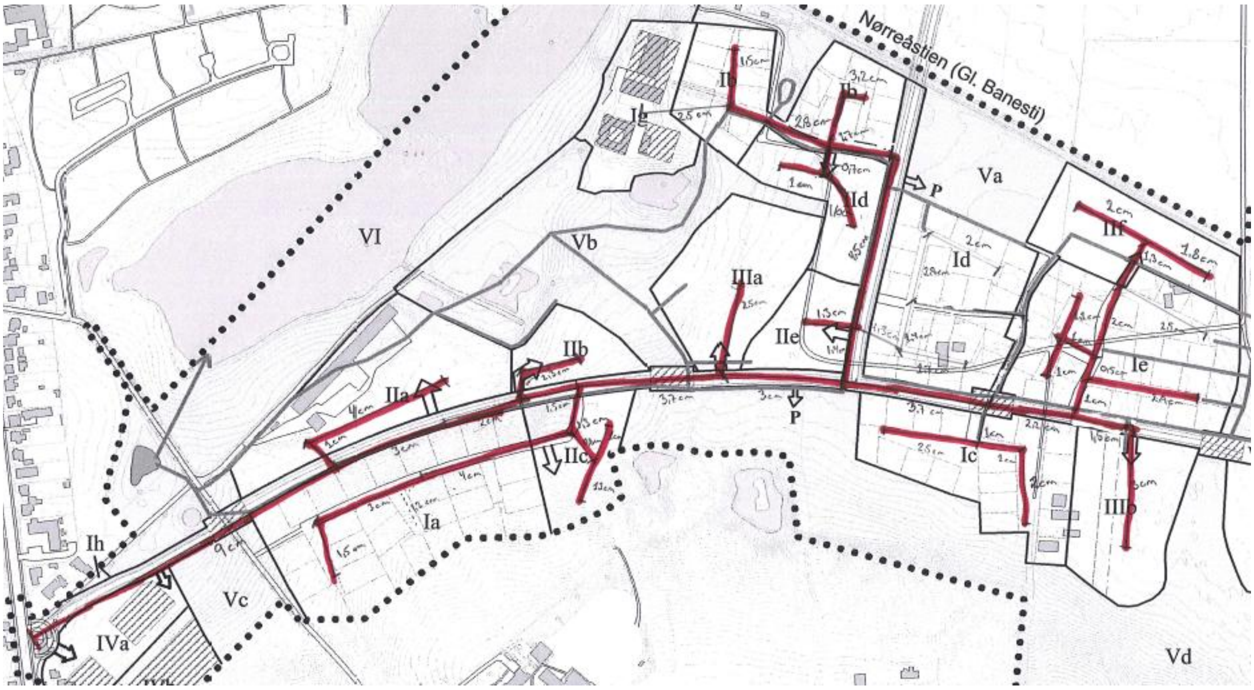

Figure 1. Layout of the distribution network.

NETWORK DESCRIPTION

The network that is analyzed consists of 125 175 m^2 single family houses, 150 110 m^2 row houses and 4 apartment buildings with 25 apartments each. It is assumed that the buildings are build according to the Danish BR2015 building standard but having increased heat consumption due to natural behavior of the inhabitants. To factor in more realistic heat consumption then is stated in the BR2015 standard the building heat consumption is adjusted according to the expectations of a realistic heat demand in low energy buildings put forth in [6]. The expected heat consumptions per consumer can be seen in Table 1. The total heat consumption of all the consumers in the network is assumed to be 3.400 MWh/year. If by reducing the network supply temperature would open up for less costly heat source it would benefit all the consumers.

The network layout can be seen in Figure 1**.**

COMPARISON OF DIFFERENT NETWORKS

In this analysis it is assumed that the network is built in a green field area at the same time as the housing area is being built. This has significant impact on the network investment costs, see [8].

Design parameters

In the analysis four different network profiles were compared:

1. Traditional DH with 80/40°C and 65/30°C supply and return during winter and summer respectively.

2. LTDH with 55/30°C supply and return whole year around.

3. U-LTDH with raised peak load temperatures 55/30°C and 40/25°C supply and return during winter and summer respectively.

4. U-LTDH with 40/25°C supply and return throughout the year.

In all cases the network dimensions were determined by flow velocity limitations, maximum 2 m/s, and maximum network pressure of 10 bars.

The total length of the distribution network was estimated to be 3.170 meters and in addition 5.600 meters of service pipes (20 meters per consumer).

Space heating

In all the cases it is assumed that the space heating is achieved with floor heating technology.

DHW preparation

For the 1st and 2nd network profiles the DHW is produced instantaneously via heat exchanger, see Figure 3. The DHW capacity in the instantaneous DHW application is chosen as 32 kW. To avoid over dimensioning the distribution network a simultaneity is considered in steps, for the last 5 consumers at each brand the network design considers an average 20 kW DHW capacity and for all prior consumers the design DHW capacity is chosen as 4 kW.

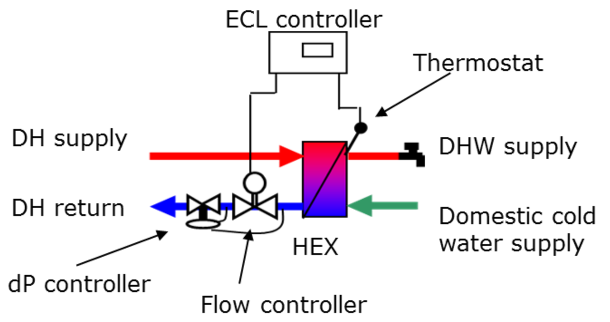

Figure 3. Schematic of instantaneous DHW application.

In the 3rd and 4th network profiles a micro booster application is applied to raise the supply temperature to 50°C, when required, and store it in primary side storage tank until taping occurs, see Figure 2 for schematics of the micro booster. The connection capacity of the micro booster application was decided as 3,5 kW, to address simultaneity the network was designed with 2 kW.

Another difference between the two DHW applications is that the heat pump in the micro booster unit requires electricity to operate. The additional electricity consumption needs to be considered when assessing the benefits of applying U-LTDH network design.

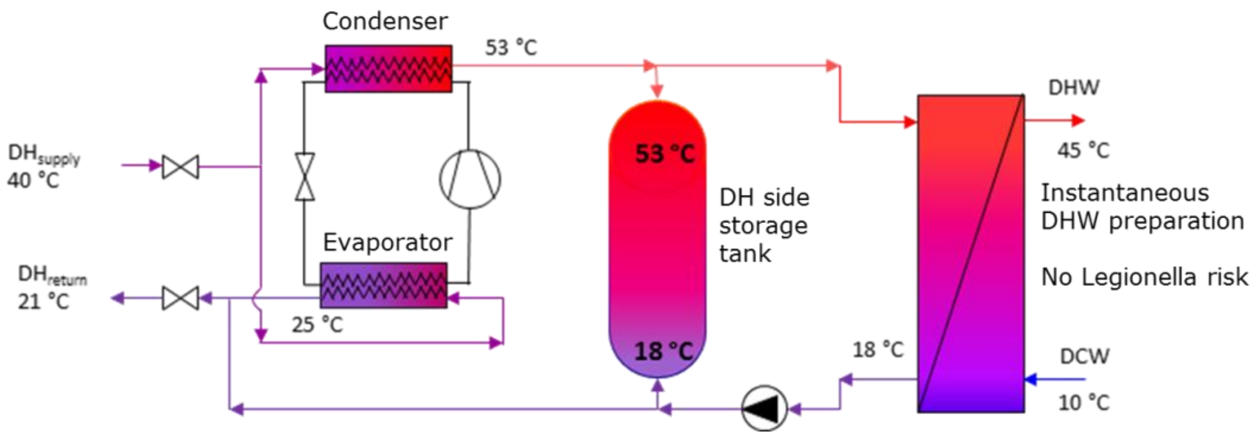

Figure 2. Schematic of the micro booster application.

Table 2. Estimated cost of the distribution network given different temperature profiles.

Network investment costs	80/40 // 65/30°C	55/30°C	55/30 // 40/25°C	40/25°C	
Main network	2.166.116	2.459.047	2.231.175	2.417.343	DKK
Distribution network	2.404.414	2.684.667	2.501.835	2.683.249	DKK
Service pipes - Small buildings	3.211.224	3.211.224	3.211.224	3.211.224	DKK
Service pipes - Large buildings	93.417	93.417	93.417	93.417	DKK
Pumps	44.520	44.520	44.520	44.520	DKK
Cost of consumer interfaces	7.500.000	7.500.000	13.125.000	13.125.000	DKK
Total	15.419.692	15.992.874	21.207.171	21.574.752	DKK
Difference from 80/40 // 55/30°C	0	573.183	5.787.480	6.155.060	DKK

Table 3. Estimated operational costs for the different network profiles.

Operational costs	80/40 // 65/30°C	55/30°C	55/30 // 40/25°C	40/25°C	
Distribution network heat loss	330	302	227	229	MWh/year
Service pipes heat loss	277	221	143	133	MWh/year
Pump electrical consumption	49	53	59	50	MWh/year
Micro booster electricity consumption	0	0	56	75	MWh/year

RESULTS

Network investment costs

The cost of laying down the distribution network given the above mentioned design criteria can be seen in Table 2. Estimated cost of the distribution network given different temperature profiles. From the table it can be seen that the cost of the network increases as the network supply temperature decreases, as would be expected. Additionally the cost of the consumer interfaces depends on the DHW application applied, weather it is the instantaneous DHW application or the micro booster application. The base assumption is that the cost of the instantaneous DHW application is 20.000 DKK and the cost of the micro booster is 35.000 DKK.

Distribution heat losses and pump costs

For estimating the heat losses it was assumed that the average soil temperature is 10°C, the heat losses were then calculated according to heat loss coefficients stated by pipe manufactures. In normal operation the network supply temperature is varied according to the outside air temperature, in this study however the assumption is that the network is running on high temperature profile for three months of the year and on part load temperature profile the reminder of the year. This is a simplification and may have an impact on the estimated heat losses in the distribution network. An estimation of the heat losses can be seen in Table 3. The table also shows the estimated pump electrical consumption of the pump, this is an important parameter as the pump costs are directly dependent on the operational temperature differences. The pump electrical consumption was estimated by representing the yearly consumption profile in 5 parts, see Table 4.

Table 4. Assumed consumption profile throughout the year.

Heat demand of peak load	Operating hours
100%	398
75%	796
55%	1195
35%	2389
12%	3982

Total cost of operation

The cost of the heat depends among other factors on the available heat source. In 2011 the end consumer prices of heat from district heating companies varied from 410 DKK/MWh to 2.050 DKK/MWh including VAT, see [7]. It is therefore clear that there can be huge opportunities to reduce the consumers heat bills, this could for example be achieved by lowering the temperature profiles and thus open up the possibilities of applying alternative and less expensive heat sources compared to what is currently being used.

As can be seen from Table 2 the network investment costs grow with decreased supply temperatures, this is due to the decreased temperature difference between the supply and return. The smaller the temperature difference is the more volumetric flow is required to transport the same amount of heat, which results in larger pipe dimensions in the network. To compensate for the increased investment costs the cost of operating the network needs to decrease, see Table 3. The cost of the operation depends on the electricity and heat costs. The cost of electricity to industry is assumed to be 690 DKK/MWh and 1.425 DKK/MWh to consumers, without VAT.

The cost of heat to district heating utilities in 2013 depended on the heat source and varied from 40 DKK/MWh to 1.000 DKK/MWh, where the cheapest

Table 5. Cost of operating the networks.

Operational and heat costs	80/40 // 65/30°C	55/30°C	55/30 // 40/25°C	40/25°C	
Distribution network heat loss	165.000	150.845	113.615	114.423	DKK/year
Service pipes heat loss	138.500	110.500	71.580	66.565	DKK/year
Pump electrical consumption	33.810	36.528	40.992	34.841	DKK/year
Micro booster electricity consumption	0	0	79.800	106.875	DKK/year
Cost of heat to consumers	1.701.500	1.701.500	1.701.500	1.701.500	DKK/year
Total	2.038.810	1.999.373	2.007.487	2.024.204	DKK/year
Difference from 80/40 // 65/30°C	0	-39.437	-31.323	-14.606	DKK/year
Simple payback time from 80/40 // 65/30°C network		15	185	421	years

heat is surplus heat from industry and the most expensive heat was from a small decentralized heat plant.

The base assumption in this analysis is that the heat price is 500 DKK/MWh. In Table 5 it can be seen from the long simple payback time that for the given heat cost and the cost of the micro booster the U-LTDH concept cannot be carried out on the heat losses alone when compared to Traditional DH and LTDH networks. However if using the micro booster could open up the possibility of using less costly heat sources the heat cost reduction should be used to pay for the increased investment costs in the U-LTDH network.

Sensitivity analysis

To access the influence of both the cost of the heat and the cost of the micro booster on the simple payback time a sensitivity analysis were made.

For accessing the influence of the cost of the micro booster the cost was varied from 40.000 DKK/unit down to 25.000 DKK/unit. From Table it can clearly be seen that the concept of U-LTDH is mainly dependent on the potential of decreased heat prices but not on the cost of the micro booster application.

Table 6. Sensitivity analysis on the effects of the cost of the micro booster.

	Simple payback time	
Micro booster [DKK]	55/30 // 40/25°C	40/25°C
40.000	241	501
35.000	185	421
30.000	125	293
25.000	65	165

As for the influence of the heat cost it is assumed that the heat cost savings are due to the ability of the micro booster to utilize lower temperatures than can be used in the alternative solutions, hence the savings on the heat expenditures should be allocated to the micro booster and consequently reduce the payback time. Table shows the effects of the heat price on the simple payback time by applying the U-LTDH instead of the Traditional DH network. It is clear that even with only moderate heat price reduction the U-LTDH is a competitive solution.

Table 7. Sensitivity analysis on the effects of the heat cost on the simple payback, base line is 500 DKK/MWh.

	55/30 // 40/25°C		40/25°C	
Heat price [DKK/MWh]	Savings achieved	Simple payback time	Savings achieved	Simple payback time
500	31.323	185	14.606	421
450	219.730	26	203.013	30
400	408.137	14	391.420	16
350	596.545	10	579.828	11
300	784.952	7	768.235	8
250	973.359	6	956.642	6

From Table 7 it can be seen that if 200 DKK/MWh reduction in the heat cost can be achieved by using the micro booster the simple payback time would be 7 and 8 years for the 55/30 // 40/25°C and 40/25°C respectively. This is very interesting by the fact that the cost of heat to Danish DH systems vary from 40-1.000 DKK/MWh.

CONCLUSIONS

When establishing a new district heating network it is important to access all possible heat sources and how they can work with currently available technologies. By applying the micro booster concept it is possible to reduce the supply temperature further than has been considered in the low temperature concept, since the micro booster is used to boost the supply temperature to a temperature level that is sufficient for DHW preparation. This implies that the only limitation towards the supply temperature is the space heating installation and with a modern floor heating technology the supply temperature can easily be as low as 35-40°C.

In the paper it has been shown that the main influence on the economic feasibility of applying U-LTDH is the cost of heat supplied to the network, the cost of the micro booster application has only a minor influence.

If applying the micro booster can result in reduced heat costs to the network it can be a very attractive solution that deserves an attention in the future district heating networks.

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SESSION 10

Urban Energy systems, planning and development

The 14th International Symposium on District Heating and Cooling,
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PROGRESS AND RESULTS FROM THE 4DH RESEARCH CENTRE

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ABSTRACT

With lower and more flexible distribution temperatures, fourth generation district heating systems can utilize renewable energy sources, while meeting the requirements of low-energy buildings and energy conservation measures in the existing building stock. 4DH is an international strategic research centre located at Aalborg University, which develops 4th generation district heating technologies and systems (4GDH). This technology is fundamental to the implementation of the Danish objective of being fossil fuel-free by 2050 and the European 2020 goals. The research centre is working between 2012 and 2017, with The Danish Council for Strategic Research as main financier and the participating 31 Danish and international companies and universities as co-financiers. Thirteen PhD student projects constitute a vital part of the research centre. In 4GDH systems, synergies are created between three areas of district heating and cooling, which also sum up the work of the 4DH Centre: Grids and components; Production and system integration, and Planning and implementation. This paper presents an overview of the progress and results achieved after more than two years of work. This includes the basic definition paper, the two Heat Roadmap Europe pre-studies, annual conferences, additional demonstration projects, initiated European project proposals, an international PhD course based on the new international textbook, PhD student seminars, all PhD student subjects, and a list of major papers and articles written so far within the research centre.

INTRODUCTION/PURPOSE

With lower and more flexible distribution temperatures, 4th generation district heating systems can utilize renewable energy sources, while meeting the requirements of new low-energy buildings and energy conservation measures in the existing building stock. Another important change in the energy system is the transition from fossil to renewable input into the electricity market. Hereby, traditional CHP plants using fossil fuels will lose its competitiveness in favour of wind and solar power. Therefore, many European district heating systems will lose their traditional heat source. These challenges for district heating systems have earlier been described in [1] and [2].

Labelling this next generation of district heating technology as the fourth generation requires the definition of the three preceding technology generations.

The first generation of district heating systems used steam as a heat carrier. These systems were first introduced in the USA in the 1880s. Almost all district heating systems established before 1930 used this technology, both in the USA and in Europe. Typical components were steam pipes in ducts, steam traps and compensators. Today, steam distribution can be considered as an outdated technology in district heating systems, since high steam temperatures generate high heat losses, and severe accidents from steam explosions have even killed pedestrians in streets. The condensate return pipes have often corroded, resulting in less condensate returns and lower energy efficiency. Steam is still used as the main heat carrier in the old New York (Manhattan) and Paris systems and is partly used in Copenhagen, while replacement programs have been successful in Hamburg, Salzburg, and Munich.

The second generation of district heating systems used pressurised hot water as a heat carrier, with temperatures mostly over 100ºC. These systems emerged in the 1930s and dominated all new systems until the 1970s. Typical components were water pipes in concrete ducts, large shell-and-tube heat exchangers, and material-intensive, large, and heavy valves. The large Soviet-based district heating systems used this technology but with a low level of quality without any local heat demand or flow control in the overall control systems. Outside the former USSR, the quality level was much higher and remnants of this technology can still be found making up older parts of the current water-based district heating systems.

The third generation of district heating technology was introduced in the 1970s and took a major share of all extensions in the 1980s. Pressurised water is still the heat carrier, but the supply temperatures are often below 100ºC. This third generation is sometimes referred as Scandinavian district heating technology, since some well-known district heating component manufacturers are Scandinavian companies. Typical components are pre-fabricated and pre-insulated pipes buried directly into the ground, compact substations using braze heat exchangers, and material-lean components. This technology is used for all replacements in Central and Eastern Europe and the former USSR. Almost all extensions and all new systems in China, Korea, Europe, the USA and Canada now use this third generation technology.

The purpose with this paper is to summarise the activities from the start of the Danish 4DH research centre, designed for taking a wide approach for facilitating the development of the new enhanced fourth generation of district heating technology.

METHODS/METHODOLOGY

4DH is an international research centre located at Aalborg University, which develops 4th generation district heating technologies and systems (4GDH). This technology is fundamental to the implementation of the Danish objective of being fossil fuel-free by 2050 and the European 2020 goals. The research centre is working between 2012 and 2017, with The Danish Council for Strategic Research as main financier and the participating 31 Danish and international companies and universities as co-financiers. The total project budget is almost ten million euro during the six years of activity. Currently, the 4DH research centre is the largest academic district heating project in Europe.

The 4DH research centre is headed by professor Henrik Lund at Aalborg University in Aalborg, while professor Brian Vad Mathiesen at Aalborg University in Copenhagen is deputy head with a special coordination responsibility for the PhD students and their projects.

Partners

The project partners are listed in Table 1. These partners are universities, district heating companies, consulting companies, and manufacturers of district heating components. Some international partners come from China, Croatia, and Sweden.

Table 1. List of the current 31 project partners.

1	Aalborg Forsyning, Varme	Denmark
2	Aalborg University, Department of Development and Planning, AAU-PLAN & AAU-CPH	Denmark
3	Aalborg University, Department of Energy Technology, AAU-IET	Denmark
4	AffaldVarme Aarhus	Denmark
5	Chalmers University of	Sweden
6	COWI	Denmark
7	CTR	Denmark
8	Danfoss	Denmark
9	DESMI	Denmark
10	EMD	Denmark
11	Fjernvarme Fyn	Denmark
12	Grøn Energi	Denmark
13	Halmstad University	Sweden
14	Kamstrup	Denmark
15	HOFOR	Denmark
16	Linnaeus University	Sweden
17	LOGSTOR	Denmark
18	NIRAS	Denmark
19	Planenergi	Denmark
20	Rambøll	Denmark
21	Ringkøbing-Skjern Kommune	Denmark
22	SPX	Denmark
23	Technical University of Denmark – Department of Civil Engineering, DTU-BYG	Denmark
24	Technical University of Denmark – National Laboratory of Sustainable Energy, DTU-RISØ	Denmark
25	Tsinghua University	China
26	University of Southern Denmark, SDU	Denmark
27	University of Zagreb	Croatia
28	VEKS	Denmark
29	Vestforbrænding	Denmark
30	Viborg Fjernvarme	Denmark
31	Wallenius Water	Sweden

Organisation

In 4GDH systems, synergies are created between three areas of district heating, which also sum up the work of the 4DH Centre: Grids and components; Production and system integration, and Planning and implementation. These areas are organised in work packages.

Work package 1, District Heating Grids and Components: This first area focuses on the research, development and evaluation of low-temperature district heating systems based on renewable energy. The research basically provides new knowledge of the hardware and software technologies of the new generation of district heating systems supplying heat to existing energy renovated buildings and new low-energy buildings.

The hypothesis is that low-temperature district heating, with a general supply and return temperature of about 50°C and 20°C, respectively, can be used in existing district heating systems, if minor modifications are implemented in the systems for room heating and domestic hot water supply of the existing buildings. The immediate implementation of the low-temperature technology (10 years) in existing and new district heating systems and buildings makes it possible to use low-temperature renewable heat from geothermal plants and central solar heating plants as well as waste heat from industrial processes directly and thereby replace fossil fuels and imported biomass in the district heating systems.

Work package 2, District Heating Production and System Integration: The hypothesis of this second area is that 4DH has an important role to play in efficient future energy systems. This work package develops energy systems analysis tools, methodologies and theories for the study and scenario-building of future sustainable energy systems with the aim of identifying the role of district heating systems and technologies in various countries.

The European project partners are engaged in the development of EU policies and strategies to define the role of district heating, and similar activities are carried out by the Chinese partner. This includes an investigation of the balance between heat savings and heat supply as well as the balance between the supplies to individual houses through collective or individual systems, respectively. Moreover, the work package focuses on the development of strategies and software tools for decision-making support to local district heating companies and energy planners.

Work package 3, District Heating Planning and Implementation: This third area focuses on the further development of the planning and management systems based on spatial analysis and geographical information systems (GIS) as a tool for planners and decision-makers. This includes the further advancement of theories and methodologies as well as the design of specific public regulation measures. The latter focuses on how to manage the conflict between implementing energy conservation in buildings and, at the same time, utilising available low-temperature heat sources in district heating, seen from planning, organisational and legal perspectives.

PhD student projects

Thirteen PhD students with their different projects constitute a very vital part of the research centre. Each PhD student will be active during three years before obtaining their PhD degrees. The subjects chosen and appointed PhD students are presented below by their work package affiliation.

WP1: District Heating Grids and Components

1.1 Heating of existing buildings by low-temperature district heating, position not yet filled, DTU-BYG, Lyngby.

1.2 Supply of domestic hot water at comfort temperatures without Legionella, Xiaochen Yang, DTU-BYG, Lyngby.

1.3 Conversion of existing district heating grids to low-temperature operation and extension to new areas of buildings, Soma Mohammadi, AAU-IET, Aalborg.

1.4 Minimising losses in the DH distribution grid, position not yet filled, AAU-IET, Aalborg.

WP2: District Heating Production and System Integration

2.1 Energy Scenarios for Denmark, Rasmus Lund, AAU-CPH, Copenhagen.

2.2 Thermal storage in district heating systems, Sean Bryant, AAU-PLAN, Aalborg.

2.3 Distributed CHP-plants optimized across more electricity markets, Peter Sorknæs, AAU-PLAN, Aalborg.

2.4 Low-temperature energy sources for district heating, Urban Persson, Halmstad University, Sweden.

2.5 The role of district heating in the Chinese energy system, Weiming Xiong, Tsinghua University, Beijing, China

WP3: District Heating Planning and Implementation

3.1 Strategic energy planning in a municipal and legal perspective, Michael Herborn, SDU, Odense.

3.2 Price regulation, tariff models and ownership as elements of strategic energy planning, Søren Djørup, AAU-PLAN, Aalborg.

3.3 Geographical representations of heat demand, efficiency and supply, Position not yet filled, AAU-PLAN, Aalborg.

3.4 Geographical representations of renewable energy systems, Stefan Petrovic, DTU-RISØ, Roskilde.

RESULTS

This paper presents an overview of the progress and results achieved after more than two years of work. These results include the basic 4GDH definition paper, the two Heat Roadmap Europe pre-studies, annual conferences, additional demonstration projects, international PhD courses based on the new international textbook, annual PhD student seminars, and a list of all major papers and articles written so far within the research centre.

Basic 4GDH definition paper

Why should we develop a new generation of district heating technology? Because we need the integration of smart electricity, gas and thermal grids in order to obtain the least cost solution from a combination of renewables and energy efficiency measures in the future energy system. This answer was recently elaborated in the 4GDH definition paper [3], collectively written by senior researchers within the 4DH research centre. The concept of 4th Generation District Heating (4GDH) was defined including the relations to District Cooling and the concepts of Smart Energy and Smart Thermal Grids. The motive was to identify the future challenges of reaching a future renewable non-fossil heat supply as part of the implementation of overall sustainable energy systems.

The basic assumption is that district heating and cooling has an important role to play in future sustainable energy systems - including 100 percent renewable energy systems - but the present generation of district heating and cooling technologies will have to be developed further into a new generation in order to play such a role. Unlike the first three generations, the development of 4GDH involves meeting the challenge of more energy efficient buildings as well as being an integrated part of the operation of smart energy systems, i.e. integration of smart electricity, gas and thermal grids.

Heat Roadmap Europe pre-studies

One early initiative within the 4DH research centre was the Heat Roadmap Europe pre-studies performed together with Euroheat & Power. The main purpose with these European heat market studies was to verify the future long term benefits of district heating, which never had been estimated before. It was also vital for the 4DH research centre to prove that district heating is long term viable within the European Union before elaborating the fourth generation district heating technology.

The benefit of district heating was measured against corresponding scenarios in *Energy Roadmap 2050*, published by the European Commission in December 2011. This communication report presumed a low market share of 10% for district heating in buildings. We estimated the benefits with higher district heating market share, by assuming it to be 30% in 2030 and 50% in 2050.

The first Heat Roadmap Europe pre-study [4] was published in June 2012. The benefits of district heating were then measured in a business-as-usual scenario. The district heating pathway generated less primary energy use, lower carbon dioxide emissions, additional job creation by investments, and lower total costs for heating European buildings than the Energy Roadmap 2050 scenario. The 2050 cost reduction was estimated to be 14 billion euro. These results were obtained by a novel combination of mapping regional conditions and energy system simulation of the chosen alternatives. The mapping part of the first pre-study was presented at the last International District Heating and Cooling Symposium in Copenhagen [5].

The second Heat Roadmap Europe pre-study [6] was published in May 2013: The benefits of district heating were in this second pre-study measured in an energy efficiency scenario. However, the comparison with the Energy Roadmap 2050 scenario was performed differently. The district heating pathway was designed to give the same primary energy supplies and carbon dioxide emissions as the Energy Roadmap 2050 scenario. The benefit of district heating was then mainly measured as the cost difference. District heating investments replaced then the most expensive end use investments for obtaining higher energy efficiency. More district heating systems became in this case a part of the energy efficiency solution. The 2050 cost reduction was estimated to 100 billion euro, seven times higher than in the business-as-usual scenario. Hereby, we revealed a paradox: District heating has a higher competitiveness in an efficient energy system than in the traditional energy system. A general opinion in the European energy debate is often the opposite.

The results from the Heat Roadmap Europe have been disseminated and communicated in various ways. A scientific summary of the second pre-study has been published in [7]. Numerous presentations of the results have been held in European and various national conferences and seminars. The two pre-studies have also become an essential input to the ongoing discussions about a future heat strategy within European energy policy.

Henrik Lund, the head of the 4DH research centre, has summarised the overall conclusion from the two pre-studies as: **District heating is here to stay, but district heating has to change.**

Annual conferences

Annual 4DH conferences are arranged every year in order to disseminate activities and results from the project. However, the conference perspective changes from year to year. The first conference took place in Aalborg on October 3, 2012, where the initial perspective was to launch and present the new 4DH research centre. The 2013 conference was held in Copenhagen on August 21, and the theme was 'Combined heat and power plants - now and in the future', focusing on the interaction between electricity markets and district heating systems. The third conference in Aalborg is planned for August 18, 2014 with a theme of 'District Heating in Areas with New Buildings'.

Additional demonstration projects

Four working groups have been initiated concerning additional demonstration projects in conjunction to the 4GDH technology. The first working group is about reduced temperature levels in existing district heating systems, the second is about interfaces with electricity markets including heat pumps, the third is about Danish/Chinese collaboration of universities and consultancies, while the fourth working group has a full-scale supply chain (from supply to demand) perspective at national level.

International PhD courses about DHC

Two international PhD courses based on the new international district heating and cooling textbook [8] have been arranged at Halmstad University with Sven Werner as coordinator and main lecturer. They lasted for two weeks with fulltime activities as ordinary lectures associated to the textbook, invited guest lecturers, study visits, daily concluding discussions, and one final examination test.

The first course was held in August 2012 with 36 participants from 12 countries and performed in conjunction with the Swedish Fjärrsyn research program. The gathering basic level of these special district heating courses is presented by the ten exam questions:

1	Express the fundamental idea of district heating with maximum 12 words!
2	We have discussed that the overall control system for a whole district heating system is based on four different control systems. Which are the four target purposes for these four control systems? (One answer for each control system)
3	What is the direct rate of return in percent for an extension of the distribution network, if the linear heat density for the extension is 25 GJ/m, the extension cost is 250 €/m, the current heat price is 14 €/GJ, and the marginal heat supply cost is 9 €/GJ?
4	Why is normally the district cooling pipe wider than the district heating pipe at the same capacity demand?
5	What is the specific distribution capital cost for the combination of an investment cost of 300 €/m, an annuity of 8%, and a linear heat density of 12 GJ/m?
6	A performance indicator for a CHP plant is the power-to-heat ratio. How is it defined?
7	a) What is the difference between a direct and an indirect connection of the customer space heating circuit in a substation?

	b) What is the difference between an open and a closed connection of the customer domestic hot water circuit in a substation?
8	Why is a low return temperature preferred in a district heating substation?
9	Why is a full-loaded wide pipe (large diameter) more cost-effective than a full-loaded narrow pipe (small diameter)?
10	What was the market share for district heating during 2008 in the heat market for heating buildings within the European Union?

Some examples of spontaneous course assessments were received in some e-mails arriving after the course:

I would like once again to thank you for an amazing PhD course in Halmstad. I have gained an unforgettable experience about DHC systems. I really appreciate all your efforts, organisation of course structure and study visits.
Thank you for an awesome good course. Made a great difference for me and I feel that many important pieces have found its place.
I want to take advantage of this mail as to thank you again of this excellent PhD course about DHC. For sure, I will promote your "summer university" and also your textbook in COFELY.
Thanks for this very useful course!
Thank you very much for the rewarding course. I learned plenty.

The second course was held in November/December 2013 with 32 participants from 7 countries. The participating PhD students from the 4DH research centre were very active in this course. Almost all PhD students from the large Swedish research program of RESBEE [9] participated also in this second course. This research program is almost completely devoted to the future balance between heat supply and end use energy efficiency in Swedish buildings connected to district heating systems.

PhD student seminars

Internal PhD student seminars have been held at March 7, 2013 and March 13, 2014. In these seminars, the PhD students present their progress and obtained results, and these findings are discussed with the supervisor group and interested participants from the project partners.

List of publications and presentations

The website www.4dh.dk/publications-reports contains currently about ten pages with links to reports, papers, and seminar and conference presentations provided from the project participants, since the start in 2012.

DISCUSSION

District heating is challenged in Europe today with respect to heat supply and heat demands. The current heat supply from CHP plants based on fossil fuels needs to be replaced by other heat supply in the future. This transition has already started in some places where long term contracts of heat supply from CHP plants have been cancelled for termination within some years. New buildings can nowadays be built with considerable lower heat demands than existing buildings, giving lower heat densities and higher heat distribution costs in the future. Existing buildings are also expected to use less heat in the future.

The 4DH research centre is a good example of how countries can support and facilitate district heating research concerning the transition of the current district heating technology to a new generation of district heating technology, more suitable for the future energy market conditions.

The focus on many PhD students in the research centre will also keep the knowledge gained within universities and the energy system for many years.

OUTLOOK

The first years has been characterised by initiation, recruitments of PhD students, work programs, PhD student courses, and the Heat Roadmap pre-studies. The three ending years will be more focused on results and conclusions concerning the future 4GDH technology with respect to heat distribution, heat supply, and integration into the energy system. Coming results will be presented at the research centre website: www.4dh.dk

The first PhD degree from the 4DH research centre is expected to be obtained by Urban Persson from Halmstad University this coming autumn. The following 2015 and 2016 years will also see further PhD degrees from the rest of the PhD student group.

The research centre has also become an arena for ideas of new international research projects by bringing together researchers will common interests. Participants from the 4DH research centre were active in the European Stratego project application. This project has been granted funding from the IEE 2013 program and will work between 2014 and 2016. This project is planned to contain regional studies of the results obtained in the two Heat Roadmap Europe pre-studies. Several research applications have also been submitted to the 2014 energy efficiency calls within Horizon 2020, the new European framework research program for 2014-2020.

CONCLUSIONS

Two major conclusions can be identified from this early summary of the progress and results from 4DH research centre:

- 4GDH has become a standard label for something new to expect and is used in most discussions about future district heating systems.
- The 4DH research centre has a size beyond the critical mass threshold in order to initiate new sustainable ideas. This is especially valid concerning the mixture of very curious PhD

students and more experienced senior researchers.

ACKNOWLEDGEMENTS
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TRADITIONAL BUILDINGS SUPPLIED BY LOW-TEMPERATURE DISTRICT HEATING

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ABSTRACT

Low-temperature district heating (DH) with supply temperature low as 50°C provides combination of high security of heat supply and CO_2 reductions by exploiting of renewable heat sources while being economically feasible also for low-energy buildings. However share of low-energy buildings grows slowly and recently represents below 5% of the Danish buildings stock, while the rest is formed by traditional buildings designed with high temperature space heating and domestic how water systems. Therefore question of using low-temperature DH in traditional buildings arise, needed to be seen from perspective of both, the customers and the DH utilities.

We chose single-family house from 1970s as a typical example of Danish building stock and made investigation in energy calculation software IDA-ICE to realize for how many days during the year the 50°C warm DH water covers the requirements for space heating. To reflect various stages of the building states we modelled the building in the original state from 1970, but also in two stages of envelope refurbishment.

The results show that for the well-maintained house the DH supply temperature should be increased above 50°C approximately for 7% of the year, with the maximum temperature 62°C. In case the customers requires operative temperature 22°C instead of 20°C the maximum temperature further increases to 67°C and the DH supply temperature is above 50°C approximately for 17% of the year . Nevertheless high comfort of 22°C can be for whole year kept also with supply temperature of 50°C if the existing radiators are replaced with low-temperature ones. Domestic hot water substation should be always changed to the special low-temperature one to guarantee that the customers have required temperature of domestic hot water without increased risk of Legionella bacteria.

Traditional buildings can be therefore integrated to the low-temperature DH networks if is the DH supply temperature increased to sufficient level during the periods with cold outdoor temperature and the substations for domestic hot water are replaced.

INTRODUCTION

To reduce CO_2 emissions and increase the security of supply, in 2011 the Danish Government decided to achieve a fossil-free heating and electricity sector for buildings by 2035 and complete independence of fossil fuels by 2050 [1]. The Energy Performance of Buildings Directive (EPBD) [2] requires that all new public and other buildings should be constructed as nearly-zero energy buildings [3] from 2018 and 2020 respectively. The Danish national heating plan [4] judges that this will be achieved mainly by a further spread of district heating (DH) based on renewable heat sources. The most cost-effective use of these sources is related to their efficiency [5], so the DH supply and return temperatures should be as low as possible. This is also required by the need to reduce the heat loss from DH networks, which will make it economically possible to supply buildings with reduced heating demand, such as low-energy and refurbished existing buildings, which it would be uneconomical to supply with traditional medium temperature DH. To reflect these needs, the concept of “low-temperature DH” with supply/return temperatures of 50/25°C respectively (see Figure 1), matching the exergy levels of supply and demand sides, has recently been developed and successfully tested in a settlement of low-energy houses [6], [7]. The deployment of low supply/return temperatures and DH pipes designed with smaller diameters and greater insulation thicknesses reduces the heat loss from the network to one quarter of the heat loss expected from a traditionally designed and operated DH network with 80/40°C [8].

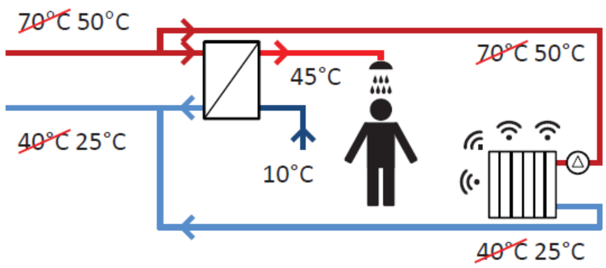


Figure 1 Concept of low-temperature district heating [9]

However most of the Danish building stock consists of buildings built around the 1970s, as a result of a peak in population growth [10]. In what follows, these buildings are called “existing buildings”, meant in the sense of a counter-pole to low-energy buildings. Compared to low-energy building, e.g. class 2010 [11] with an energy framework of 63 kWh/(m^2.a), existing building from the 1970s have considerably greater energy demand, resulting in a typical energy use of about 200 kWh/(m^2.a) [12]. The energy demand of buildings built after 1977 drops significantly as a consequence of the building regulations (BR1977) demanding a lower U-value for construction elements to reflect the oil crisis in the 1970s [13]. The existing buildings will continue to make up a large share of the building stock for many years to come and it is estimated that their share in Denmark in 2030 will be about 85-90% [3].

So the question arises as to whether such buildings can cope with low-temperature DH with supply temperatures of 55-50°C and, if not, what renovation measures need to be carried out on the building envelope and the SH and DHW systems, and how should the DH network be operated. These buildings are usually equipped with SH and DHW systems designed for supply temperatures of around 70°C or higher, so a reduction of DH supply temperature would be expected to cause discomfort for the occupants. So one possible solution is to operate the DH network with a supply temperature of 50°C for most of the year and increase the DH supply temperature only during cold periods. However, once the DH supply temperature drops below 60°C, the DHW substation needs to be replaced with a low-temperature version, with highly efficient heat exchanger as for example shown in successful low-temperature district heating project in Lystrup, Denmark [7].

Reduction of DH supply temperature

From the perspective of occupants, the DH supply temperature can be reduced as long as it does not violate requirements for DHW or thermal comfort. This needs to take account of the fact that occupants tend to maintain operative temperature of 22°C rather than 20°C [7] and should truly focus on the operative temperature rather than the air temperatures sometimes experienced. From the perspective of DH, the maximum hydraulic capacity of the DH network and the availability of the heat sources that can provide peaked DH supply temperature during cold periods also need to be considered.

The maximum supply temperature needed in the SH systems can be further reduced by improving the building envelope or by replacing the original SH system with a low-temperature system extracting more heat by better cooling of DH heating water. From the long-term perspective, the preferred solution is to reduce the heat demand by improving the building envelope, but due to the investment cost not every house owner is willing to do this. Replacing the SH system is a cheaper and faster solution, but it does not bring any energy savings; it just allows existing buildings to be supplied by DH with reduced supply temperatures. Refurbishment measures carried out on existing houses vary from no measures (original state) to extensive renovation, including replacing the windows and wall and roof insulation. Replacing the windows is the most typical refurbishment, because the window lifetime of 30 years has passed and a relatively small investment brings considerable heat savings.

However the renovation of existing buildings should be seen also from the perspective of the integration of renewable sources of heat which needs to be built before 2035 because it is cheaper to refurbish the

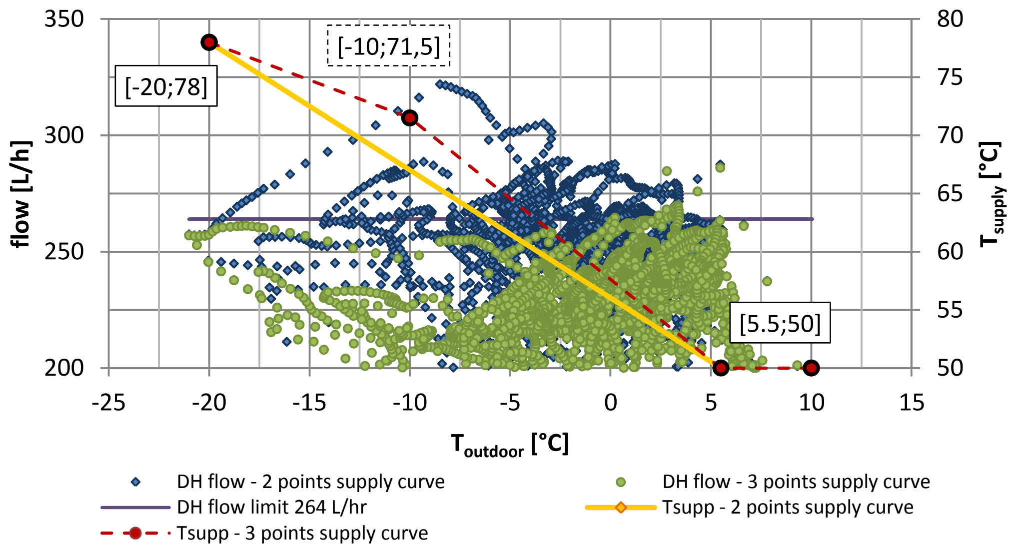


Figure 2 Construction of weather-compensated curve supply temperature curve for non-renovated house, set-point temperature 22°C [15]

existing buildings as fast as possible to reduce their peak capacity and thus also the investment costs for low-temperature DH. Subsidies for the building refurbishment could be therefore from the long-time perspective advantageous [14].

OBJECTIVES

Objective of the study was to investigate possibility of reducing the DH supply temperature for typical single-family house from 1970 at three stages of building envelope refurbishment, so that we can evaluate possibility of their integration to the low-temperature DH networks.

METHODS

The feasibility of integrating existing buildings to low-temperature DH with a design supply temperature of 50°C was modelled in the advanced level of the IDA-ICE program, version 4.22. [16], by finding the minimal supply temperatures required by SH system to keep 20°C or 22°C operative temperature. The approach applied was to define new supply temperature curve (i.e. dependency of the temperature supplied to the space heating system on the outdoor temperature) by reducing the supply temperature to the space heating system until the operative temperature indoors drops below the desired value of either 22°C or 20°C.

Modelling of the building

We chose a 157m^2 single-family house built in 1973 as a typical representative of the Danish building stock. The house was part of a Realea renovation project to investigate the reduction in energy demand for refurbished houses from the 1970s and the project reported enough information to develop and verify a model of the house [12]. The house was modelled as a multi-zone model with 12 zones (see Figure 3), each representing one room. The difference between the measured and modelled heat demand for the reference case of the non-renovated house was only 2.5%.

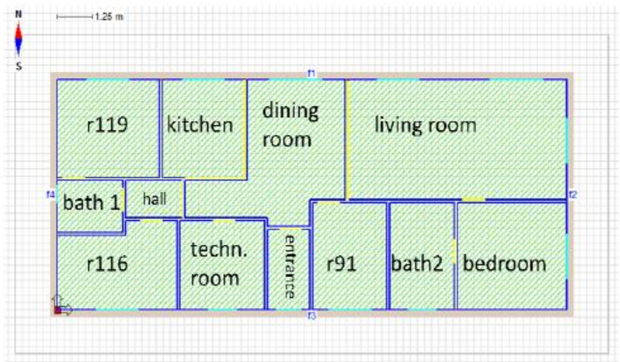


Figure 3 Ground plan of 157m^2 single-family house built in IDA-ICE

To account for the refurbishment measures, possibly already made on many houses from the period around 1970, we defined three states of the building envelope:

- Non-renovated house in its original state from 1970
- Light-renovated house
- Extensively renovated house

Light renovation was considered as replacement of original windows with new ones with standard double glazed panes around year 2000 because of end of life-time of original windows. The new windows has overall U-value 1,2 W/(m^2.K) instead of 3,2 W/(m^2.K) originally installed. At the same time new windows decreased the infiltration by 15% to 0,41 h^{-1} (0,278 L/m^2.s).

The extensive renovation was based on the example of Realea project. It accounts for adding the 300 mm of insulation (λ_{ins}=0,56 W/(m2.K) including the effect of wooden beams) above the ceiling, and by insulating the wooden beams bearing the roof construction with 125 mm of insulation (λ_{ins}=0,039 W/(m^2.K) and 13 mm gypsum board. The overall heat transfer coefficient U for the ceiling construction was reduced 0,48 to 0,14 W/(m^2.K) and for the insulated beams from 1,1 to 0,24 W/(m2.K). Moreover the thermal bridges around the windows were reduced by adding the 30 mm of polystyrene, in the simulations modelled as reduced linear heat loss from 0,0736 to 0,0192 W/(m^2.K). Windows facing the west and north were replaced with triple-glazed low-energy windows with an overall U values of 0,9 W/(m^2.K) and g value of 0,5. The change of the windows reduced infiltration to 0,613 h^{-1}.

Finding the minimal supply temperature

First we dimensioned the SH system with radiators for temperature levels of 70/40/20 (supply temperature, return temperature, air temperature) based on DS 418 [17] to cope with a constant outdoor temperature of -12°C without internal or external heat gains. The nominal heat output of real radiators [18] was chosen as close as possible to the dimensioned values. The more over-dimensioned the radiators are, the more the supply temperature can be reduced, which means the model would not reflect the design conditions.

Then we included the heat gains expected from occupants and equipment (4.2 W/m^2 – constantly) [19] and ran the model with the Danish design reference year weather file. By step-by-step lowering of the supply temperature for various outdoor temperatures, we found a supply temperature curve for the SH system. To maintain the same hydraulic conditions in the DH network, the minimal supply temperature was limited by the maximum flow rate from the DH network defined originally for the design conditions of radiators 70/40/20, i.e. 264 L/h.

Figure 2 shows total flow of heating water needed from the DH system for linear (yellow) and non-linear (red, dashed) supply temperature curve. It can be seen that considering the supply temperature curve as linear results in non-uniform use of DH capacity (blue diamonds) and since the flow is many times above the DH flow limit (based on the design conditions 264 L/h), it will be needed to further increase the supply temperatures to reduce the maximal flow of DH water below the limit. However, defining the supply temperature curve with at least one additional point results in equalized use of flow capacity of the DH network (green circles) and thus reducing the supply temperature to the minimal possible values. The additional points on the supply temperature curve were found by continuous adjustment of the supply temperature curve for various outdoor temperatures until the actual flow in the SH system approached close to the hydraulic limit of the DH network. Based on the mentioned reasons, the supply temperature curves were constructed as non-linear.

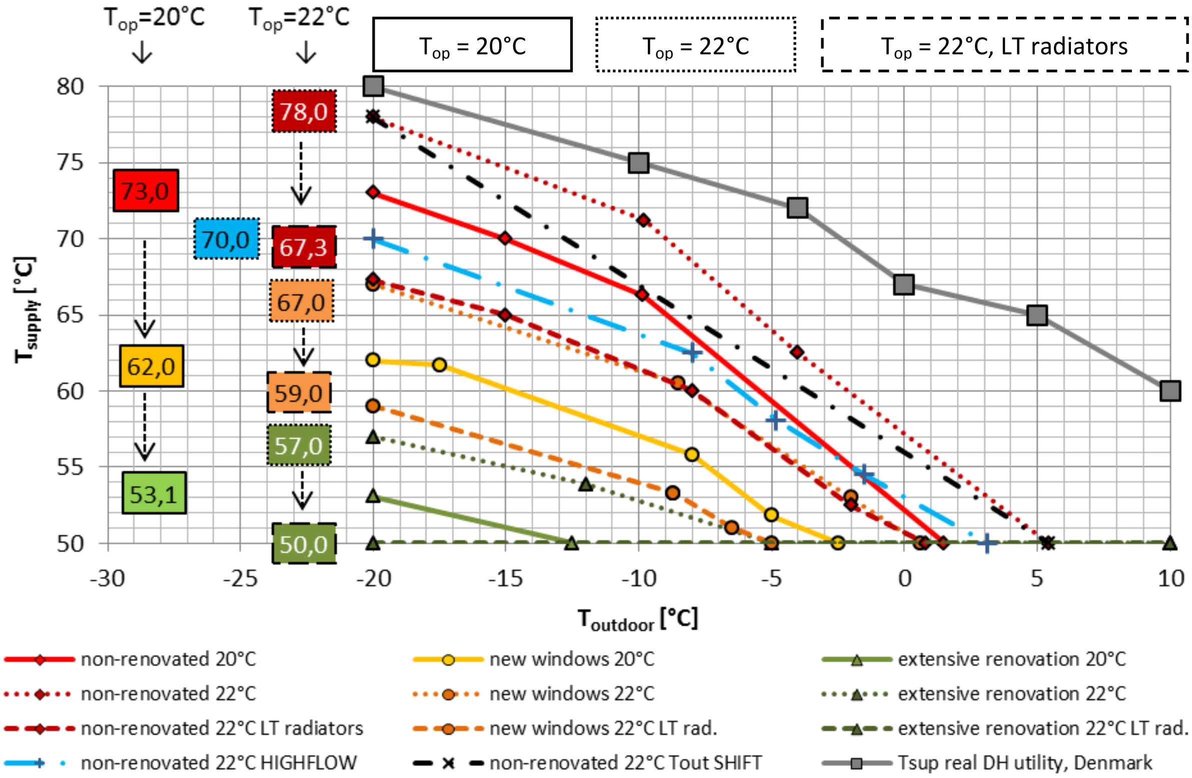
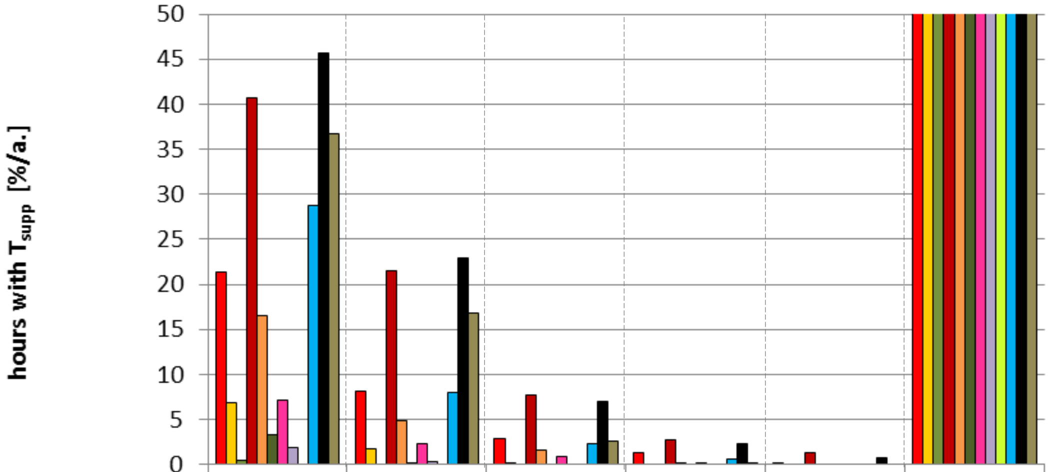


Figure 4 Supply temperature curves for all the cases investigated. LT – low-temperature radiators, HIGHFLOW – hydraulic limit of SH system and DH increased to 400 L/h; $T_{outSHIFT}$ – 6 hours time delay when the T_{out} increases

Non-linearity of the supply temperature curve is caused by the thermal capacity of the building. Even the outdoor temperature rises and thus gives signal to reduce the supply temperature to the SH system, the building still keeps the “cold” accumulated from the previous period and it takes some time to heat up this mass to the new thermal condition. An alternative solution to define the supply temperature curve by more than two points is therefore “delay” in reduction of heating supply temperature for the periods when the outdoor temperature increases. To investigate this option we chose time delay of 6 hours and this condition is in further text called “$Tout_{SHIFT}$”.

Considering possible integration of renewable sources of heat, we also investigated case with supply temperature limited to 70°C, resulting in maximal flow rate increased from designed 264 L/h to 432 L/h. This condition is denoted “HIGHFLOW” and represent condition when the DH network has enough reserve in capacity to increase the flow. In reality this condition is very relevant because the DH networks are usually built with capacity reserve up to 30% [20]. Possibility to increase the maximal flow in the SH system depends on the design conditions for the SH system, but for the case of investigated house it doesn’t represent problem [15]. Using the same approach, the supply temperature curve was also defined for the “light renovated house” with the original windows replaced around the year 2000 with standard ones and for the “extensively renovated house” with low-energy windows and additionally insulated ceiling. Table 1 reports the complete list of simulated cases. Moreover, for all three building states, we investigated replacing the original radiators (designed for conditions 70/40/20) with low-temperature radiators (designed with condition 50/25/20), with the same length and height, but deeper (increased number of convection plates). Finally, we also investigated influence of milder outdoor temperatures then defined in Danish design reference year but considering the supply temperature curve defined for Danish design reference year. The outdoor temperature used is the outdoor temperature measured in 2009 during Realea project [12].



	> 50	> 55	> 60	> 65	> 70	= 50
non-renovated 20°C	21,4	8,1	2,9	1,3	0,2	78,6
new windows 20°C	6,8	1,8	0,2	0,0	0,0	93,2
extensive renovation 20°C	0,4	0,0	0,0	0,0	0,0	99,6
non-renovated 22°C	40,8	21,5	7,7	2,7	1,2	59,2
new windows 22°C	16,5	4,8	1,6	0,1	0,0	83,5
extensive renovation 22°C	3,4	0,2	0,0	0,0	0,0	96,6
non-renovated 22°C LT radiators	7,2	2,3	0,9	0,2	0,0	92,8
new windows 22°C LT rad.	1,8	0,3	0,0	0,0	0,0	98,2
extensive renovation 22°C LT rad.	0,0	0,0	0,0	0,0	0,0	100,0
non-renovated 22°C HIGHFLOW	28,8	8,0	2,4	0,5	0,0	71,2
non-renovated 22°C Tout SHIFT	45,6	22,9	7,0	2,3	0,8	54,4
non-renovated 22 °C ODUM	36,7	16,9	2,5	0,2	0,0	63,3

T_{supply} [°C]

Figure 5 Percentage of hours during a year with supply temperature higher than 50°C; case of non-renovated ODUM

RESULTS AND DISCUSSION

Supply temperature curves

Figure 4 shows the supply temperature (T_{supply}) curves needed for the SH system to maintain an operative temperature (T_{op}) of 20°C and 22°C for the typical single-family house from the 1970s according to the numerical simulations. The curves represent results for the building in three different stages of envelope refurbishment and include the option of the installation of low-temperature (LT) radiators. The maximum flow in the DH network and the SH system is exceeded only in the case of "HIGHFLOW".

Figure 4 shows that reducing the desired set-point of operative temperature T_{op} from 22°C to 20°C reduces the maximum supply temperature needed by about 5°C for non-renovated and house with new windows and by 4°C for extensively renovated house. Installation of low-temperature radiators with the same high and length, just with more heat transfer plates (see Figure 4 numbers in dashed rectangles), makes possible to keep 22°C T_{op} while compared to 20°C with the radiators traditionally designed for 70/40/20 further reduces the maximum supply temperature needed by 6°C for the non-renovated house, by 3°C for the house with new-windows, and by 3°C, i.e. down to 50°C for the extensively renovated house.

Increase of flow limit to 432 L/h while keeping the original radiators in case of non-renovated house means reduction of maximal supply temperature from 78°C to 70°C and reaching the value of 50°C supply temperature already for outdoor temperature 3°C instead of 5°C.

Comparing the supply temperature curve for the example of non-renovated house heated to 22°C (dotted dark-red line) with realistic supply temperature curve obtained from DH utility in Denmark (solid grey line with squares) it can be seen, that the DH utility provides higher supply temperatures than needed for the non-renovated house from 1970, considered as the example of building defining required DH supply temperature.

Duration of increased DH supply temperatures

Reduction of the maximal supply temperature extends the possibility of supplying 50°C DH water and thus shorten the period requiring increase of supply temperature over 50°C. Figure 5 reports the duration of the period (in percentage of hours during the year) when the supply temperature needed to be increased over 50°C for all the cases investigated. The house after light renovation, i.e. with new windows can be supplied with low-temperature DH at 50°C and maintain an operative temperature of 22°C for approx. 83.5% (see Figure 5; 100 – 16.5%) of the year and needs a maximum supply temperature of 67°C (see Figure 4).

Table 1 Comparison of heating demand, peak power (P_{max}) and weighted average return temperature (T_{rw}) for all the cases investigated.

$T_{operative}$ [°C]	internal heat gains [W/m²]	T_{supmax} [°C]	RAD[a]	P_{max} [kW]	TRW [°C]	heating demand [MWh/a]	P_{max} reduction [%]	heating demand reduction [%]
non-renovated house - basic								
20	0	70.0	O	9.4	40.2	x	-	-
20	4.18	73.0	O	9.9	30.1	20.0	-	-
22	4.18	78.0	O	10.5	32.9	24.6	-6%	-23%
22	4.18	67.3	LT	10.5	27.6	24.6	-6%	-23%
non-renovated house - advanced								
22[b]	4.18	70.0	O	10.5	35	24.5	0%	0%
22[c]	4.18	78.0	O	10.5	33.1	24.6	0%	0%
22[d]	4.18	78.0	O	7.8	32.5	21.7	25%	12%
light renovation - new windows								
20	0	70.0	O	7.7	33.0	x		
20	4.18	62.0	O	7.8	27.1	14.9	21%	26%
22	4.18	67.0	O	8.3	30.4	18.4	21%	25%
22	4.18	59.0	LT	8.3	25.7	18.4	21%	25%
extensive renovation								
20	0	70.0	O	5.8	28.2	x		
20	4.18	53.1	O	5.47	24.7	9.9	45%	50%
22	4.18	57.0	O	5.80	28.1	12.4	45%	49%
22	4.18	50.0	LT	5.82	24.1	12.4	44%	50%

[a]: O = original radiators, LT = low-temperature radiators

[b]: maximum flow limit increased to 432 L/h

[c]: time delay in DH supply temperature control

[d]: simulated with "measured weather data input"

The increase in the DH supply temperature above 60°C is needed only for 1.6% of the time (140 hours). This result is based on an operative temperature of 22°C as a realistic temperature desired by customers. The operative temperature of 20°C, which is usually used for energy calculations, means the period with DH supply temperature increased above 60°C drops to 18 hours (0.2%) and the maximum supply temperature drops to 62°C. However, considering 22°C as a realistic operative temperature desired by customers is crucial for a proper evaluation of the feasibility of supplying existing buildings with low-temperature DH. Underestimation of the desired operative temperature will result in underestimation of the maximum supply temperature needed, and therefore in complaints from customers. With the additional improvements on the building envelope, such as low-energy windows and ceiling insulation (i.e. extensive renovation) and the installation of low-temperature radiators, DH with a supply temperature of 50°C will ensure 22°C operative temperature during the whole heating season.

Keeping the supply temperature curve linear but apply six hours delay for the calculation of new supply temperature when the outdoor temperature increases lead in reduction of maximal water flow in SH system from original 432L/h (flow in SH system for T_{op} set-point 22°C) to 280 L/h, which is fairly comparable with the design limit of 264L/h, but the period with supply water temperature of 50°C-60°C is increased by 12% (from 41% of the year to 46%).

The limitation of supply temperature to 70°C and allowance of maximal flow 432 L/h resulted in decrease of period with supply temperature over 50°C by 30% (from 41% of the year to 29%). Applying the real weather data input resulted in reduction of hours with supply temperature over 50°C by 10% (from 41% to 37% of the year).

Maximum heating power and average return temperature

Table 1 compares the annual heating demand, the maximum heating power (P_{max}) needed for SH system (equal to the heating power delivered by DH system), the maximum supply temperature needed, and the weighted average return temperature (T_{RW}) from the SH system for all the investigated cases. It can be seen that the light (replacement of windows with standard ones) renovation reduces in comparison to the non-renovated building the maximum heating power needed for the SH system by about 21% while the annual heating demand by 25%. The percentage reduction of maximal heat power and annual heating demand are not the same and therefore the reduction in annual heating demand can be used only as a rough estimation for the reduction in peak heat power. The similar is valid also for the case of extensive renovation (low-energy windows and ceiling insulation), just with the numbers 45% reduction for the maximum heating power and 50% reduction for annual heat demand. Both values are usually needed in relation to the connection of refurbished buildings to the DH network.

Applying the weather file measured in the real location of the house in 2009 for the non-renovated house reduces the maximum heat power needed for SH by 25% and the annual heating demand by 12% in comparison to the DRY weather file. Using an operative temperature of 20°C instead of 22°C during the design phase leads to underestimation of the DH connection heat power for SH and would lead to people feeling thermal discomfort and asking the DH utility to increase the DH supply temperature.

With regard to the DHW system, once the DH supply temperature drops below 60°C, it will always be necessary for the original DH substation for DHW heating to be replaced with a specially designed low-temperature DH substation – depending on the original design, either one using the instantaneous principle of DHW heating or one with a storage tank for DH water. The existing DHW pipes will also need to be replaced with new pipes preferably with dimension DN10, to fit the requirement that the overall volume of DHW pipes is below 3L [21], [22].

CONCLUSIONS

Single-family house built in 1970s, representing the typical example of Danish building stock, can be heated by DH to indoor temperature of 22°C during whole year without compromising thermal comfort or exceeding the design flow rate in the DH network and without any renovation measure if the DH supply temperature is raised above 60°C for roughly 8% of year (700 hours). This result shows that even under these unfavourable conditions it is possible to decrease the DH supply temperature for considerable periods during the year.

In reality, most houses from the 1970s have already replaced their original windows, which mean that the maximum value and the duration of increased DH supply temperature can be further reduced. In our example, it means a reduction from 8% to only 2% of hours in the year when the temperature is above 60°C.

By installing low-temperature radiators (with the same height and length, just increased number of convection plates), the maximum supply temperature can be reduced further to 59°C so that there is no period with a DH supply temperature over 60°C. The same supply temperature curve is also valid for the extensively renovated house (new low-energy windows and attic insulation) with the original SH system. If the extensively renovated house also replaces its space heating system with low-temperature radiators, it can then be supplied all year around with a DH supply temperature of 50°C.

The duration of periods with a DH supply temperature above 50°C is reported for an operative temperature of 22°C to model a realistic set-point temperature preferred by occupants. The durations for an operative temperature of 20°C will be shorter.

Reduction of the DH supply temperature to below 60°C does require changing DHW heat exchangers to special low-temperature heat exchangers and traditional DHW storage tanks to low-temperature DH storage tanks. Therefore DH utilities should start require replacement of existing DH substations with low-temperature DH substations already today, because this will ensure that in 20 years (the typical lifetime of a DH substation) all newly installed DH substations will be ready for low-temperature DH.

The DH supply temperature curve needs to be defined by more than two points ensuring optimal use of flow capacity of the DH network and thus minimal DH supply temperature. Operation of DH network on lower than maximal flow capacity will result in higher heat losses and poor cost-effectiveness. The alternative solution to non-linear supply temperature curve is linear supply temperature curve with time delay in increase of supply temperature when the outdoor temperature increases.

The supply temperature curve can be further shifted to lower temperatures if the maximum guaranteed DH flow rate is increased. This is documented in the example of the non-renovated house where the maximum supply temperature decreased from 78°C to 70°C while the annual weighted average return temperature increased only by 3°C. DH networks are in fact usually over-dimensioned by 20-30%, therefore additional pumps to increase the head pressure maybe not needed. This solution will therefore make it easier to integrate renewable sources of energy, but the impact on DH networks needs further investigation. However, we cannot rely on the over dimensioning.

The heating demand of existing buildings is expected to decrease linearly to 50% of its present value by 2050. This reduction in heating demand, however, will cause no difficulties, if the present DH concept is changed to low-temperature DH. The low-temperature DH concept still requires further optimisation, and more work is needed on DH network design and operation to take into account the integration of renewable sources of energy, but the low-temperature DH concept can be introduced already today because existing buildings do not represent such big problems as might have been expected.

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PERFORMANCE ASSESSMENT OF DISTRICT HEATING SUBSTATIONS BASED ON DYNAMIC SIMULATIONS

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ABSTRACT

An exemplary district heating systems is being implemented in the city of Kortrijk in Belgium, as part of a demonstration zero-carbon neighborhood. This study deals with the energy performance assessment of one of the systems component installed in this low-temperature district heating system -the consumer substation. A comparative analysis of the energy performance with several existing district heating substations was carried out. Three different district heating substation models are set up (using TRNsys) for investigation of the gross energy use, energy-efficiency and comfort issues. In order to evaluate the performance of the analyzed substations two scenarios concerning the space heating system (radiator or floor heating system) were considered. The study aims to investigate the impact of different operational circumstances on the performance of district heating substations. The study generate understandings for energy saving operational strategies to be developed. Results indicate that the design concept together with a suitable selection of the substation has an important impact on the energy performance of the entire system.

INTRODUCTION

The energy sector is central in sustainable development and it affects all aspects of development – social, economic and environmental. Precisely, environmental concerns and fuel supply security are the main driving factors behind the growth of district heating in most countries. District heating networks gain in importance, since they facilitate large scale renewable energy integration and a better matching between supply and demand [1]. A district heating system is composed of many elements, building a chain from the heat source to the heated buildings.

During the last years it has been demonstrated that low-temperature district heating (supply temperatures lower than 65°C) is the next evolution in district heating systems. Recently, the performance of two consumer units for a low temperature district heating net was investigated using TRNsys [2]. A numerical modeling and experimental measurements for a low-temperature district heating substation for instantaneous preparation of domestic hot water was presented by Marek Brand [3]. While Rämä and Sipilä [4] studied the problem on low heat density district heating network design in a representative case of a low heat density area. In this context, simulation tools play an important role for design, operational optimization, and performance evaluation of those complex systems.

Examples of district heating systems are scarcely found in the Belgian housing sector, as they were rarely implemented in the past. However in the current evolution towards renewable energy supply, district heating networks are seen as a promising solution. Therefore, in the city of Kortrijk in Belgium an exemplary district heating systems is being implemented as part of a demonstration zero-carbon neighborhood with about 200 dwellings that is under construction in the context of the ECO-Life project within the CONCERTO initiative. This study deals with the energy performance assessment of one of the systems component (consumer substation) installed in this low-temperature district heating system. In this study a comparative analysis of the energy performance with several existing district heating substation was carried out.

This paper describes the simulation model and the performance evaluation of several configuration of district heating substations. Three different district heating substation models are set up (using TRNsys) for investigation of the gross energy use, energy-efficiency and comfort issues. The building energy simulation model is used to investigate three types of dwelling substations: a direct substation type DSH -without heat exchanger in the space heating circuit and instantaneous hot water preparation-, a direct substation type DSHST -with local storage tank and without heat exchanger in the space heating circuit- and an indirect substation type ISH (without a local storage tank but with heat exchanger in the space heating circuit.

For each type of substation two scenarios regarding space heating system were analyzed: a) Radiator system; b) floor heating system. The study generate understandings for energy saving operational strategies to be developed. Results indicate that the design concept together with a suitable selection of the substation has an important impact on the energy performance of the entire system.

DISTRICT HEATING DESCRIPTION

The case-study collective heating systems are designed for a multi-family building with 25 dwellings on 5 floors. The collective heat distribution system distributes heat for space heating and domestic hot water production from a central plant in the basement to the individual apartments, which are equipped with the customer substation. For this general building and system geometry, two variants were designed with a similar energy performance of the building but different space heating system.

The analysis was carried out for a low-energy building with a heat supply temperature of 60°C to the substations and highly insulated collective heat distribution pipes. One case is the one where the space heating system is based on radiator with supply temperature of 60°C and return temperature of 40°C. The other case is the option with space heating system based on floor heating with supply temperature of 35°C and return temperature of 25°C. Both cases work with variable supply temperature in function of the outdoor condition as control strategies for space heating.

First the apartments are designed and their heat demand for space heating and domestic hot water is calculated with the Flemish building energy performance (EPB) software. Three types of apartments were designed, with different floor areas (90 to 150 m²), and different thermal performance. The resulting net energy demand for space heating of the apartments is between 15 and 30 kWh/m²/year, so the dwellings are low-energy or passive dwellings [5]. The domestic hot water (DHW) demand is equal for dwellings in both cases, since those are only dependent on the dimensions of the dwellings. Table 1 summarizes the information regarding the selected dwellings.

Table 1 Energy use for the low, normal and high profile

Type of House in the building	Num. house	Area (m²)	Volume. (m³)	Space heating (kWh/m²/year)	Hot tap water (kWh/day)
1	10	90	312	15	2.7
2	5	119	427	22	3.5
3	10	148	490	27	3.9

In the EPB calculations the monthly heating demand of the energy sectors is calculated and the monthly energy demand for domestic hot water is estimated. For the purpose of dynamic simulations with smaller time steps (30 seconds), energy demand profiles for space heating and domestic hot water were developed such that they equalise the energy demands in EPB when accumulated to monthly values.

Although a multi-family buildings is a representative case, it contains all components of a district heating system: a central plant, a distribution network and a number of dwelling substations. The distribution networks of the buildings are connected to a central heat generation plant through simple pipes. The one-way network length is *125 m*. The diameters of the pipes in the network were calculated for network layouts with 25 connected dwellings with supply pipe temperatures of *60°C*. Fluid velocities were restricted to *1 m/s* inside dwellings, *1.5 m/s* in trunks, *2 m/s* in the basement and *2,5m/s* outside [6] and [7].

In order to reduce the heat losses in the distribution system, the pipes are insulated with PUR-foam that has linear heat conductivity (*λ-value*) of *0,022 W/mK* at *60°C*. The pipes themselves are assumed to be made of copper (*λ = 401 W/mK*) and the outer casing around the insulation layer is made of polyethylene. An important function of the outer casing is to protect the pipes from direct contact with the surrounding, thus avoiding moisture damage of the pipes insulation material.

MODELLING AND SIMULATION

The network and building energy simulation model was carried out by using TRNsys software. Following, the main components in the TRNsys model are described, based on the mathematical reference user guide of TRNsys [8]. A flow mixer component (TRNsys Type11) guarantees the addition of two inlet liquid streams to one outlet stream according to an internally calculated control function. The heat exchangers (TRNSYS Type 91 and Type 5) are respectively used for space heating and domestic hot water circuits. Type 91 is a constant effectiveness heat exchanger, so the effectiveness and the inlet conditions are inputs to the type. Type 5 relies on an effectiveness minimum capacitance approach to modelling a heat exchanger. Under this assumption, it is necessary to provide the heat exchanger's *UA* and inlet conditions.

Thermal stratification in the insulated storage tank (TRNsys Type 4) is modeled by assuming that the tank consists of a number of fully-mixed equal volume segments. In the mathematical user guide of TRNsys a detailed description of the model can be found [8].

The pipe model (TESS Type 709) models the thermal behavior of the pipe by splitting the pipe in a number of fluid segments at different temperatures. The calculation of the temperature in each segment takes into account the heat losses to the environment by solving the following differential equation at every time step:

$$M_j C_p \frac{dT_j}{dt} = (UA)_j (T_j - T_{environment}) \tag{1}$$

With *UA* the overall energy loss rate from the pipe (*kJ/h*), C_p the specific heat of the fluid in (*kJ/kgK*) and $T_{environment}$ the temperature of the surroundings of the pipe (*°C*).

Direct substation type DSH

As was mentioned before, in this study three substation unit has been used. In a directly connected substation the heat is transferred to the house space heating system by the primary water flow through the internal house circuit. The direct substation type DSH is equipped with a heat exchanger for transferring heat from the network to the tap water, while the individual SH systems are supplied with hot water from the collective network (figure 1). The return pipe of the space heating has a bypass which allow regulate the flow rate in function of the heat demand and supply temperature required.

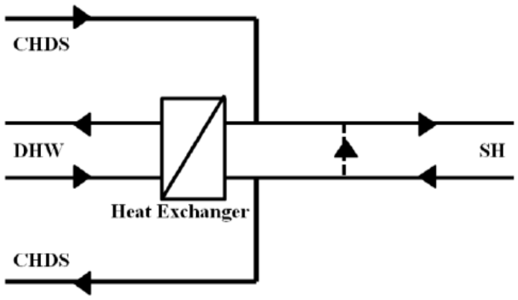

Fig. 1 Scheme of the direct system [9].

In addition to the geometrical properties of the network, the impact on the working mode of the distribution system by the control strategies of the local unit at customer side have to be considered. In the analyzed substation, a self-sensing temperature regulator indexed in the plate heat exchanger controls the hot water temperature. This measures the temperature of the hot water in the heat exchanger and automatically adjusts the outgoing flow. Besides, the control activate a minimum flow rate when the temperature drop below 50°C degrees after a long period without demand [9].

Indirect substation type ISH

In an indirect connection the secondary system is hydraulically separated from the primary side with a heat exchanger. The indirect substation type ISH have two heat exchangers for transferring heat from the primary water flow of the network to both the tap water and the SH systems. This substation presents a self-sensing temperature regulator indexed in the plate heat exchanger to controls the hot water temperature, as well. Thus, regarding recirculation control, performance in a similar way of the DSH substation.

Direct substation type DSHST

The substation type DSHST is a more complex type of substation (figure 2). Its main components are a tank for storing water from the collective part of the district heating system , a plate heat exchanger for heating tap water, a connection from the collective network to the dwelling space heating system and a bypass between the storage tank outlet and the space heating system which can be used to further reduce the temperature of the water returning to the DH network. The entire system is provided with a rather complex control system [10].

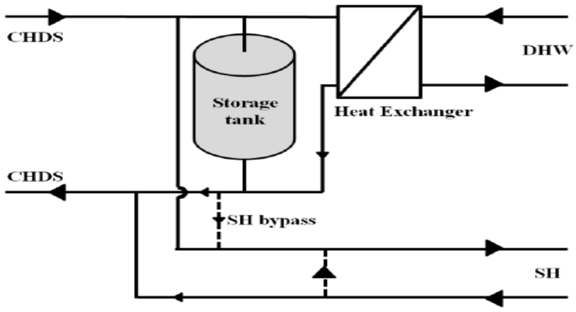

Fig. 2 Scheme of the direct system with storage tank [10].

The storage tank is filled with heating water coming from the district heating supply. On the moment that domestic hot water is wanted, heating water is extracted at the top of the storage tank and sent through the heat exchanger. The cold water returning from the heat exchanger is pushed into the tank at the bottom. When the tank is getting too cold, heating water is immediately supplied from the district heating network and return water goes immediately back to the district heating (DH bypass). During this operation mode, if space heating is required, heating water is immediately commanded at the district heating supply so heating water from the storage tank is not used for space heating. In the space heating circuit, heating water from the district heating supply is mixed with colder heating water at the floor heating outlet, in order to provide the desired temperature in the space heating circuit.

When the temperature in the storage tank is too low (because there has been a domestic hot water tap or because of the heat losses of the tank during long waiting periods), heating water from the district heating supply is led into the tank and the colder water at the bottom of the tank is led out the tank. If the temperature of the water going out of the tank is lower than the temperature in the space heating circuit, than it is immediately sent to the district heating return network. If the temperature of the outgoing water is higher than the temperature of the space heating circuit, the water is sent through the bypass and mixed into the space heating circuit. Thus, the colder heating water is further cooled down before it is sent to the district heating return. In order to guarantee a proper operation of the substation, a control strategy is imposed.

SYSTEM SIMULATION RESULTS

Simulations were made on the different levels of the district heating system, starting from the individual substation up to the distribution system. In this section, some results on the characteristics and behaviour of the substations and network are reported.

The behaviour of the individual dwelling substations is investigated with regard to the flow rate as well as to the supply and return temperature, so the district heating distribution network is not considered here. Figure 3 presents the results of the simulations for a DHS substation of the low-energy building where design temperatures for the substations are 60°C /22°C for DHW production and 60°C/40°C for space heating.

The simulation period is one day and the energy demand profile corresponds to dwelling type 2.

Results reflect the behavior of the supply temperature, red line with a trend to reach 50°C when there is not domestic hot water demand. The value increases up to 60°C when there is a heat demand, this can be seen between 6.00 and 8.00h. After this hours of demands, the gradient of temperature drop as a result of the heat losses in the substation can be observed. The orange lines represent the flow rate of space heating. It can be noticed that the system is only active during a certain period of the day. The return temperature of the total substation to the collective heating network is showed with a blue line.

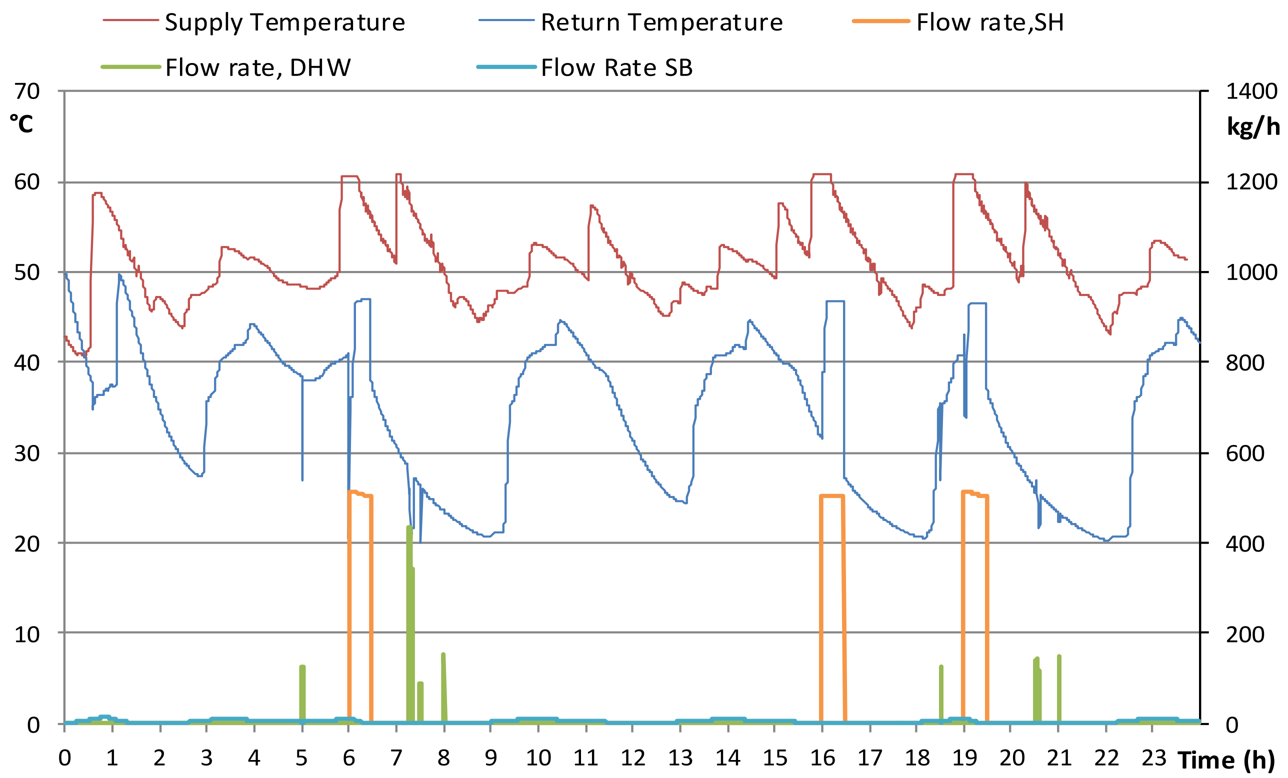

Fig.3 Supply and Return temperature at the substation of one dwellings with DHS substation

Results denote the return temperature behaviour in function of the heat demands with higher value when there is space heating demand and lower value during domestic hot water demand. When there is not domestic hot water demand for a long period the return temperature tends to rise, converging to about 40°C during recirculation.

Return temperatures from the substation to the network

In the next sections, the temperatures appearing in the distribution network are discussed. In the distribution system the temperature produced at the plant is 61°C and the design temperature at the substation is 60°C. The return temperatures from the substations of the three different dwelling types were analysed in detail, based on simulation results with a time-step of 30 s. during winter and summer conditions. In figure 4 the return temperatures from the substations are summarised per operation mode for one week simulation in January.

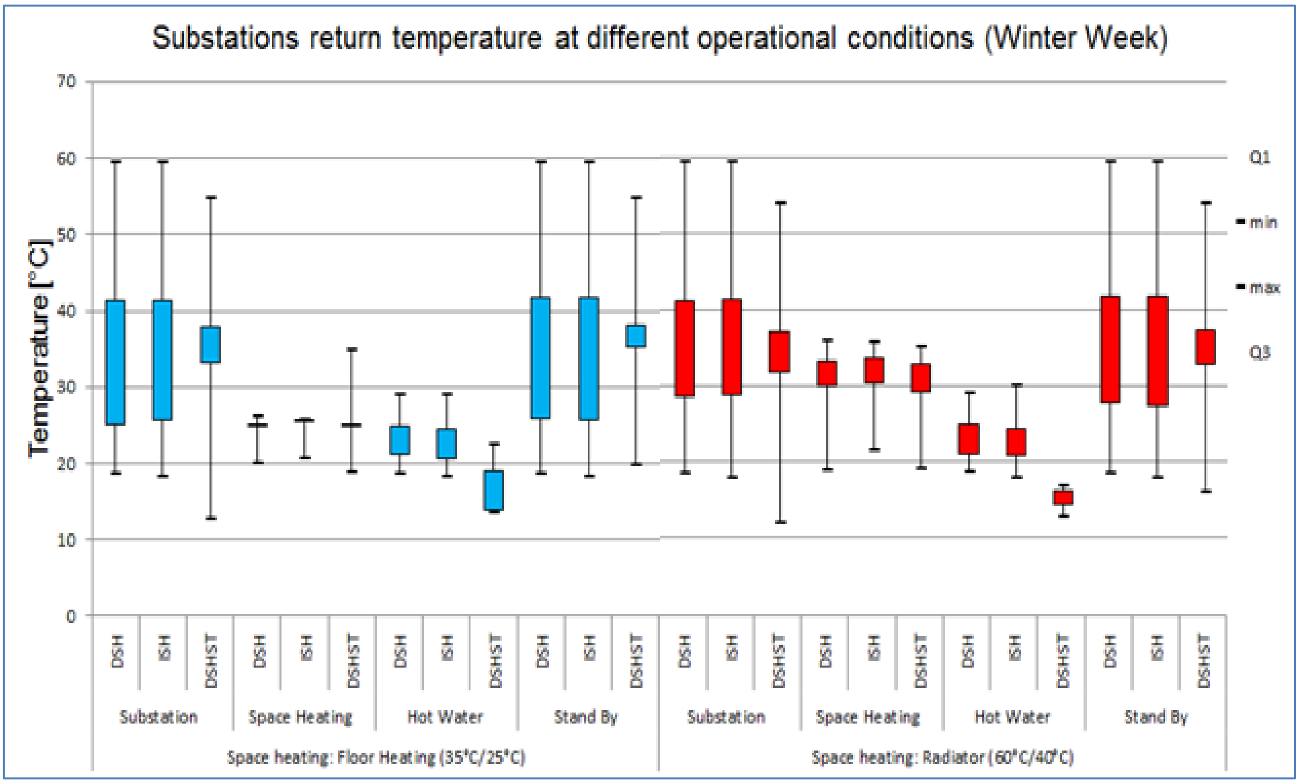

Fig.4 Return temperatures at different operational conditions radiator and floor heating for space

The results for the 3 different dwelling types were integrated, taking into account the proportions in which they appear in the multi-family building. A variable space heating supply temperature dependent on the outdoor temperature as a control strategy was considered. Two operational range of temperature 60°C/40°C (radiator) and 35°C /25°C (floor heating) for each substation were simulated.

The three variants of substation type differ with regard to the interactions between space heating control and domestic hot water circuit. In two of the analysed substations direct heating supply , DHS and indirect heating supply IHS, there are not interaction between domestic hot water and space heating circuit, so the return temperatures during hot water generation and stand-by are similar independently of the space heating system (ie., radiator or floor heating). The return temperatures during domestic hot water generation are on average 23°C and vary between 18 and 29°C. During stand-by the minimal temperature equals the minimal temperature during domestic hot water demand and the maximal temperature comes close to the district heating supply temperature at the substation. The average return temperature during stand-by is 35°C for the DHS substation and 34,5°C for the IHS system in both situation with radiator and floor heating system.

On the other hand in the substation type DHSST there is interaction between the control of both type of energy demand. As was aforementioned an important components of this substation is the storage tank for storing water from the collective part of the district heating system. Since the cold water returning from the DHW heat exchanger is pushed into the tank at the bottom and there is a bypass between the storage tank outlet and the space heating system, the influence of the entire control system is rather complex. Results denotes that the hot water return temperature is lower when using radiator as space heating system with an average value of 15 °C. In both cases with radiator and floor heating system this substation type presents lower values of hot water return temperature in comparison with other two substation types

The primary return temperature during space heating demand is on average 32°C, with a maximum return of only 36°C for the three substation when using radiator as space system. For the case of floor heating system the substation presents an average around 25°C. While the difference in return temperature during space heating is significant for both system, the overall return temperature of the substation is on average 36,5°C for the substations DHS and IHS as well as 34,5°C for the substation with storage tank DHSST in both cases with radiator and floor heating .

Temperatures in the distribution network

Figure 5, display the monthly average temperatures in the supply (blue) and return (green) pipes of the heat distribution system, from the pipes near the central plant (darkest colours) to the substation connection pipes (lightest colours) for the case of substation type DHS. The heat generation plant provides a temperature of 61°C to the distribution network. The yearly average temperature of the first supply pipe of the network (TSPO) is almost 61°C, and the hourly temperatures in this pipe are always between 59 and 61°C. Due to heat losses to the pipe environment, the monthly average temperature in the next supply pipes will decrease. Figure 5 shows clearly that the more distant a supply pipe is from the plant, the lower its monthly average temperature. In the substation supply connection pipes (TS1F1 to TS1F5), the monthly average temperature is between maximum 55°C in winter and minimum 50°C in summer. The lower averages during summer appear as a result of the cooling down of the network pipes when the substations are in stand-by mode. The hourly average temperatures of these pipes are between 45°C and 60°C, and thus despite of their low monthly average temperatures, the space heating design supply temperature of 60°C can also be obtained in the most distant substation connections when needed.

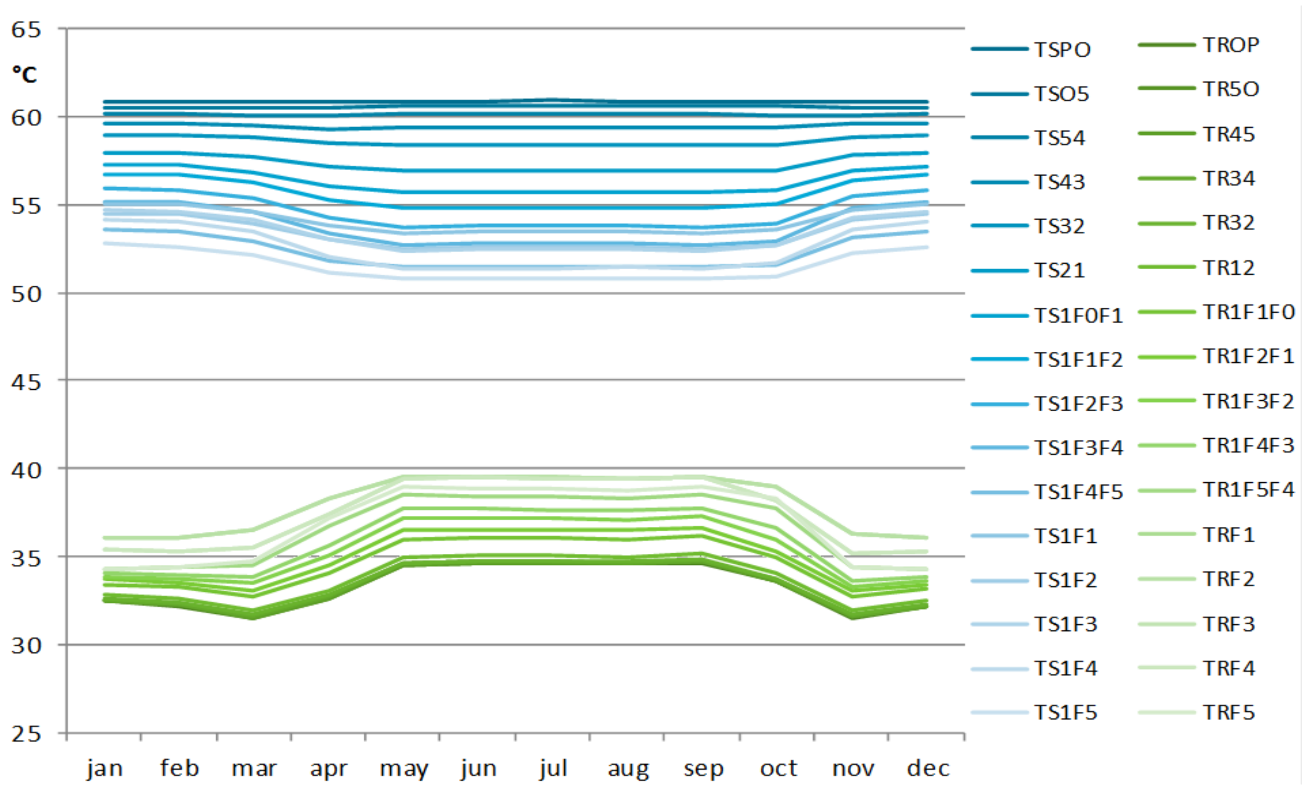

Fig. 5 Temperatures in Supply and Return pipes from main pipes (in dark) to substation connections (light)

The return temperatures from the substations (TRF1 to TRF5) are dependent on the space heating and domestic hot water demand profiles. As a result, the hourly average return temperatures vary between 19°C and 49°C, leading to monthly average return temperatures of minimum 34°C in winter and maximum 39°C during summer (averaged over the three profiles). Cooling-down of the network finally leads to return temperatures at the central plant of around 33°C in winter and 35°C in summer.

Heat losses in the distribution network

Figure 6 illustrates the distribution heat losses for the different variants analysed. The heat losses are higher in winter than in summer, as a result of the higher temperature of the heating medium and the lower temperature of the pipe environment. However since the seasonal temperature variation both inside and around the pipes is not that big (the pipes are located in an unheated part of the building, not outside), the differences between summer and winter season are smaller than 15%. The differences between the system with the substations without storage tank, thus instantaneous preparation of domestic hot water and the one with storage tank remind somewhat about 12% and it is related to the reduction of the pipe diameter in the distribution network and the decrease of flow rate requirement during operation when a storage tank is used.

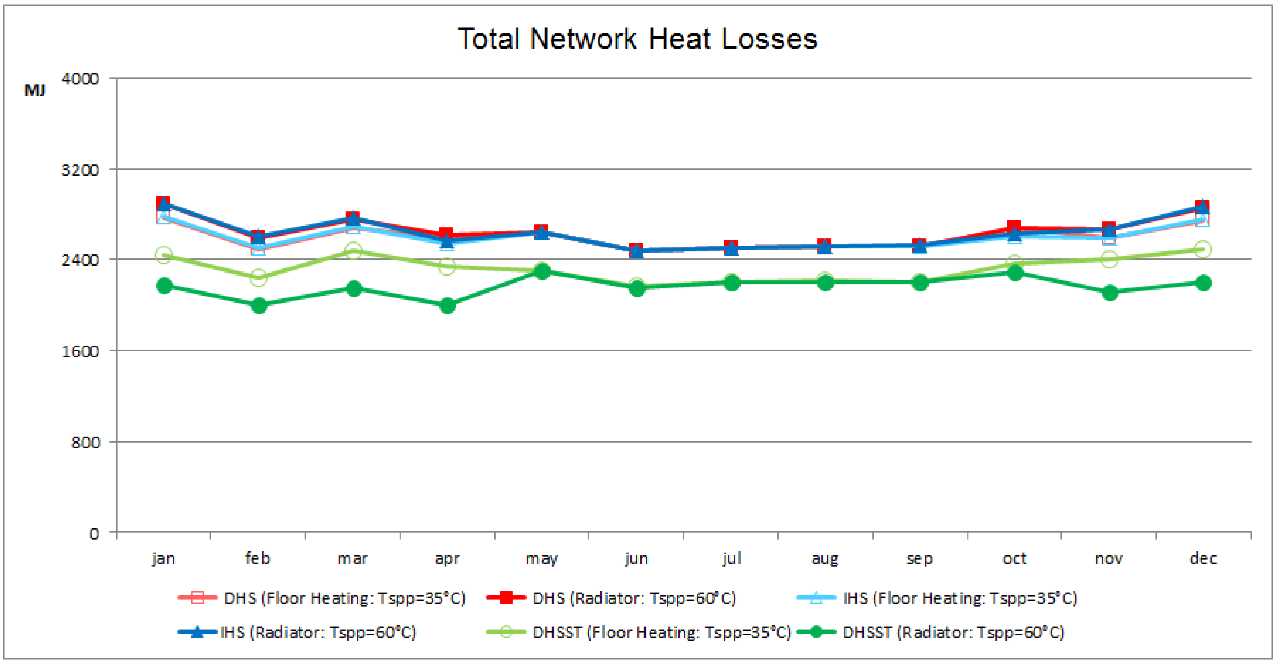

Fig. 6 Heat losses in the distribution network

It can be clearly seen that for the two substations with instantaneous hot water production, DHS and HIS, during the summer there is not difference of the heat losses when a different space heating system is used. Similarly occur with the substation DHSST during summer, where the losses are equal independently that radiator or floor heating is used. An interesting behaviour can be identified during winter in the case of the substation with storage tank. Two elements of the heat losses during winter for the case of DHSST are remarkable. Firstly a reduction of the heat losses somewhat about 15% when a radiator is used with respect to the heat losses when floor heating is installed. An explanation of this behaviour can be on the combination of the effect of increased operational temperature difference between supply and return of the space heating for the two analysed system. Noted that when radiator is used the difference is twice that those for the floor heating. Similar explanation can be used to understand the difference between winter and summer in the case DHSST with radiator. In addition to the significant reduction of the flow rate as a result of a larger temperature difference during winter, the increase of the recirculation during summer due to larger period of stand by without demand contribute to rice the heat losses in the summer. As a result of more recirculation the average temperature in the return pipe network increases causing an increase of the heat losses, as well.

Hot water comfort

Takes into account customer satisfaction becomes an important element when evaluating district heating substation performance. Therefore, beside to the gross energy use and energy-efficiency of the different studied substations, comfort issues were also investigated. The domestic hot water comfort is calculated as the mass flow rate that is withdrawn at temperatures above 40 °C divided by the total hot water consumption. The three studied substations presents a high level of hot water comfort reaching values around to 98% of comfort in all the different alternatives analyzed. In addition to the temperature conditions, customer comfort satisfaction is influenced by time required for DHW to reach a fixed temperature level after tapping was started, the so called waiting time. This parameter is also known as recovery time or tap delay. Based on the European standard EN 13203-1 [11], the waiting time t_m *(s)* is defined as the time taken to reach, at appliance outlet, a domestic hot water temperature higher than 44°C. Figure 7 presents an evaluation of this indicator for the three different dwelling studied. The graphic show the temperature of tap water deliveries at each substation after a long period without hot water demand.

It can be clearly see that the three substations guarantee temperature higher than 50 °C between the first five second. The substation DHSST presents a lower value of waiting time and the stability delivery temperature is more rapidly reached. Substations with instantaneous hot water production, DHS and IHS presents a quite good performance, as well.

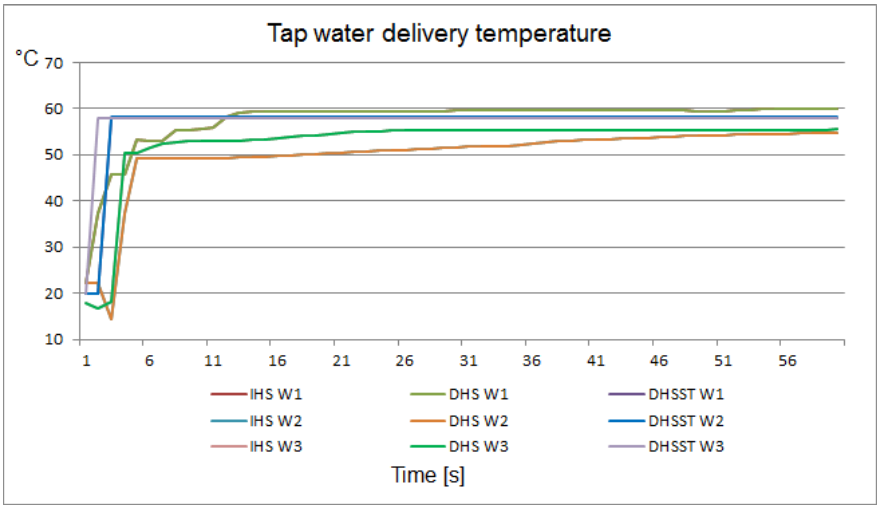

Fig. 7 Substations Tap water deliveries temperature

CONCLUSION

The study aims to investigate the impact of different operational circumstances on the performance of district heating substations. Results indicate that the design concept together with a suitable selection of the substation has an important impact on the energy performance of the entire system. Regarding heat losses in distribution network the substation with storage tank performance better that those without storage tank. However, for a whole view of the efficiency aspect the losses in the storage tank should be taken into account. In addition economical consideration should also be studied in order to evaluate if the heat losses reduction as well as the reduction on pipe cost presented when installing a substation with storage tank compensate the increases of the initial investment as a result of the substation cost. From the comfort point of view the three substation performance in a satisfactorily way.

ACKNOWLEDGEMENT

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ON DISTRICT HEATING AND COOLING RESEARCH IN CHINA

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ABSTRACT

The growth of the Chinese district heating sector has been very rapid during recent years. No other country in the world can show the same rapid growth of district heating systems during the last decades. Heated building area increased six times between 1995 and 2008 according to the Chinese district heating statistics. China has also enjoyed strong growth of scientific articles and papers published about district heating in recent years. During 2010-2012, one third of all international scientific journal articles and conference papers about district heating came from Chinese scientists, while Swedish researchers accounted for one quarter. It is important to identify the Chinese district heating and cooling research to judge the potential for future collaborative research on district heating systems between Sweden/Europe and China. Until 2013, Chinese district heating and cooling scientists have published 205 international publications on district heating and 36 publications on district cooling. In this paper, these articles are mapped and summarised with respect to topics, active research institutions, and their technology focuses. Another approach is to grasp the Chinese interest for more diversified heat supply, since many new systems are established and thereby have more degrees of freedom when choosing by various heat supply and technology options.

INTRODUCTION/PURPOSE

China is the second largest building energy user in the world, ranked the first in residential energy consumption, the third in commercial energy consumption [1], and the highest ranks in CO_2 emission, about 27% of world's CO_2 emission in the world [2]. The average annual growth rate of CO_2 emission from urban district heating has been 10.3%, it was responsible for 4.4% of China's total CO_2 emission in 2009 [3]. Coal is the primary fuel in Chinese heat supply. About 40% of the air pollution in China came from coal dust [4]. In order to improve energy efficiency and reduce CO_2 emission, many scientists work within the field of district heating and cooling system.

The growth of the Chinese district heating sector has been very rapid during recent years. No other country in the world can show the same rapid growth of the district heating during the last 10-15 years. Heated building area and total pipe length increased 8 and 17 times, respectively, between 1995 and 2012 according to the Chinese district heating statistics [5]. In many respects, the technology used in China is similar to the technology in Scandinavian, which is characterized by high quality and has been a prerequisite for district heating high market shares in Sweden, Denmark and Finland.

In the 1950s, both China and Sweden started to build district heating systems. Denmark became the guiding example for Sweden, while the former Soviet Union became the guiding example for China. Both these guiding examples started their first district heating systems in the 1920s. One important feature of Danish district heating was customer heat demand control and flow control in each substation. This feature gave automatically a proper flow allocation. The Russian systems lacked this feature, and worked with balancing valves creating average constant flow in the system. This Russian principle is a major drawback in system functioning, giving severe flow allocation problems.

The huge amount of district heating comes from both Combined Heat and Power (CHP) and boilers in China, about half of each. The heat supply from CHP and boiler continues increased by year to year. In Sweden, the CHP accounted for 45% of the supplied district heating in 2011 [6]. In recent years, the interest on biofuel based CHP has increased in Sweden, while China will transfer coal boilers to natural gas boilers with higher efficiency. More than half of the heat supply to district heating systems in Sweden came from biofuel and waste, while the fuel used in China is still dominant by coal.

China has become the largest national air conditioning equipment market in the world, the annual growth rate of urban households have been very high during the last 10-15 years [7]. In Sweden, district cooling is used mainly in offices and business premises and for cooling some industrial processes.

To our knowledge there is no organised research cooperation between China and Sweden for district heating system and district heating technologies.

The purpose of this paper is to identify the Chinese district heating and cooling research to judge the potential for future collaborative research on district heating systems between Sweden/Europe and China.

STATE OF THE ART

Sweden has had district heating research since 1975 in various research programs, but most of them were written in Swedish, making them unknown for foreign researchers. Also many Chinese research projects are unknown in Europe. There should be a future value for the Swedish/European district heating sector to undertake a benchmarking against the rapidly growing district heating sector in China. Many newly built Chinese district heating systems have had more degrees of freedom to consider in their expansion, while old systems have been locked in their technology choices. The existing Swedish district heating systems have a very strong market position with more than half of all Swedish building spaces connected after 60 years of expansion, giving less degree of freedom for the future. An important issue for a benchmark is how the technical choices influence the district heating research in China and Sweden/Europe.

The two major research questions identified are:

- What can Sweden/Europe learn from Chinese district heating and cooling experiences?
- What can China learn from Swedish/European district heating and cooling experiences?

METHODS/METHODOLOGY

The Scope scientific search engine was used for the analysis of the current district heating and cooling research in China. Articles written by Chinese district heating and cooling scientists in international scientific journals have been mapped according to markets, demands, loads, supply, environmental impact, distribution technology, substations, system functioning, as well as economics and planning. These articles have been evaluated and summarised in order to draw conclusions.

RESULTS: PAPERS ON DISTRICT HEATING AND COOLING

International analysis

Between 1970 and 2013, 5627 international scientific publications have been written about district heating and 278 for district cooling, according to the scientific search engine Scopus, as shown in Figs 1-2.

Numbers of district heating publications from Germany are in first place since the journal Euroheat & Power (formerly Fernwärme International) has been published district heating articles for more than 40 years in Germany. The district heating articles from Sweden are still in the second place over countries since 1975, USA comes to the third place, and China is in the fourth place. However, one third of all international district heating journal articles came from Chinese scientists during 2010-2012.

Numbers of district cooling publications from USA are in the first place since ASHRAE Transactions is published in USA. China is in the second place during 1970-2013, followed by Malaysia, Germany and Sweden. This means that the Chinese academic researchers are supporting the expansion the Chinese district heating and cooling systems by their increased number of publications.

Analysis of Chinese district heating papers

Chinese authors have written 232 of the 5627 publications about district heating according to the Scopus scientific search engine. However, 16 are non-district heating papers and 11 are only about district cooling, since the Scope scientific research engine seems to regard the labels 'heat generation', 'heat source', and 'heat load' as 'district heating', so the total number of publications becomes 205 as shown in Table 1. 28% of the district heating papers have been published in conference proceedings and 27% in the international journals in Elsevier, of which 19% are published in the Elsevier energy journals, such as Energy, Energy policy, Applied Energy, and so on. Many universities in China have also their own journals, so 20% of the district heating papers have been published in these kinds of journals.

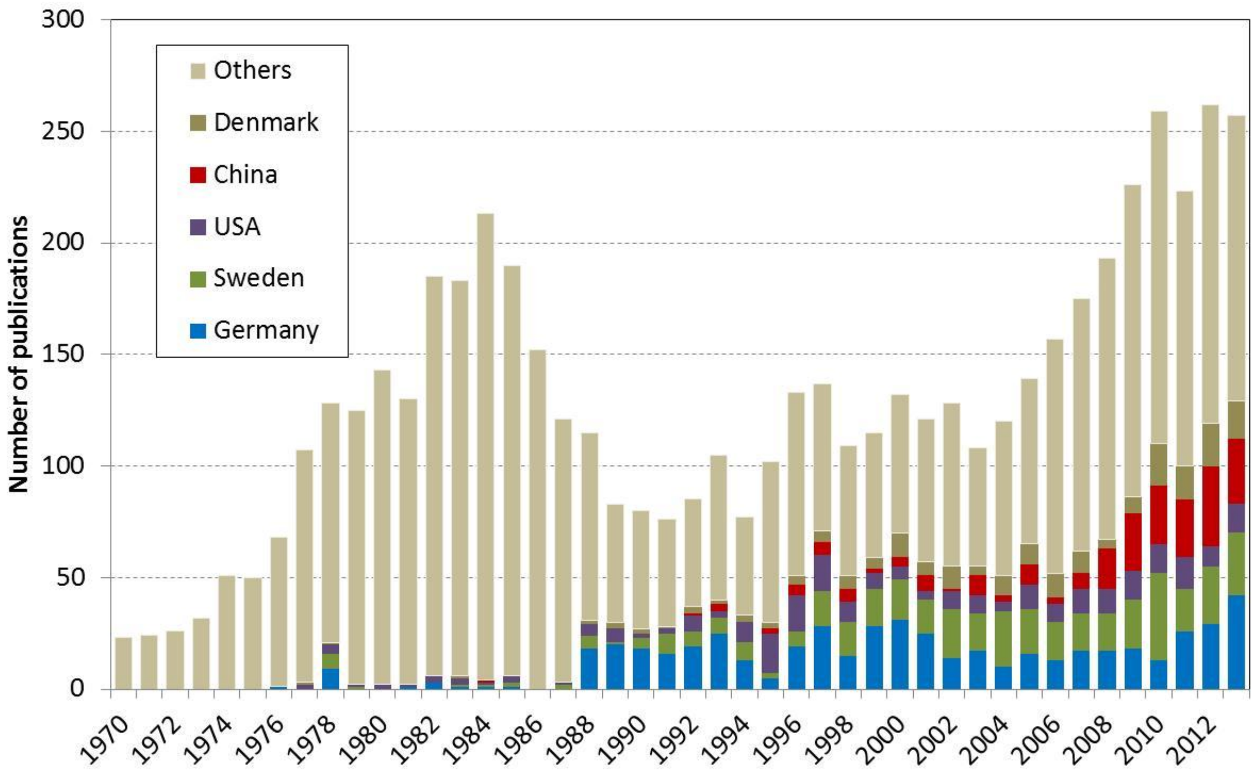

Fig. 1 Published articles and other papers with the 'district heating' label 1970-2013 by country affiliation. (Data from the Scopus scientific search engine)

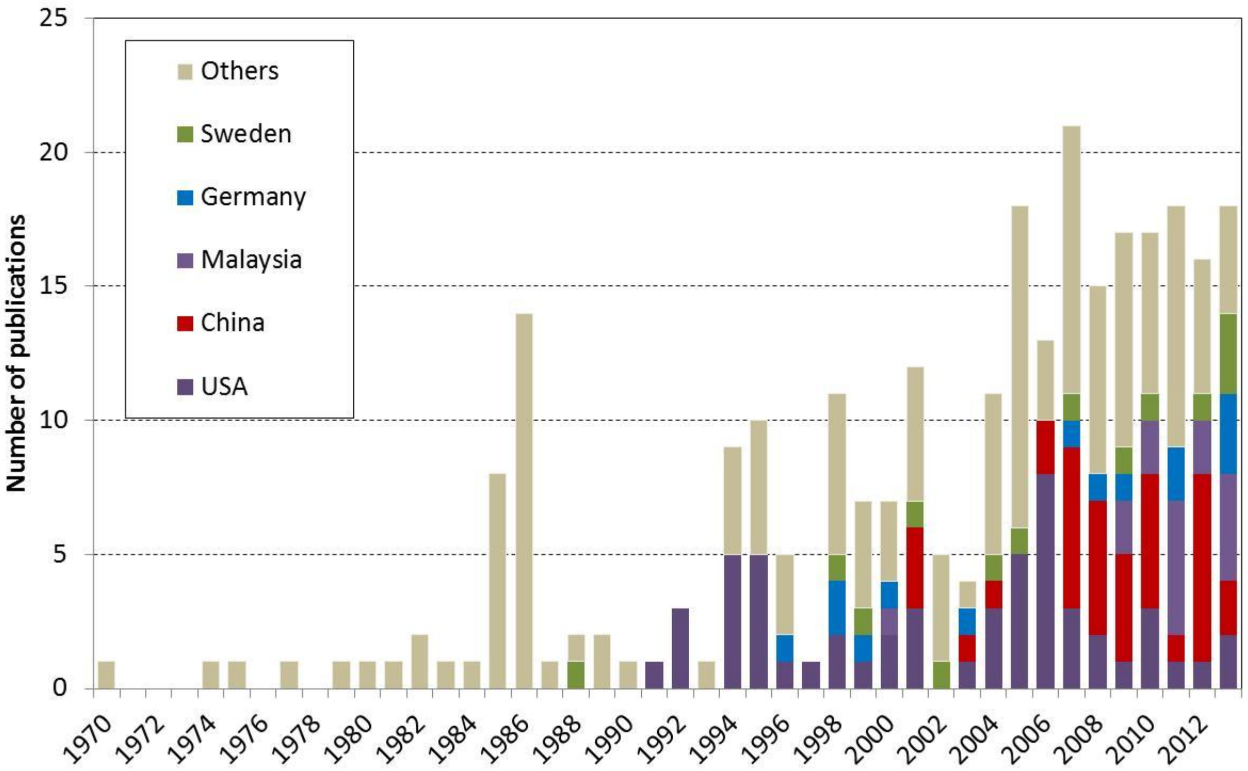

Fig. 2 Published articles and other papers with the ‘district cooling’ label 1970-2013 by country affiliation. (Data from the Scopus scientific search engine)

The first international district heating paper [8] by Chinese researcher was published in the special workshop issue of The International Journal of Energy in 1984. Eight years later, the second international district heating journal paper [9] was published. These two papers focused on heat from nuclear energy for district heating.

The chapters in the textbook “District Heating and Cooling” [7] have been used as subject classification to analyse these papers. The chapter numbers in Table 1-2 are:

Chapter 3: Energy, heat, and cold markets

Chapter 4: Heat and cold demands

Chapter 5: Heat and cold loads

Chapter 6: Heat and cold supply

Chapter 7: Environmental impact and opportunities

Chapter 8: Heat and cold distribution technology

Chapter 9: Substations

Chapter 10: System functioning

Chapter 11: Economics and planning

The identified papers are dominated by 81 papers about heat and cold supply methods, since many old inefficient and high pollution coal-fired boilers need to be replaced, and 49 papers focus on system functioning, as shown in Table 1.

Publications on energy, heat, and cold market are very few, since the Chinese district heating systems by tradition have been part of the welfare system without competition in heating market. Another low focus research field is on heat and cold distribution technology; all 5 papers have been published since 2009. The earlier technology was based on former Soviet Union standards, and this need to be improved with new enhanced technology. Recently, three papers on heating meter reform have been published, since Chinese district heating systems are expected to turn from public welfare systems into commercialized systems.

Table 1 Publications of district heating by Chinese research according to the chapters in [7]. (Data source: the Scopus scientific search engine)

Count of CH										
Year/Chap.	3	4	5	6	7	8	9	10	11	Total
1984				1						1
1992				1						1
1993	1			2						3
1995				2						2
1996				3				1	1	5
1997				4				2		6
1998				5	1					6
1999				1				1		2
2000				2				2		4
2001				3				2	2	7
2002									1	1
2003	1	2		6						9
2004				1				2		3
2005			3		1		2	3		9
2006				2				1		3
2007		1		2				2		5
2008			2	5			3	1	1	12
2009		1	3	7		2	3	5		21
2010			1	12	2			5		20
2011	1	2		7	4		3	5	1	23
2012	1	3		9	1	1	6	10	2	33
2013		3	2	6	7	2		7	2	29
Total	**4**	**12**	**11**	**81**	**16**	**5**	**17**	**49**	**10**	**205**

Analysis of Chinese district cooling papers

According to the Scopus scientific search engine, 37 of 278 publications on district cooling were written by Chinese researchers, one of them was a non-district cooling paper, so the total number of papers by Chinese researcher became 36, as shown in Table 2. The number of papers on heat and cold supply method and system functioning are equal, about 28% each, together account for more than half of publications. The publications on substations and planning are the third and fourth places.

Table 2 Publications of district cooling by Chinese research according to the chapters in [7]. (Data source: the Scopus scientific search engine)

Count of CH								
Year	**4**	**6**	**7**	**8**	**9**	**10**	**11**	**Total**
2001		3						3
2003			1					1
2004						1		1
2006				1	1			2
2007		2			1	1	2	6
2008					1	3	1	5
2009		1		2			1	4
2010	1	2			1	1		5
2011						1		1
2012		2			2	1	1	6
2013						2		2
Total	**1**	**10**	**1**	**3**	**6**	**10**	**5**	**36**

Most active district heating and cooling research institutions

However, the Chinese researchers working on district heating and cooling systems are spit into many affiliations. During the recent four years, the total publications from the top five universities are almost equal to the rest of the universities. Figure 3 and Figure 4 show the top five most published district heating and cooling university affiliations in China during 1990-2013, respectively.

District heating researchers at Tsinghua University are the leader in this field, accounting for 28% of total Chinese district heating publications. They were dominant five years ago. However, during recent five years, the publications at other universities have expanded faster, especially at Harbin Institute of Technology. The total number of publications at Harbin institute of technology has grown from third place during all years to the second place during 2010-2013.

Out of 64 papers totally from Tsinghua University in Beijing, 39 papers were related to heat and cold supply, 9 papers on system functioning, and 7 papers on substations.

Out of 24 papers totally form Harbin Institute of Technology, 10 papers were related to system functioning, and 7 papers on heat and cold supply.

The total number of district cooling publications is low compared to district heating. Most publications came from Tongji University in Shanghai, followed by Tsinghua University. Prof. Long Weiding took part in all 8 publications on district cooling at Tongji University. Most of these publications were related to optimization of pipe networks and community energy planning. A district cooling and heating system named regional distributed heat pump energy bus system was introduced by [10, 11] in order to achieve maximum urban energy efficiency, and to use clean energy, renewable energy sources, and end-use energy saving.

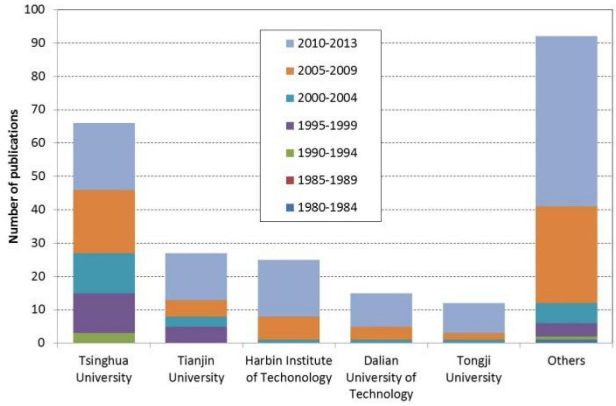

Fig. 3 Published articles and other papers with the 'district heating' label 1970-2013 by University affiliation. (Data from the Scopus scientific search engine)

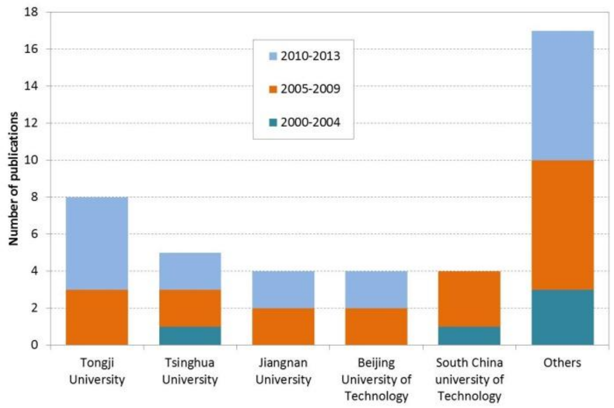

Fig. 4 Published articles and other papers with the 'district cooling' label 1970-2013 by affiliation. (Data from the Scopus scientific search engine)

RESULTS: RESEARCH AREAS

The topic of heat and cold supply methods are the most interesting subject for Chinese researchers during the analysed years. The system functioning topic was the second most interesting area after 1996. Recently, substation technologies grasp the Chinese researchers' interest as well.

Heat and cold supply

Table 3 summarise papers about heat supply methods during 1984-2013. Early papers on heat and cold supply are mostly related to nuclear energy, later research focus more on renewable energy sources, such as geothermal and solar heat. Waste heat from thermal power plants (combined heat and power) and industrial processes are recently focused on. Boilers generate about half of all heat supply in district heating systems, but there was only one paper [12] published in 2011 on analysing 472 heating boilers in Tianjin. The statistics from these boilers showed very low energy efficiency. Heat pumps and CHP are the main direction of the development, as well as Combined Cooling Heating and Power (CCHP). The recently published papers on heat supply method align with most of the five current, suitable, strategic local heat and fuel resources for district heating. These five strategies are CHP (usable upgraded excess heat from thermal power station) plants, waste-to-energy plants (usable heat obtained from waste incineration), usable excess heat from industrial processes and fuel refineries, fuels that are difficult and bulky to handle and manage in small boilers, and natural geothermal heat sources [7].

Recent publications on heat pumps are the number one topic among the heat supply methods. Li et al. [13] proposed a district heating system based on distributed absorption heat pumps in order to supply low-grade renewable heat directly in the substations. It can save primary energy supply by 23-46% compare to conventional district heating systems. Ying & Yufeng [14] describes the dilatancy technology of district heating system with high-temperature heat pump to enhance the capacity of district heating system, to increase the temperature difference, to reduce the diameters and the initial investment of primary side network, and to save the operation consumption of circulating pumps.

Table 3 Summary of papers about heat supply methods in district heating systems during 1984-2013.

Heat supply	1984	1992	1993	1995	1996	1997	1998	1999	2000	2001	2003	2004	2006	2007	2008	2009	2010	2011	2012	2013	Total
absorption							1														**1**
bioenergy																	1		1		**2**
boiler																		1			**1**
CCHP									1	1										1	**3**
CHP			1						1						2	2	2	2	2	1	**13**
flue gas condensation															1						**1**
geothermal					1	2	2	1			2	1	1		2		1		1		**14**
heat pump											2		1	2		4	8	3	4	1	**25**
industrial waste heat																		1		1	**2**
mulitiple heat sources											1								1		**2**
nuclear	1	1	1	2	2	2	2			2	1					1				1	**16**
solar																				1	**1**
Total	**1**	**1**	**2**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**6**	**1**	**2**	**2**	**5**	**7**	**12**	**7**	**9**	**6**	**81**

Zhang et al. [15] proposed an ejector heat pump-boosted district heating system with CHP in order to recover waste heat from circulating cooling water in the CHP plant and to improve the heating capacity of existing district heating systems with CHP. Sun et al. [16] developed a new waste heat district heating system with CHP based on absorption heat exchange cycle in order to increase the heating capacity of CHP through waste heat recovery and reduce district heating cost.

A number of heat pump district heating systems using renewable/free energy source have been analysed, such as geothermal [17-19], seawater [20-25], lake water [26], ground water and sewage [27].

Chen et al. [28] proposes that heat pump heating serves as a replacement for urban district heating, in result the replacing coal-based urban district heating with heat pump heating decreases energy consumption and CO_2 emission by 43% in the heating sector, however, there is no explanation on how to calculate CO_2 emissions in this paper.

Geothermal is one of the important research topics on the heat supply method. Six early publications on geothermal are related to indirect geothermal district heating systems and plate heat exchangers. Later, Lei & Valdimarsson [29] used a dynamic simulation model to optimize geothermal energy with temperature 70-90°C heating system in Tianjin. Gao et al. [30, 31] applied large-scale ground-source/coupled heat pump to access geothermal energy for a district heating and cooling system in Shanghai. Zheng et al. [32] propose a comprehensive and systematic operation strategy for a geothermal step utilization heating system in order to utilize geothermal energy efficiently.

Two papers on industrial waste heat are related to low temperature industrial waste heat sources. The universal design approach to industrial-waste-heat based district heating is proposed by Fang et al. [33] with a case study.

No paper was found with search word "waste incineration" and "district heating" from Chinese researchers according to the Scopus scientific search engine.

System functioning

First international paper on system functioning [34] was published on water leakage and blockage detection in 1996 according to the Scopus scientific search engine.

The heritage of the Russian principle with calculated balancing of heat distribution networks is still major problem in China, giving misallocations of heat deliveries to customers. Some buildings are overheated, solved by using open windows, while other buildings are underheated giving low indoor temperatures and critical customer viewpoints. These problems must be solved if payments for heat deliveries should be based on actual heat use based on heat meter readings. The number of articles about system functioning can be tracked to these major flow allocation problems in the Chinese district heating systems.

Some papers focused on analysis and optimization of networks, such as [35-38]. Some models on pipeline network with multiple heat sources were proposed, e.g. hydraulic model of looped pipeline network [39, 40]; object oriented based method [41].

The traditional regulation methods include quality regulation, quantity regulation, intermittent regulation etc. are all static regulation methods without considering the thermal inertia of the heating systems and buildings.

By tradition, Chinese district heat deliveries have been invoiced by the building spaces connected. Due to the heat meter reform, Chinese district heating systems are introducing heat meters and customer control systems in the buildings.

The application of thermostatic radiator valves has become popular. Yan et al. [42] investigated consumer behaviour including regulation of thermostatic radiator valves and opening of windows and its influences on the hydraulic performance and energy consumption of individuals and the whole system. They concluded that 30% deduction of the pump consumption with 10% deduction of the flow rate and 10% energy savings with the heat metering billing systems.

Liu et al. [43] compared the pros and cons of several metering methods, these methods charge fees according to heat-allocation meters on radiators, heated areas (traditional way), hot water meters in each household (volumetric meter), calorimeters in each household, and room temperature. After comparison, they proposed a new method that the total heating fee of a building is allocated according to the accumulated on-time (on/off valves) as well as the floor space of each household.

DISCUSSION AND SUMMARY OF RESULTS

Chinese researchers have achieved an impressive growth of number of papers published on district heating and cooling during the recent years compared to all papers published internationally.

Many Chinese research groups are represented in the literature survey. Tsinghua University is the dominant research group among Chinese district heating and cooling researchers, but Harbin Institute of Technology have expanded their publication rate rapidly during recent years.

The large Chinese interest of various heat and cold supply methods as CHP, CCHP, and heat pumps can be seen as an introduction to the required transfer from coal-fired CHP plants and boilers to other heat supply options, including using natural gas as fuel. However, no paper on waste incineration with heat recovery and only two papers on industrial heat recovery were identified in the literature analysis. Several Swedish cities use the heat from waste incineration as base load heat supply, since dumping combustible waste and organic waste was prohibited in 2002 and 2005.

With respect to system functioning, China has an important future challenge of installing customer heat control and flow control in substations in order to eliminate the flow misallocations in the heat distribution networks. New regulation methods are required considering all important parts: heat sources, heat networks, substations, and heat users.

A successful district heating and cooling manager must always minimise both the heat generation costs and the heat distribution costs in order to compete in the heating and cooling market. Earlier, the district heating systems in China were welfare systems, now with the implement of heat reform in 2003, new methods on heating fee are suggested. In Sweden, the district heating systems were commercial from the beginning and have very good market experience.

OUTLOOK

This paper is a short intermediate report from an ongoing assessment project. It will be followed by a study tour to China and discussions with four Chinese universities active in district heating and cooling research. The results from the Scopus scientific search engine show the structure of the district heating and cooling research in China. However, it is not the whole truth. More detailed studies should be made.

CONCLUSIONS

This paper has mapped scientific papers written by Chinese researchers about district heating and cooling. Some answers to the two corresponded research questions are:

What can Sweden/Europe learn from Chinese district heating and cooling experiences?

- Technologies on CCHP
- Hybrid systems of CHP and heat pumps

What can China learn from Swedish/European district heating and cooling experiences?

- Customer control systems for both heat demands and flow, giving automatic flow allocations in networks, are well developed in Sweden as well as the price of the district heat is competing with other source in the heating market.
- Multiple heat sources are easy to implement in district heating systems with customer control systems. Hence, almost perfect merit order heat supply can be applied. Hereby, various heat sources as waste incineration, biomass, heat pumps, and CHP at different locations can be utilised in the same distribution network.

ACKNOWLEDGEMENT

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SESSION 11

Resource efficiency and environmental performance

HEAT LOSSES IN COLLECTIVE HEAT DISTRIBUTION SYSTEMS: AN IMPROVED METHOD FOR EPBD CALCULATIONS

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ABSTRACT

Heat losses in collective heat distribution systems can be reduced significantly in well-insulated and well controlled low-temperature networks. However, this reduction is not always rewarded for in legislative energy performance of building standards in Europe, since the applied simplified calculation methods can overestimate the distribution heat losses significantly, especially in those systems that distribute heat for both space heating and domestic hot water generation. Therefore in this paper, a general approach for the development of more accurate simplified heat loss calculation methods is proposed in the context of the EPBD-legislation. The approach is applied for the development of simplified calculation methods for a specific type of collective heat distribution system design and evaluated by comparison to dynamic simulation results for a case-study. The results demonstrate that using the proposed approach, it is possible to make good estimations of the yearly and monthly distribution heat losses in the system, by using a limited amount of input data from the EPBD calculations and design data from the network, thus avoiding the need for detailed dynamic simulations or in situ measurements.

INTRODUCTION

In the current evolution towards renewable energy supply in buildings, collective heat distribution systems (CHDS) are a promising solution for the distribution of renewable heat from a central generation plant to the heat consumers. The more so as distribution heat losses can be reduced significantly in well insulated and well controlled low-temperature networks. However, this reduction is not always rewarded for in the simplified heat loss calculation methods of the Energy Performance of Building Directive (EPBD) implementations in Europe, for example in Belgium, thus preventing the application possibilities of collective heat distribution systems and district heating.

In a previous study, simplified heat loss calculation methods (SCM) were compared to dynamic simulations (DSM) of a collective heat distribution system providing heat for both space heating (SH) and domestic hot water (DHW) production. Results showed that the simplified calculation methods largely overestimate the heat losses and possibilities to reduce this gap were explored [1]. The purpose of this study is to develop an improved simplified heat loss calculation method for a specific type of substation and network control, with no need for input data from dynamic simulations or measurements, using an approach that suits the EPBD calculations and, more specifically, is applicable to the Belgian EPBD calculation method.

The paper starts with an introduction to heat loss calculation methods in the context of the EPBD and the conclusions and perspectives from the previous study. Then the methodology of this study is explained: a dynamic simulation model of a collective heat distribution network, substations, a control system and EPBD-based energy demand profiles was developed and calibrated with lab test results of the substation. The heat losses in the system were also calculated using the Belgian EPBD heat loss calculation method. Finally, the dynamic simulation results are used to investigate improvements to the simplified calculation method.

STATE OF THE ART

In calculations of the energy performance of buildings in Europe according to the EPBD, the heat losses in collective heat distribution systems are usually incorporated. If the energy performance is calculated per month, the calculation of heat losses in the distribution network is based on the general formula:

$$Q_{loss,net,m} = t_{net,m} \times \sum_j (\theta_{net,m} - \theta_{amb,j,m}) \times \left(\frac{l_j}{R_{l,j}}\right) \; [MJ] \quad (1)$$

in which $t_{net,m}$ is the monthly operation time of the distribution network, $\theta_{net,m}$ is the monthly average temperature of the heat conducting medium in the network, l_j is the length of a pipe element *j*, $R_{l,j}$ is the linear thermal resistance of this pipe element and $\theta_{amb,,j,m}$ is the average temperature of the pipe environment. The parameters in the general equation (1) are defined according to the local legislative EPBD-implementations and standards and to the type of system. Dependent on the final use of the heat, three types of CHDS are recognised: systems that serve heat for space heating only, for domestic hot water only and for combined space heating and domestic hot water production. In this last type of systems, the collective heat is used to generate domestic hot water in the local substations.

In a previous study, the simplified heat loss calculation methods used in the Flemish (Belgian), Dutch and

European standards were reviewed [1-6]. It was found that the few available SCMs for combined SH and DHW production are not well adapted to the specificities and the design of this type of systems. Therefore the Flemish SCM was compared to the dynamic simulation results of a low-temperature CHDSs for both SH and DHW with different types of substations and network control strategies. It was found that the SCM largely overestimates the heat losses. This is mainly caused by an overestimation of the average temperature of the heat conducting medium in the distribution network, which is minimum 60°C and actually reflects the typical operation of a domestic hot water circulation loop. Secondly, the seasonal variation in heat losses was poorly approached by the SCM, because of the estimation of the average temperature of the heat conducting medium in the network and the assumption of a continuous operation of the system. These parameters are influenced by the control strategies (e.g. intermittent operation) and substation properties. An investigation of improvements to the SCM for the various types of the system led to the conclusion that simplified heat loss calculation methods can be significantly improved when the estimation of two influential parameters, that is the average temperature of the heat conducting medium and the working time of the system, reflects the actual design and operation of the systems. However, in the previous study dynamic simulations or measurements were needed to estimate these influential parameters. The aim of the current study is to compose more accurate EPBD based SCM while avoiding the need for input data from simulations or measurements. And in contrast to the previous study, where various types of substations and network controls were investigated, in this study a method is developed for one specific substation control type.

METHODOLOGY AND SIMULATIONS

The subject of this study is a small-scale collective heating system, providing heat for both space heating and domestic hot water in a multi-family building with 25 apartments (Fig. 1). This system contains the essential parts of a district heating system: central heat generation, a collective heat distribution network, 25 dwelling substations and energy demand functions for SH and DHW. The transient system simulation tool TRNSYS is used to make a dynamic simulation model of this system. The Flemish EPBD-calculations are the starting point for the simplified calculations [2, 3].

The design of the collective heat distribution system and the development of a dynamic simulation model are extensively explained in [7].

Energy demand

Since the goal is to evaluate the distribution heat losses according to SCMs and DSM, the energy demand of the buildings according to both simulations are to be similar. Starting from the heat demand calculations in the Flemish calculation software, a case-study building was designed with three types of apartments with different thermal performance. The building is a low-energy building, with net energy demand for space heating of the apartments between 15 and 30 kWh/m²/year. The domestic hot water demands are between 2,5 and 4 kWh/day per apartment. For the purpose of the dynamic simulations, SH and DHW profiles were designed with 30 sec. time steps. The space heating design temperature regime is 60/40°C and the domestic hot water regime is 60/10°C.

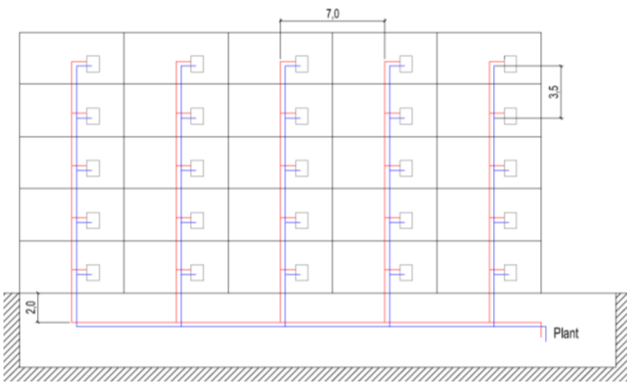

Fig. 1: Building and distribution network scheme

Substations

The case-study substation is equipped with a heat exchanger for transferring heat from the network to the domestic hot water, while the individual space heating systems are supplied with heat from the collective network. The return pipe of the space heating has a bypass which allows to regulate the flow rate in function of the required heat demand and supply temperature.

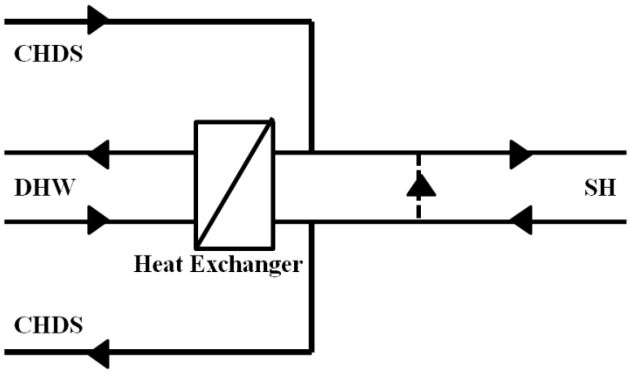

Fig. 2: Substation scheme [8]

The hot water temperature is controlled by a self-sensing temperature regulator that is embedded in the plate heat exchanger. This patented system gives a constant hot water temperature and a low return temperature to the district heating irrespective of volume and pressure flow [8]. In addition this control activates a minimum flow rate, "*idle flow*", through the heat exchanger in order to prevent it from cooling down and to keep it ready for DHW production during periods without demand. As a result, the recirculation of the primary heating medium through the collective heating network is controlled by the substation operation, dependent on the heat demand, the moment of the day or the season of the year. Fig. 3 presents the simulated return temperatures from the substation to the network per operation mode in January. During heat demand, the return temperature in the network is dependent on the space heating regime return temperature, which is on average 40°C, and the DHW return temperature of ca. 22°C. When there is no heat demand, the return temperature will stabilise around 42°C.

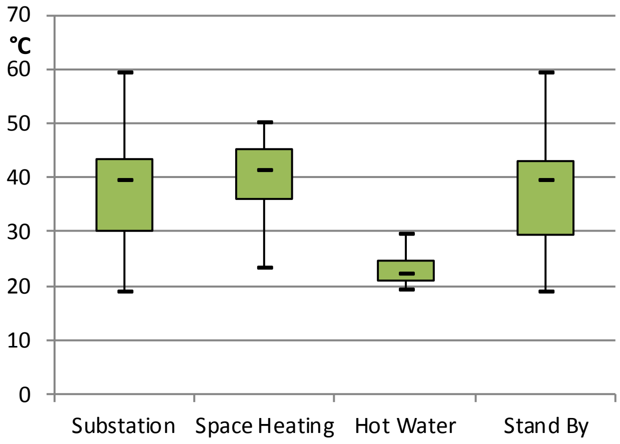

Fig. 3: Substation return temperatures

Distribution network

The collective heating system is a low-temperature system with fixed central supply temperature of 61°C. The distribution network consists of supply and return pipes, measuring 145m each (Fig. 1). There are no by-passes in the network and the central pump is a variable pump which can deliver very low flows. As a result the flow is driven by the substation control only. The internal pipe diameters are between 22 and 42 mm and the linear heat resistance is on average 8,5 mK/W. Heat losses through special and irregular elements (bearing structures, flanges, fittings…) are not considered in this study.

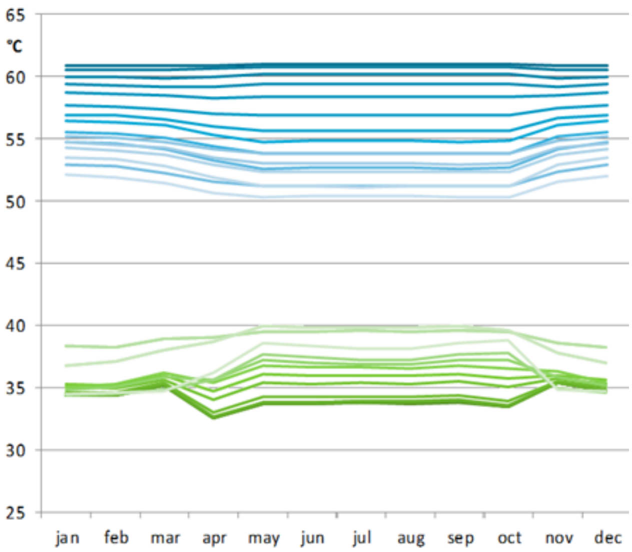

Fig. 4: Temperatures in the supply and return pipes

Fig. 4 presents the temperatures in the supply *(blue)* and return *(green)* pipes of the network, from the central main pipes *(dark)* to the substation connections *(light)* as a result of the dynamic simulations. The monthly average supply temperature in the network is clearly lower than the central heat supply temperature. This is a result of the cooling down of the network to min. 50°C at the substation connection during stand-by, when no flow or an extremely small flow appears.

The simulated heat losses of the network are illustrated in Fig. 5 *(DSM-Tot, DSM-Sup and DSM-Ret)*. The total heat losses of the network are about 32 GJ/year, or 8% of the total heat use in the collective heat distribution system. During summer, the heat losses are lower in absolute values, but relative to the heat use, they are higher (30%) than in winter (3%).

SIMPLIFIED CALCULATION METHOD SCM-0

First, the dynamic simulation results are compared to an existing simplified heat loss calculation method *SCM-0*, that is the Flemish/Belgian simplified calculation method for distribution heat losses in systems for combined space heating and domestic hot water production. The method starts from equation (1) and defines the monthly working time t_m of the system as the length of an entire month, and the average temperature of the heat conducting medium in the network is the maximum of 60°C and the monthly average temperatures in the space heating emission systems. In this case-study, the monthly average temperature in the space heating systems is 50°C, so $\theta_{net,m}$ is 60°C.

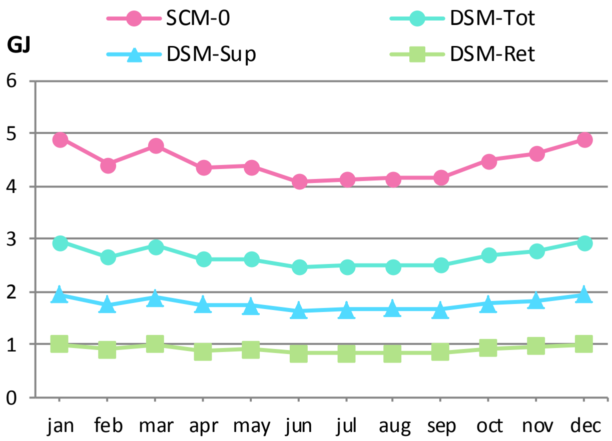

Fig. 5: Heat loss calculations: DSM and SCM-0

Fig. 5 illustrates the heat losses in the entire network according to SCM-0. In comparison to the simulated heat losses DSM-Tot, the heat losses are overestimated with about 50%. The main reason for this discrepancy is obviously the assumption of a continuous operation of the entire system at an average temperature of 60°C. This assumption actually reflects the behaviour of a typical DHW circulation loop, but is clearly quite different from the operation of the case-study system (see Fig. 4).

SCM+1

The development of an improved simplified calculation method starts with the subdivision of the monthly working time of the distribution system in three parts, according to three operational conditions of the substation that will influence the temperatures in the network: the time that the system delivers heat for space heating $t_{h,m}$, the time $t_{w,m}$ for domestic hot water generation and the time $t_{sb,m}$ that the system is in stand-by. For each part, a specific monthly average temperature of the heating medium in the network is calculated: $\theta_{combik,h,m}$, $\theta_{combik,w,m}$ and $\theta_{combik,sb,m}$. This method *SCM-1*, is expressed in equation (2):

$$Q_{loss,net,m} = t_{h,m} \times \sum_j \frac{l_j}{R_{l,j}} \times \left[\theta_{net,h,m} - \theta_{amb,j,m}\right] + t_{w,m} \times \sum_j \frac{l_j}{R_{l,j}} \times \left[\theta_{net,w,m} - \theta_{amb,j,m}\right] + t_{sb,m} \times \sum_j \frac{l_j}{R_{l,j}} \times$$

$\theta net,\quad sb,\quad m - \theta amb, j,m \qquad [in \quad MJ]$ (2)

Calculation of the working times

The working times for the three operation modes are estimated by use of information that is available in the EPBD calculation method, without the need for dynamic simulations or measurements. The three working times of the network are the average of the respective working times of each of the substations connected. First the working time per working mode is estimate for each individual substation or apartment.

The monthly working time for space heating of an apartment is based on the conventional monthly working time $t_{h,unit,m}$ of the heat emission system of the apartment unit that is connected to the substation, which is calculated according to the EPB calculation method. In case of a heat emission system with a constant supply temperature, equation (3) is applied:

$$t_{h,unit,m} = \frac{Q_{heat\ net,unit,m}}{[29 \times (H_{T,unit,m} + 0.27 \times V_{unit}) + 10 \times V_{unit}]} \quad [in\ Ms] \qquad (3)$$

With $Q_{heat,net,unit,m}$ the monthly net energy demand for space heating in the dwelling unit (in MJ). V_{unit} is the volume of the unit (in m³) and $H_{T,unit,m}$ is the monthly average specific heat loss of the unit through transmission at design outdoor temperature (W/K).

For the estimation of the individual domestic hot water working times, a similar approach is used by estimating the conventional monthly working time for domestic hot water production. In contrast to the space heating case, this parameter is not available in the Flemish EPBD legislation. Therefore a formula is developed, based on available parameters:

$$t_{w,unit,m} = \frac{\sum_i Q_{water,bath,m}}{P_{water,bath,operation}} + \frac{\sum_i Q_{water,sink,m}}{P_{water,sink,operation}} [in\ Ms] (4)$$

With $Q_{water,bath,m}$ and $Q_{water,sink,m}$ is the monthly energy demand for domestic hot water for baths (including showers) and sinks at the level of the substation (including secondary distribution heat losses). $P_{water,bath,operation}$ and $P_{water,sink,operation}$ are the average operational power (in W) at the secondary side for domestic hot water production for the use of baths/showers and sinks respectively. Fixed and standardised values for these parameters are estimated in this study with the aim of having realistic domestic hot water working times as a result (Fig. 6):

$$P_{water,bath,operation} = 10\ kW;\ P_{water,sink,operation} = 8\ kW$$

Finally, the individual stand-by period $t_{sb,unit,m}$ is the remaining time of the month when $t_{h,unit,m}$ and $t_{w,unit,m}$ are subtracted from t_m.

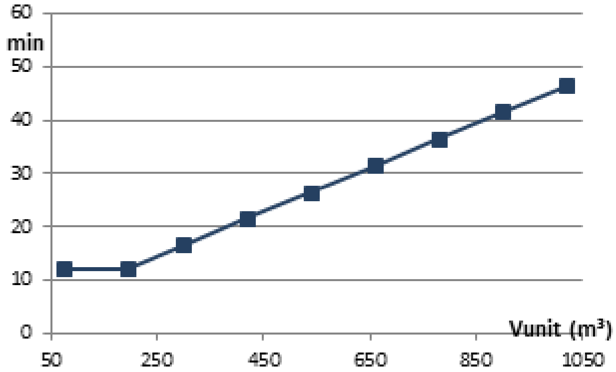

Fig. 6: Daily working time for domestic hot water

Calculation of the monthly average temperatures in the network

The monthly average temperature of the heating medium in the network for each operational mode is the average of the temperatures in the supply and return parts of the network, measured in the network at the substation connections for each working mode.

The monthly average supply temperature at the substation is equal for all working modes, since it is dependent on the design supply temperature:

$$\theta_{sup,net,h,m} = \theta_{sup,net,w,m} = \theta_{sup,net,sb,m} \qquad (5)$$

Therefore, it is the maximum of all individual design supply temperatures for SH and DHW at the secondary side, assuming an efficiency of 100% of the heat exchange between primary and secondary circuits. For example in the case-study, the supply temperature is 60°C, the maximum of space heating design supply (60°C) and DHW design supply (also 60°C).

The monthly average return temperatures $\theta_{ret,net,h,m}$, $\theta_{ret,net,w,m}$ and $\theta_{ret,net,sb,m}$ result from a time-weighted average of the return temperatures for the respective functions in each of the *n* substations, for example:

$$\theta_{ret,net,h,m} = \frac{\sum_{unit=1}^{n} t_{h,unit,m} \times \theta_{ret,unit,h}}{\sum_{i=1}^{n} t_{h,unit,m}} \qquad (6)$$

The return temperature for space heating of an individual unit is influenced by the operation of the substation, the space heating temperature regime and control and the primary supply temperature. For example, in the case study, it is 40°C.

The DHW temperature regime at the secondary side of the network is 60/10. Using data from the product information of the substation, the average return temperature at the substation assigned is 22°C [8].

The return temperature during stand-by is a characteristic of the network control, and in this case also of the substation. For example in a traditional substation with high flow recirculation, this temperature equals the supply temperature. Based on the product information and laboratory test results of the case-study substation, the average return temperature during stand-by is estimated for this specific substation. It is set to 42°C, independent of the primary supply temperature of the substation [8].

Results for SCM+1

The *SCM+1* method is now applied to the case-study collective heating system and compared to the dynamic simulation results. The working times and average supply and return temperatures are calculated starting from the design data of the substation (see Table 1).

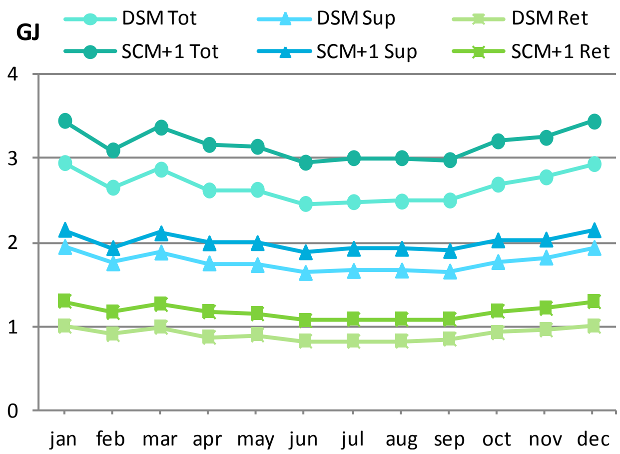

Fig. 7: Heat loss calculations: DSM and SCM+1

Using the *SCM+1* method, the estimation of the total heat losses in the system is 25% lower than in the original *SCM-0* method, but is still ca. 20% higher than the dynamic simulation results. In the supply pipes, the heat losses are overestimated with 13% on a yearly basis. The reason for this overestimation is that the yearly average supply temperature is lower than the design supply temperature of 60°C, as a result of the cooling down of the supply pipes during stand-by (see Fig. 4). The heat losses in the return part of the system are overestimated with 29%. This can be explained by the average return temperature during stand-by, which will decrease as a result of the cooling down of the network during stand-by periods shortly after a heat demand, when the heat exchanger is still warm and the idle flow is not yet activated.

As a conclusion, the proposed improvements lead to a better estimation of the heat losses, but a better estimation of the temperatures during stand-by time will probably lead to further improvements of the SCM.

SCM+2

In the *SCM+2* method, the general approach from *SCM+1* method is maintained, that is the splitting up of the monthly working time in three parts, as expressed in equation (2). The proposed adaptation is an improved estimation of the supply and return temperature at the substation during stand-by periods, $\theta_{sup,sb,m}$ and $\theta_{ret,unit,sb,m}$.

The behaviour of the substation during the stand-by period is one of the essential characteristics of the case-study substation [8]. After a heat demand for space heating or domestic hot water, the supply temperature at the heat exchanger will decrease from the substation design supply temperature $\theta_{sup,net,h,m}$ to a minimal temperature $\theta_{sup,min,sb}$ that is allowed to keep the heat exchanger hot. When this value is reached, an idle flow is activated and the temperature at the supply side is maintained in order to keep the heat exchanger hot. A simplified estimation of the average supply temperature of the substation during stand-by is therefore:

$$\theta_{sup,sb,m} = \frac{\theta_{sup,net,m} + \theta_{sup,min,sb}}{2} \quad (7)$$

Likewise, at the primary district heating return pipe of the substation, the temperature after a heat demand will decrease starting from $\theta_{ret,h,i}$ or $\theta_{ret,w,i}$ (dependent on whether the previous demand was for space heating or domestic hot water). Then, when the heat exchanger has cooled down and the idle flow is activated, the return temperature of the idle flow goes to $\theta_{ret,sb,i} = 42°C$. The average temperature during stand-by can be estimated in a simplified way according to equation (8):

$$\theta_{ret,unit,sb,m} = \sum_n \frac{\frac{t_{h,unit,m}\times\theta_{ret,unit,h}+t_{w,unit,m}\times\theta_{ret,unit,w}}{t_{h,unit,m}+t_{w,unit,m}} + \theta_{ret,unit,sb}}{2} \quad (8)$$

	Space Heating	DHW	Stand-by
SCM+1	$t_{h,unit,m} = \mathbf{2,5}\frac{h}{day}$ *in jan*	$t_{w,unit,m} = \mathbf{0,5}\frac{h}{day}$	$t_{sb,unit,m} = \mathbf{21}\frac{h}{day}$ *in jan*
	$\theta_{sup,unit,h} = \mathbf{60}\,°C$	$\theta_{sup,unit,w} = \mathbf{60}\,°C$	$\theta_{sup,unit,sb} = \mathbf{60}\,°C$
	$\theta_{ret,unit,h} = \mathbf{40}\,°C$	$\theta_{ret,unit,h} = \mathbf{22}\,°C$	$\theta_{ret,unit,sb} = \mathbf{42}\,°C$
SCM+2	$t_{h,unit,m} = \mathbf{2,5}\frac{h}{day}$ *in jan*	$t_{w,unit,m} = \mathbf{0,5}\frac{h}{day}$	$t_{sb,unit,m} = \mathbf{21}\frac{h}{day}$ *in jan*
	$\theta_{sup,unit,h} = \mathbf{60}\,°C$	$\theta_{sup,unit,w} = \mathbf{60}\,°C$	$\theta_{sup,unit,sb} = \mathbf{55}\,°C$
	$\theta_{ret,unit,h} = \mathbf{40}\,°C$	$\theta_{ret,unit,h} = \mathbf{22}\,°C$	$\theta_{ret,unit,sb} = \mathbf{39}°C$ *in jan*

Table 1: Average working times and temperatures

Results for SCM+2

In Table 1 the working times and temperatures according to the *SCM+2* method are given. As a result of the estimation of the supply temperature during stand-by, the average temperature $\theta_{sup,net,m}$ at the supply side of the substation, decreases to around 55°C. This leads to a much better estimation of the heat losses (see Fig. 8). Also at the return part of the network, the estimation of the heat losses comes much closer to the DSM results, with over- and underestimations of about 20% during winter and summer respectively. When the heat losses are aggregated to yearly values, the supply, return and total heat losses equalise the DSM results.

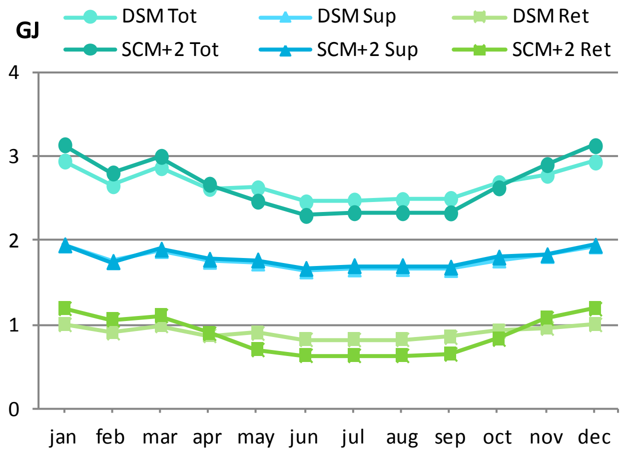

Fig. 8: Heat loss calculations: DSM and SCM+2

SCM+3

A third alternative *SCM* that is explored, starts from splitting the monthly working time in four parts, instead of three parts, through a portioning of the stand-by time $t_{sb,m}$ into a day time $t_{sb,day,m}$ and night time $t_{sb,night,m}$. The specific monthly average temperature of the heating medium in the network is now calculated for each of the four parts: $\theta_{combik,h,m}$, $\theta_{combik,w,m}$ and $\theta_{combik,sb,day,m}$ and $\theta_{combik,sb,night,m}$.

$$Q_{loss,net,m} = t_{h,m} \times \sum_j \frac{l_j}{R_{l,j}} \times \left[\theta_{net,h,m} - \theta_{amb,j,m}\right] + t_{w,m} \times \sum_j \frac{l_j}{R_{l,j}} \times \left[\theta_{net,w,m} - \theta_{amb,j,m}\right] + t_{sb,day,m} \times \sum_j \frac{l_j}{R_{l,j}} \times$$
$$\theta net,\ sb,day,\ m - \theta amb,j,m + tsb,night,m \times jljRl,j \times \theta net,\ sb,\ night,m - \theta amb,j,m \ \ in\ MJ \qquad (9)$$

Calculation of the stand-by parameters

The calculation method is based on the *SCM+1* and *SCM+2* methods, with the exception of the estimation of the stand-by working times $t_{sb,day,m}$ and $t_{sb,night,m}$, and the temperatures $\theta_{net,sb,day,m}$ and $\theta_{net,sb,night,m}$.

The subdivision of the stand-by time starts from the assumption that in a dwelling, and certainly in a dwelling with a low heat demand, there is a period of 8 hours per day (at night) with no heat demand. The individual working time for stand-by during the night $t_{sb,night,m}$ is therefore a period of 8 hours per day:

$$t_{sb,night,unit,m} = 0{,}3 \times t_m \qquad (10)$$

Subsequently, the rest of the stand-by period takes place during the rest of the day:

$$t_{sb,day,unit,m} = t_{sb,unit,m} - t_{sb,night,unit,m} \qquad (11)$$

Since no heat demand is assumed during night time, the average supply temperature to the substation goes to the minimal supply temperature that is maintained by the idle flow:

$$\theta_{sup,net,sb,night,m} = \theta_{sup,min,sb} = 50°C \qquad (12)$$

Likewise, the return temperature goes to the return temperature during idle flow:

$$\theta_{ret,net,sb,night,m} = \theta_{ret,unit,sb} = 42°C \qquad (13)$$

During daytime, heat demand and stand-by periods are alternated, so the stand-by is defined by cooling-down after a heat demand and idle flow recirculation, for both supply and return temperatures, the expressions (14) and (15) are similar to equations (7) and (8):

$$\theta_{sup,net,sb,day,m} = \frac{\theta_{sup,net,m} + \theta_{sup,min,sb}}{2} \qquad (14)$$

and

$$\theta_{ret,net,sb,day,m} = \sum_i \frac{\frac{t_{h,unit,m} \times \theta_{ret,unit,h} + t_{w,unit,m} \times \theta_{ret,unit,w}}{t_{h,unit,m} + t_{w,unit,m}} + \theta_{ret,unit,sb}}{2} \qquad (15)$$

Results for SCM+3

A comparison of *SCM+3* and DSM results (see Fig. 9) indicates that this method is a possible alternative to *SCM+2*. The supply heat losses are estimated slightly lower than in the previous method, and the return heat losses are estimated slightly higher, but on a yearly basis, the results equalise the results of the DSM. Moreover, this method gives a little better approximation of the seasonal behaviour in the return and total heat losses.

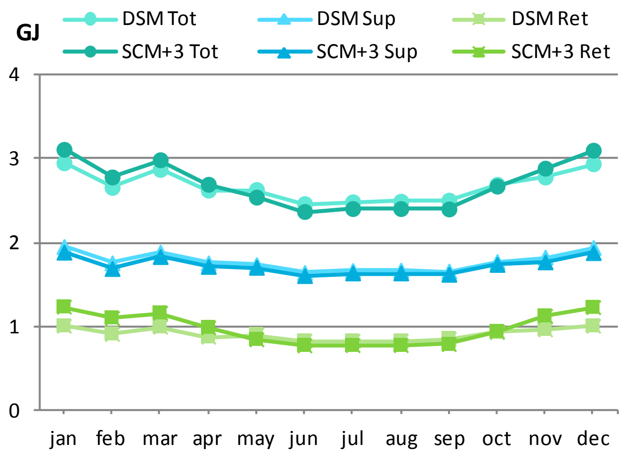

Fig. 9: Heat loss calculations: DSM and SCM+3

DISCUSSION

In this study, an improved method for calculation of the heat losses in collective heat distribution systems in the context of the EPBD legislation was investigated for a specific kind of substation and control. Three alternative methods were investigated and applied to a case-study low-temperature network connected to low-energy apartments. All of them showed improvements to the original method SCM-0, and especially method SCM-2 and SCM-3 seem promising. However, to find out which of these is the most robust method, the case-studies will need to be extended to buildings with different energy demand, heating system designs and network properties.

The main purpose for the development of simplified calculation methods is to avoid the need for detailed and time-consuming dynamic simulations or in situ measurements in order to enable a relatively quick and accurate estimation of the yearly energy performance with a reasonable amount of inputs. In this study, the methods were developed for compliance with the European Energy Performance of Building Directive, and more specifically the Flemish and Belgian legislative calculation methods in line with this Directive. This implies that when application in other building energy performance calculation methods is intended, small adaptations might be needed, dependent on the available parameters in these methods, for example those parameters that are related to the working time of the CHDS, the space heating and hot water systems. However this study demonstrates that a good estimation of the distribution heat losses is possible by use of simplified calculation methods and proposes a convenient calculation approach.

OUTLOOK

The future perspectives of this study include the evaluation of the three SCM's on a different case-study in the residential sector. In contrast to the present case-study, this would be a less-insulated and medium-temperature CHDS connected to dwellings with a higher energy demand. A second perspective is the validation of the DSM's and SCM's through comparison with measurements in a real life case-study: a low-temperature residential CHDS in the city of Kortrijk in Belgium [9].

CONCLUSIONS

In this paper, simplified calculation methods for estimation of the distribution heat losses in collective heat distribution systems in context of the EPBD-legislation were developed and compared to the dynamic simulation results of a case-study low-temperature CHDS. The paper demonstrates that it is possible to make accurate estimations of the yearly distribution heat losses in the system, and to approach the monthly and seasonal variation in heat losses quite well, by using a limited amount of input data from the EPBD calculations and design data from the network, thus avoiding the need for detailed dynamic simulations or in situ measurements.

A general approach for the development of SCM's for distribution heat losses was elaborated and evaluated. In this approach the operation of the CHDS is analysed in terms of the different operational conditions that appear as a result of the system design and their effects on the supply and return temperatures and the flow rates in the system. Therefore the general structure of a SCM is a decomposition of the working time of the CHDS into working times per operational mode, for example: the time that the system delivers heat for space heating, domestic hot water production or recirculation. Then for each of the working times of the system an average supply and return temperature is defined (see equations 2 and 9). This approach offers a manageable and effective framework for simplified distribution heat loss calculations and is flexible to a variety of CHDS designs. Dependent on the design and control of the CHDS, the operational modes and characteristics can be identified.

The general structure was applied to a specific type of CHDS technology, in which the circulation of the primary heating medium through the network is entirely controlled by the substation control and operation. Three simplified calculation methods were developed, only using parameters available in the local EPBD-calculation method and the information of the design and product information of the components in the system. The methods were evaluated by use of dynamic simulations of a case-study system. All of them were improvements to the original SCM in which the working times were not decomposed, and the second and third method did result in a very good estimation of the distribution heat losses.

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TIME-DEPENDENT CO_2 EMISSIONS BY REDUCING DEMAND IN SWEDISH DISTRICT-HEATING SYSTEMS

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ABSTRACT

Fuels and heat production technologies in district heating systems have crucial impact on carbon dioxide (CO_2) emissions, which vary with time because they depend on the heat sources used. Here, time-dependent CO_2 emissions from district heating production are calculated using cost-optimisation models. The impact of reduced demand on CO_2 emissions and their fluctuations is estimated. CO_2 emissions are calculated in two ways. Relative emissions are total CO_2 emissions relative the size of district heating demand. Marginal emissions are the CO_2 emissions from the most expensive power supply unit at the moment. Co-generated electricity is assumed to replace condensing power production. A set of four typical district heating systems, which represent all Swedish district heating concerning fuels and heat production technologies, is used to analyse CO_2 emissions. Results show that the number of peak demand hours with high marginal CO_2 emissions is significantly reduced when heat demand is reduced. For district heating systems with much fossil or biomass CHP, relative CO_2 emissions are lower during mid-load periods than during low demand periods when CHP plants are running less. Results also show that marginal CO_2 emissions vary with electricity price in systems with CHP plants or heat pumps.

INTRODUCTION

District heating is a means to utilise energy resources that are difficult to use in individual buildings, such as unrefined solid biomass fuels and municipal waste. District heating can also use waste heat from industrial processes and heat that is co-produced with electricity in combined heat and power (CHP) plants.

Some district heating production is based on fossil fuels. But district-heating systems that primarily use renewable fuels or waste heat often also use some fossil fuel. Much district heating is linked to the power system through CHP production. Therefore, district-heating production often directly causes emissions of fossil carbon dioxide (CO_2) or indirectly influences fossil CO_2 emissions from power production.

The amount of emitted CO_2 from district heating production may be seen as a single simple figure but which emissions that should be considered and how they should be accounted depends on the purpose and perspective of a CO_2 evaluation. Different perspectives are relevant to consider; *average, or relative, emissions* that are the total emissions divided by the heat demand, and *marginal emissions* that refer to the emissions emitted by the heat-producing unit that would be used to supply an increase in heat demand.

The next issue to consider is which CO_2 emissions that should be taken into account in the calculations. Most straightforward to include is the CO_2 emitted from the plants that produce district heating, that is, the local emissions. But if the district-heating production involves electricity generation, it may also influence the global CO_2 emissions through its impact on the power system. The electricity that is produced in CHP plants in a district-heating system does not need to be generated elsewhere. That is, the CHP electricity displaces other power production. This however requires a CO_2 assessment of the produced and displaced electricity.

STATE OF THE ART

The state-of-the-art for assessing CO_2 intensity of electricity use and production is either to use an average (mix) perspective, or to apply the concept of marginal electricity generation. The average power generation mix is an approach where a change in electricity demand or production is considered to equally affect all production units within the power system. Commonly used mixes in Sweden are; the Nordic mix, the European mix and the Swedish mix. According to Sjödin and Grönkvist [1], and Levihn [2] the average perspectives do not however capture the dynamics of the electricity market and the fact that different kinds of power production units have different operation priority due to costs and technological features. Both Grönkvist and Sjödin, and Levihn suggest that the marginal concept should be used to mirror the impact of actual changes, especially when changes in electricity consumption or production are investigated.

TIME DEPENDENT CO_2 EMISSIONS

Besides the methodological choices of calculating relative or marginal CO_2 emissions from the district heating plants and of which electricity interplay to consider, a third, less considered, aspect is the fluctuations, especially the *seasonal variations,* of CO_2 emissions. Such time dependencies are most pronounced in district-heating systems with many plants where different sets of plants are committed at different occasions mainly due to the heat demand level but also due to fluctuations of electricity prices if there is CHP production. Variations in waste heat supply may, for example, also imply time dependent use of other district-heating sources.

Therefore, we in this paper elucidate the issue of time-dependent CO_2 emissions in Swedish district-heating systems. The results would, for example, be useful by choices among measures that change district-heating demand to show the options that are preferable concerning climate impact. Potential end-user measures include switching to better windows, which reduce heat losses and space-heating demand primarily in winter, and installing solar heating that mainly in summer decreases the demand for district heating.

The aim of this study is to investigate how CO_2 emissions from different types of district heating systems vary, primarily between seasons, and to illustrate how emissions differ depending on the perspectives used for emission calculations. Furthermore, the impact of building energy efficiency measures on time-dependent CO_2 emissions is investigated.

METHODS

A district heating cost-optimising model is used to model a set of typical district heating systems that are based on fuel use, heat production and CHP electricity generation statistics for the entire Swedish district heating sector. The model is used to calculate the time-dependent CO_2 emissions for the four typical systems using relative and marginal CO_2 emissions. Additionally, changes in emission levels are investigated for a scenario where the total annual heat demand in the district heating systems is reduced by 10% due to assumed demand side building energy efficiency improvements.

FMS

The FMS (fixed model structure) software is a district heating optimisation tool that requires relatively small amounts of input data. The FMS is implemented in the conventional calculation softwares Matlab and Microsoft Excel, which makes the FMS more available for use than other more advanced optimisation models, such as MODEST [2] or MARKAL [3].

The FMS model uses linear programming to cost-optimise heat production in district heating systems while satisfying a given heat demand. Revenues from optional sales of generated CHP electricity are considered. Optimisation is performed separately for each time step. This means that the flexibility in the number of time-steps and the time-step lengths is unlimited. It also means that for each time-step and optimisation the FMS only considers the currently prevailing circumstances (heat demand, electricity prices, fuel costs and available heat production unit capacities).

The FMS tool is based on a fixed model structure (hence the name), with a fixed number of system components and energy flows. Figure 1 shows an overview of the 17 nodes (components) and 22 energy flows that constitute the FMS. The model is prepared to include (from left to right); three different fuels or fuel categories, six different conversion units from fuel to electricity and heat or heat only, district heating and electricity networks, an electric heat pump or boiler, industrial waste heat (IWH) utilisation, demand for district heat, a heat re-cooler for wasting heat and market nodes for purchases and sales of electricity.

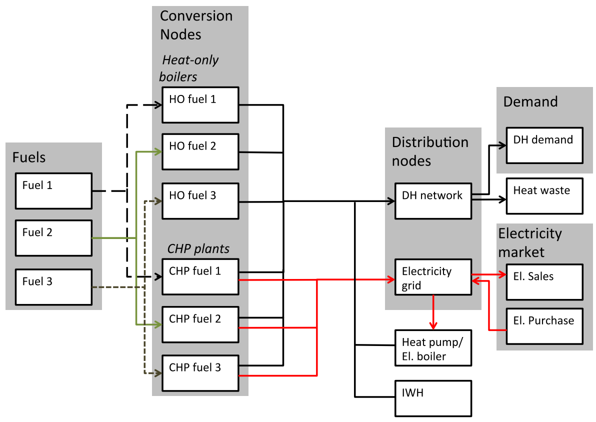

Figure 1. Energy system nodes (boxes) and the interconnecting energy flows (lines) in the FMS tool.

The input data necessary to describe a district heating system in the FMS are; maximum outputs for energy conversion units, conversion efficiencies, electricity-to-heat output ratios for CHP conversion units, heat demand, fuel costs and other heat and electricity production costs and electricity prices. The FMS tool is described in detail in [4] and used in [5].

A set of typical district heating systems

In [5] four typical district heating systems were defined to represent the entire Swedish district heating sector with differences in fuel use and heat production technologies among the Swedish systems taken into account.

The 441 Swedish district heating systems represented in the statistical data from 2011 published by the Swedish district heating association (SDHA) were divided into four groups, primarily based on wether the systems use CHP production or not, and secondly if there is CHP what the main fuel use in CHP plants is. Group I contains all systems without CHP plants and groups II-IV contain the systems with CHP production and where the main CHP fuel is waste, fossil fuels and biomass, respectively.

Four typical models were built using the FMS tool. Each model describes a district-heating system, which represents the aggregated systems in each type group I-IV. General plant efficiencies were used, obtained from [5], and output capacities and electricity-to-heat output ratios (α-values) were adjusted to make model results coincide with the annual heat and electricity production values in the aggregated statistics for each group of systems. The first rows in figures 4a and 4b show duration diagrams of the heat production in the four typical district heating systems.

CALCULATING TIME-DEPENDENT CO_2 EMISSIONS

The CO_2 emissions are calculated considering both the local direct emissions from fuel use and indirect emission impact due to CHP electricity generation. The direct emissions from the fuel types used in different heat production units are calculated by associating a CO_2 emission factor to the hourly use of each fuel. CO_2 emissions reductions due to co-generated electricity in CHP plants are credited as negative emissions. This electricity is assumed to replace the same quantity of electricity that otherwise would have been generated through the most expensive, and normally least efficient, power production elsewhere in the system. Now, this is often a coal-fired condensing power plant but in a longer term natural-gas-fired combined-cycle condensing power plants (NGCC) are likely to increasingly play this role. Here, the marginal electricity production is assumed to be gas fired condensing plants with an emission factor of 400 kg of CO_2 per MWh of electricity. The CO_2 factors for different fuel types and for electricity are presented in table 1.

Table 1. CO_2 emission factors for diferent energy carriers.

Fuel	**CO_2 emission factor** [kg CO_2/MWh]
Fossil	280
Biomass	0
Waste	100
Electricity (NGCC)	400

Furthermore, the two different perspectives on CO_2 emission calculations for district heating production described above are addressed below; relative (average) and marginal emissions.

Relative emissions

When comparing the CO_2 emissions caused by the heat production in two different district heating systems, the total emissions should be divided by the current total heat production. These relative emissions (e.g. kg/MWh) could also be called average emissions and represent the CO_2 emissions relative the size of the district-heating system.

Marginal emissions

By connection of buildings to a district-heating network, it may be desirable to compare the CO_2 emissions caused by district heating with alternative heat supply options. If all heat is produced in the same way in a district-heating system, relative emissions can be used for this evaluation, but especially larger city-wide district-heating systems host many heat-producing units, which may cause different CO_2 emissions.

For this purpose, marginal emissions should be used. That is the CO_2 emissions from the heat production unit that produces more heat when the heat demand increases. Marginal CO_2 emissions (e.g. kg/MWh) are normally the emissions from the supply unit in use at a moment that has the highest heat production cost. Marginal emissions can be used for evaluating the climate impact of measures that change heat demand.

HEAT DEMAND REDUCTION SCENARIO

Besides analysing heat supply and CO_2 emissions by present district heating demand, a 10% reduction of the total heat demand is used to illustrate how a reduced heat demand in buildings affect the seasonal CO_2 emission variations, for the relative and the marginal perspectives. The demand for space heating and domestic hot water is reduced separately. For the summer months June, July and August, the heat demand is assumed to be entirely constituted by domestic hot water demand. The mean demand level for these three months is then assumed to constitute the hot water demand level also for the other nine months. The energy efficiency improvement of a building means that the space heating demand and domestic hot water demand are reduced by 50% and 30%, respectively. Further is the number of improved buildings adjusted, so that the total heat demand reduction is 10%.

Figure 2 shows duration curves for how the annual profile of the heat demand (reference curve) in typical system I is changed by the reduced heat demand (scenario curve) due to building energy efficiency improvements. The heat demand curves for typical systems II-IV are changed in the same way.

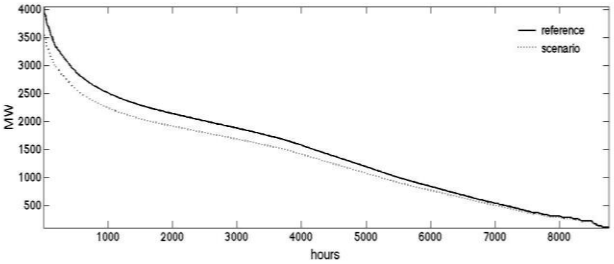

Figure 2. Annual heat demand profile for typical system I (solid line), and the reduced heat demand profile (dotted line) for the same system.

RESULTS

Initially, the relative (average) CO_2 emissions are presented and their variations. Thereafter, the results for the present situation and the heat demand reduction scenario are compared, for both relative and marginal emissions.

Variations in relative CO_2 emissions

Figure 3 shows the relative CO_2 emissions in the four typical systems for every hour of a year in consecutive order. These relative emissions are the total emissions from all plants in operation divided by the total heat production during each hour. If a higher fraction of the heat is produced with fossil fuel, the relative emissions are higher. Generated CHP electricity is assumed to reduce power production and CO_2 emissions at gas-fired condensing power plants, which is considered by the calculation of the relative emissions in Figure 3.

Generally, the relative CO_2 emissions in Figure 3 are high at some occasions in the beginning and end of the year when the outdoor temperature is low, heat demand is high and fossil-fuel-fired heat-only boilers are committed. The lowest peak and average levels for the relative CO_2 emissions are reached in spring and autumn. This is explained by two circumstances; 1. In the warm summer periods, incineration of domestic waste, which has a fossil fraction, is sufficient to cover the demand and pushes the relative emission level upwards, 2. The heat demand in the mid load periods (spring and autumn) is more commonly covered by biomass fired CHP plants, or fossil-fuel-fired CHP plants with high electricity-to-heat output ratios, that significantly reduce the average emission levels through its displacement of carbon-rich electricity elsewhere.

In systems II and III, the maximum CO_2 emission levels are higher than in systems I and IV because in II and III more fossil fuel (including fossil waste fractions) is used to cover base and intermediate loads, whereas these are primarily covered by zero emitting biomass in systems I and IV.

The minimum level of the relative CO_2 emissions for system I in Figure 3 is close to zero and occurs when the biomass-fired heat-only boiler produces its largest fraction of the heat. In a corresponding manner, system IV has the lowest emissions at the occasion when the biomass-fired CHP has its maximum share of heat production. The relative emissions are in this case lower than zero because a CO_2-neutral fuel produces electricity that displaces carbon-rich power production.

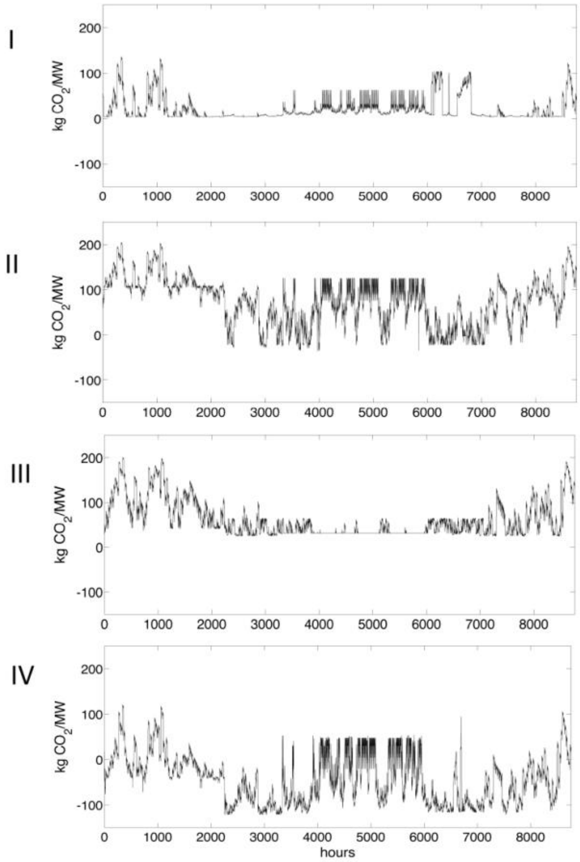

Figure 3. Hourly consecutive relative CO_2 emissions in typical systems I to IV (top to bottom).

Heat demand reduction impact on relative and marginal emissions

Figures 4a and 4b show heat production duration diagrams along with corresponding relative and marginal CO_2 emission results for typical systems I and II (4a) and III and IV (4b), respectively. The second rows of diagrams in the figure contain the reference case results and the third rows contain the heat demand reduction scenario results for the emissions.

The "striped" regions that occur in the diagrams to different degrees are effects of production unit merit-orders being dependent on the level of the electricity price, which involves CHP plants and heat pumps. Note that the stripes do not necessarily mean that plants are operated at unrealistically short time spans since the time periods are not presented consecutively.

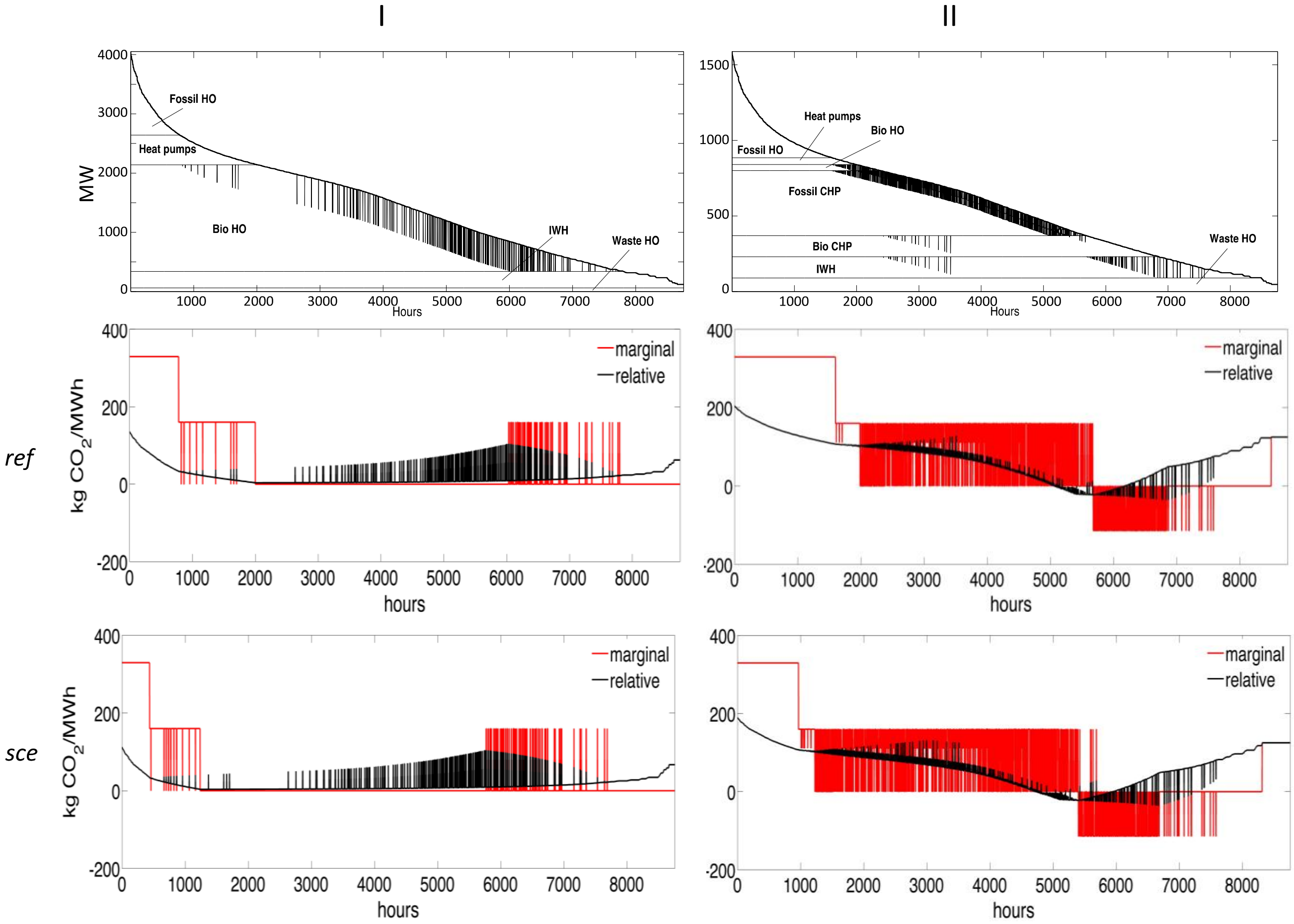

Figure 4a. The first row shows duration diagrams for the heat demand and heat production merit-orders for the typical systems I and II. [3] The second row shows relative and marginal hourly emissions for the reference case that correspond to the heat demand duration curves in the first row. The heat demand reduction scenario emissions are presented in row three.

Results for relative and marginal emissions

Fossil-fuel heat-only production that is used to cover demand peaks have significant impact on the relative and, especially, the marginal CO_2 emissions, which both are generally higher when these peak units are operated. The relative emissions however are decreased continuously with decreasing demand because the share of fossil fuel in the fuel mix is decreased, while the marginal emissions are at a constant high level during the operation hours of the fossil heat only plants. The marginal and the relative CO_2 emissions do not completely match each other in the sense that the highest relative emissions coincide with the highest marginal emissions. An example of this is for typical system III in Figure 4b where the lowest levels of marginal emissions coincide with a local peak for the relative emissions for the reference as well as the scenario case. This is explained by the marginal emissions being constituted by the biomass-fired CHP plant or industrial waste heat, depending on the electricity price level, while the total production mix to a large extent is constituted by waste-fuelled CHP and heat only waste incineration plants that increase the relative (average) emissions.

All systems that have CHP production (II-IV) also, to varying extent, have occasions with negative marginal CO_2 emissions, which means that they during parts of the year serve as carbon sinks. This effect is more pronounced for typical system IV than for the other three systems because biomass-fuelled CHP is the marginal heat production during many hours with rather low heat demand.

For typical systems I, II and IV, the relative CO_2 emissions are higher during the lowest heat demand hours than for hours with intermediate heat demand. This is because the mid-load production units (e.g. biomass CHP) in these systems cause lower CO_2 emissions than the base-load production units (waste), which dominate supply at low demand. For typical system III, relative emissions are however not higher during periods with very low demand because base-load waste-fired CHP plants with moderate emissions produce all heat also at somewhat higher demand.

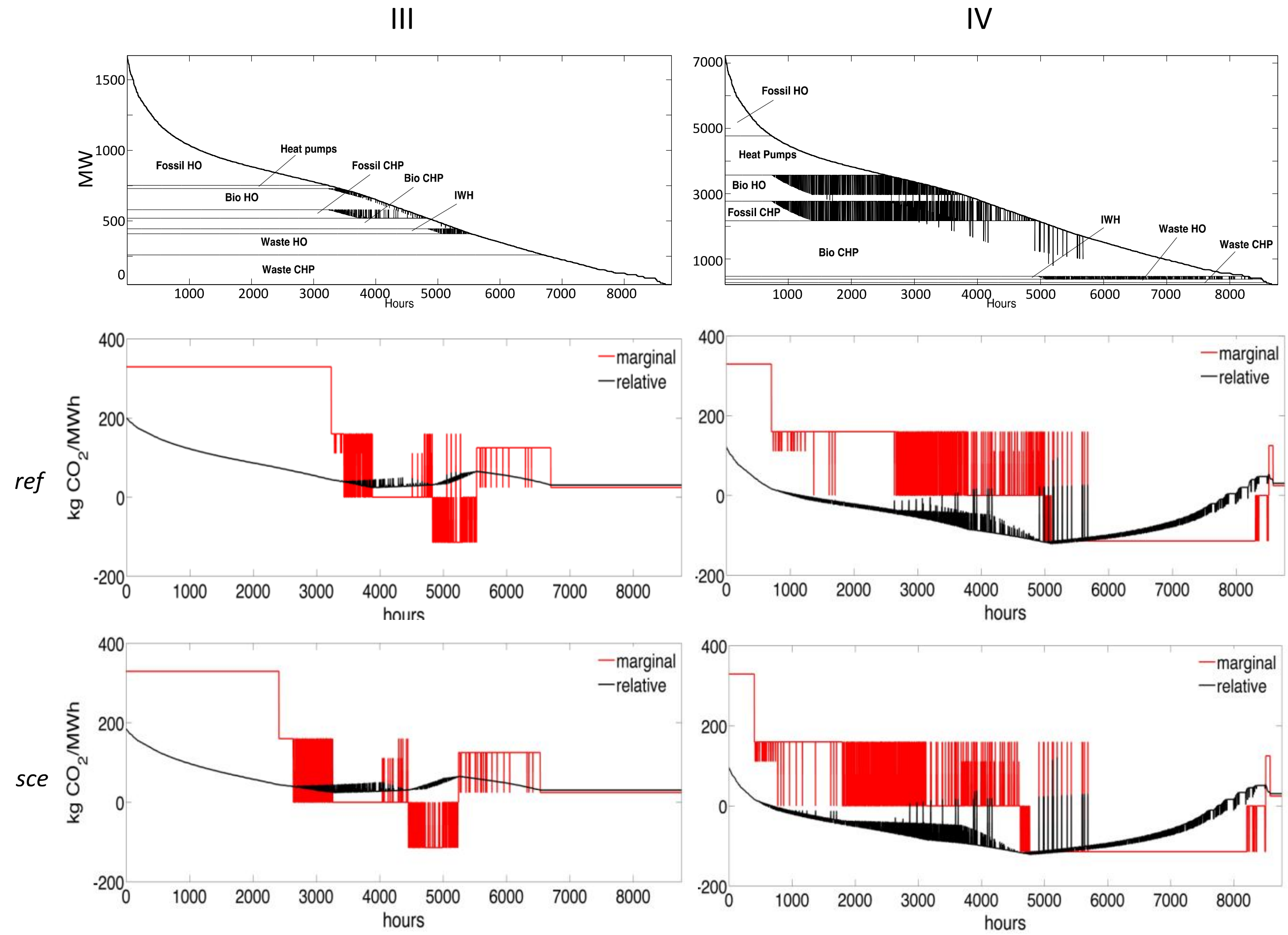

Figure 4b. The first row shows duration diagrams for the heat demand and heat production for the typical systems III and IV. [3] The second row shows relative and marginal hourly emissions for the reference case that correspond to the heat demand duration curves in the first row. The heat demand reduction scenario emissions are presented in row three.

Heat demand reduction scenario results

The main difference seen for all typical systems between the reference case and the scenario case with reduced heat demand is that the number of hours with the highest level of marginal CO_2 emissions is reduced. This is obvious by comparing the left end of the emission diagrams in the second and third rows in Figures 4a and b. This is due to the building heat demand reduction being largest during peak demand hours as was seen in Figure 2. This means that the mid-load production plants constitute the marginal production during longer periods after the heat demand is reduced. The marginal emissions for the warmer parts of the year are, however, only slightly affected by the heat demand reductions.

A reduced heat demand also affects the CO_2 emissions for systems with several different heat production units supplying mid-load demand (systems III and IV) more than systems with few such production units (systems I and II). For instance is the number of hours with electricity price dependent fluctuations in marginal emissions for typical system IV is larger in the low-demand scenario results.

The impact on relative CO_2 emissions is smaller than for marginal emissions when the heat demand is reduced. The relative-emission “peak” to the left in the diagrams is however somewhat lower and less far stretched for the heat demand reduction scenario compared to the corresponding reference cases. This is also explained by the lesser use of fossil heat only production units after heat demand reduction.

DISCUSSION

The time-dependent CO_2 emissions calculated here, both marginal and average, are larger during low demand periods than during mid-demand periods for typical systems I, II and IV. This effect is seen for systems where base load production causes higher CO_2 emissions than the mid-load production. This means that heat demand reduction during mid-demand hours would decrease the emissions less than reducing low demand further. The definitions of the marginal and the average emissions would actually mean that heat demand reductions increase emissions or leave them unaffected during these hours. This is typically true for systems that have waste incineration plants for base load production and biomass fired CHP plants for mid-load production. Heat demand reduction may cause increased CO_2 emissions due to the interplay between produced electricity and power production elsewhere.

In this study assumptions have been made regarding the indirect global effects on CO_2 levels in the atmosphere due to CHP generated electricity that displace CO_2 emissions from less efficient European power plants with higher production costs. However in coherence with this reasoning, CO_2 emissions due to combustion of renewable fuels for district-heating production could also be included. If energy saving measures in district heating supplied buildings lead to reduced use of biomass, the biomass can replace fossil fuel elsewhere. By using the biomass, this fossil fuel is also used and causes CO_2 emissions, which could be considered in a similar fashion as the emissions from marginal electricity. This would increase the incentives to reduce energy use even when biomass is used although it is considered zero CO_2 emitting within the EU.

The results presented here are not to be considered general for all district heating systems or valid for specific systems since it is clear that the types of heat production used is crucial for the results. The approach with typical systems however gives an overall picture of the variations in CO_2 emissions from district heating systems.

The obvious impact of electricity price levels on the CO_2 emissions is important since the electricity price levels are difficult to foresee. Therefore are the results presented here most likely in its details not valid for future years. At the heat demand levels with fluctuations between different production units, the calculated CO_2 emission levels are uncertain and extensively depending on the electricity price levels.

A completely different approach to estimating CO_2 emissions from district-heating production would be not to consider the interplay with other power production and to also exclude the CO_2 emissions from the fuel producing the electricity in CHP plants, That would, however in our opinion, constitute a much too narrow system boundary, which would be likely to show solutions that are less favourable from a comprehensive viewpoint.

CONCLUSIONS

There are significant differences in marginal and average CO_2 emissions from district heating production between different times of the year.

It is also clear that CO_2 emissions, both marginal and average, depend to large extent on the heat production unit composition in the system. The electricity price level dependence of the CO_2 emissions is also obvious for all kinds of Swedish district-heating systems even though the extent of electricity price level sensitivity varies between them. The emissions for typical system III with much waste CHP is for instance less sensitive to the electricity prices than typical system IV with much biomass CHP.

Both marginal and average CO_2 emissions for mid-level demand periods are generally lower than, or as low as, emissions during low demand periods in the typical Swedish district heating systems. This since low CO_2 emitting biomass CHP plants have a higher production cost than typical base-load production plants such as waste-fired heat only plants and waste-fired CHP plants, and are therefore used for mid-load production to a larger extent.

Building heat demand reductions that yield a 10% reduction on the total annual heat demand mainly affect the emissions during the peak demand hours. This means that heat demand reductions reduce expensive fossil heat only production and thus decreases the number of hours with the highest level of marginal CO_2 emissions significantly.

From the results it can be argued that demand side energy efficiency measures in district heating systems reduce CO_2 emissions most efficiently if heat demand is reduced mainly during peak demand hours.

However, an increase in heat demand during low demand hours could , on the other hand, pro-long the operational time for mid-load production units and thus reduce both marginal and average CO_2 emissions during low-demand periods. A more levelled district heat demand with small differences between seasons can be expected to have positive impacts on CO_2 emissions according to the results presented here because emissions generally are lower during periods with intermediate heat demand.

ACKNOWLEDGEMENT

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GEOTHERMAL DISTRICT HEATING SYSTEM IN ICELAND: A LIFE CYCLE PERSPECTIVE WITH FOCUS ON PRIMARY ENERGY EFFICIENCY AND CO_2 EMISSIONS

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ABSTRACT

This paper presents a cradle-to-gate life cycle assessment (LCA) of Stykkishólmur's geothermal district heating system based on a functional unit of 1 MWh_{th} of delivered heat to consumers. The study is largely based on primary data collected for the construction and operation of the system and is representative for a modern design of such a system. The LCA was performed using the SimaPro 7 software and results were obtained using CML baseline impact categories and Cumulative Energy Demand (CED) analysis, with special focus set on primary energy demand and carbon footprint of the functional unit.

The primary energy demand of producing 1 MWh_{th} of delivered heat to consumers in the Stykkishólmur DHS was calculated to be 2.73 MWh_{th}. Thereof, 0.03 MWh_{th} originate from non-renewable sources used in the construction stage, mainly for production of steel used in the various pipes within the system. Use of geothermal energy in the operational stage dominates the renewable part of the primary energy demand. The carbon footprint was calculated to be 5.8 kg CO_2 eq/MWh_{th} of district heat delivered to customers. Other impact categories were also investigated in the study.

INTRODUCTION/PURPOSE

Iceland is a leading country in annual geothermal energy use for district heating [1] and one of the fastest growing countries with respect to geothermal power capacity [2]. Well over 90% of homes in Iceland are heated by geothermal energy distributed through a district heating system (DHS), where the Reykjavik geothermal DHS is considered the largest in the world [3]. Geothermal resources in Iceland can be broadly separated into two categories: (1) high temperature, implying a temperature of at least 200 °C at depths greater than 1 km, and (2) low temperature, implying a temperature less than 150 °C at depths greater than 1km [4]. Geothermal fluids from low-temperature areas are used directly or indirectly for space heating while fluids from high-temperature geothermal areas are often utilized in combined heat and power plants, where geothermal energy is used to produce electricity and heat up fresh water in various stages within the power plants.

One example of low-temperature geothermal resource utilization is the district heating system of Stykkishólmur, shown in Figure 1. Stykkishólmur is a town of ~1100 inhabitants situated in the Snæfelsnes peninsula on the western coast of Iceland. Stykkishólmur's DHS was selected as a case study for several reasons. First, the production and reinjection wells were drilled in 1996 and 2006 respectively, implying they are about 30 years younger than those which serve the capital region of Reykjavik. Their younger age suggests that the wells were built utilizing more recent drilling technologies and modern construction techniques. Additionally, engineers familiar with the DHS' construction and operation were available for consultation and have provided access to construction and energy usage data. As the design of the system is representative of a typical modern district heating system in Iceland, results may be adapted for future systems based on similar technology. Finally, the results of this paper highlight the primary construction/operation processes and associated materials which most significantly contribute to the life-cycle emissions and energy use of a geothermal based DHS. Such knowledge may help with better environmental performance of future systems and

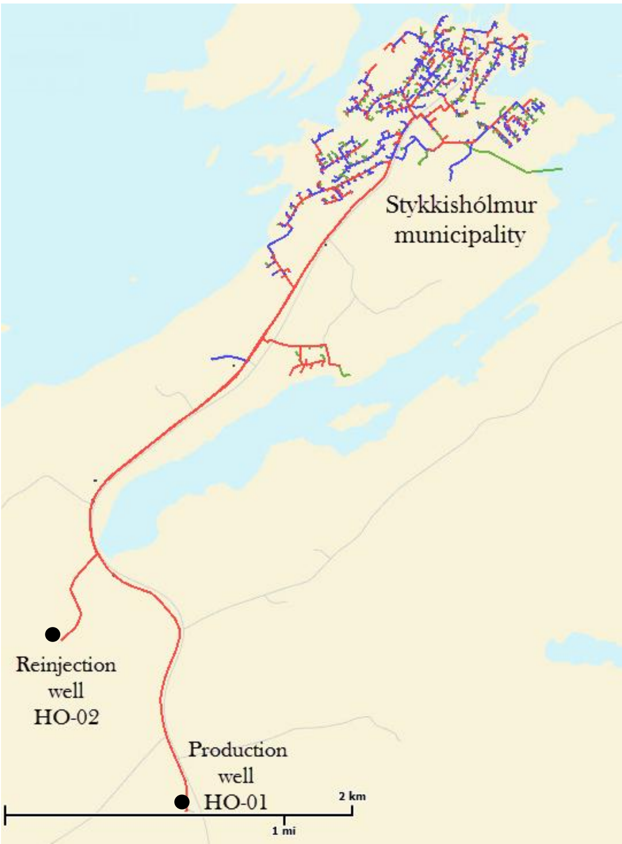

Figure 1 Overview of Stykkishólmur's district heating system, showing the location of the geothermal wells (HN-01 and HN-02) and the pipe network structure.

prioritize and focus research efforts when analysing a larger and more complex system such as Reykjavik's DHS.

Recently, the Swedish District Heating Association commissioned a comprehensive study on the environmental life cycle impacts of three different phases involved in district heat distribution. The first part of the study addresses the production of the district heat pipes [5], the second part describes construction of the district heating pipe network [6] and the third part evaluates the operation phase based on heat losses during district heat distribution [7]. The results of the study showed that additional heat production which compensates for heat losses in the pipe network account for over half of the total life cycle environmental impacts for most impact categories selected. For the construction stages of the system, the production of materials used for pipes and energy use during the network construction accounted for the largest part of the environmental impacts associated with those life cycle stages.

Ghafghazi et. al. [8] compares impacts from different base-load heat sources for district heating purposes, including heat pumps, natural gas, wood pellets, and sewer heating. The authors primarily concluded that that renewable energies saved ~ 200 kg_{eq} of CO_2 savings per MWh_{th} produced but varied depending on the efficiency of the individual system.

STATE OF THE ART

A common practice in Icelandic geothermal district heating systems is to install open-loop single pipe systems where hot water is disposed of through the sewage system after its use in domestic radiators. This is the case in most of the Reykjavik district heating system, serving almost 60% of the country's population [9]. This practice reduces costs of the network construction and is made possible by the abundance of hot water produced either from low- or high-temperature geothermal resources.

Geothermal fluid from low-temperature areas is often used directly in the district heating system if the chemical content of the fluid does not induce heavy scaling from silica deposits or corrosion of pipes, e.g. due to salinity. Otherwise, the geothermal fluid exchanges heat indirectly to fresh ground water through heat exchangers, as is the case in Stkkishólmur's DHS.

Stykkishólmur's DHS utilizes 85°C geothermal fluid from a single low temperature well (HO-01) located roughly 5 km from the municipality as seen in Figure 1. The geothermal fluid is fed through plate heat exchanger (titanium plates) in which groundwater is also fed through a separate a closed loop system. Heated groundwater leaves the heat exchanger at 79°C through the supply side of the distribution pipe system and ultimately returns to the heat exchanger at 35°C through the return side of the distribution pipe system. The distribution pipe system of the DHS features a double-pipe system which supplies water directly to radiators in homes and heat to produce hot tap water.

In contrast, 70% (by mass) of the geothermal fluid is returned to the reservoir at 47°C through a separate injection well (HO-02) located 4 km from the heat exchanger station. The remaining 30% is largely used directly in a public bathing facility and the rest is used for direct heating of summer houses within the town's vicinity. The reinjection of the geothermal fluid has been proven to support the pressure and inflow of water to the production well, ensuring a more sustainable utilisation of the low-temperature resource [10].

METHODS/METHODOLOGY

Goal and scope

The goal of this study was to create a life cycle inventory (LCI) database and perform a cradle-to-gate life cycle assessment (LCA) on Stykkishólmur's geothermal DHS, with special focus on primary energy demand and global warming potential in terms of CO_2 equivalent emissions for the delivered heat to consumers. Furthermore, the functional unit for the LCA is chosen to be 1 MWh_{th} of district heat delivered to a consumer.

The inventory collected is largely based on primary data for bulk material use within the system and with operational data based on the reference year of 2012. The operational time is chosen to be 30 years. However, geothermal resources may well exceed its design lifetime with proper resource management, as

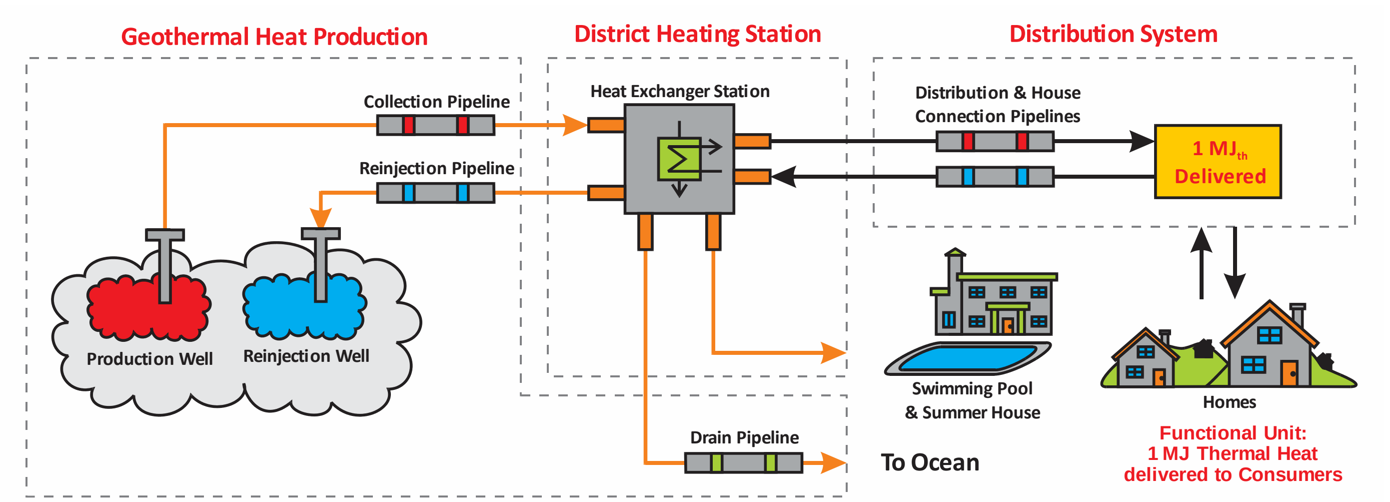

Figure 2. The physical system boundary for Stykkishólmur geothermal district heating system. The system is subdivided into three smaller physical systems: (1) Geothermal heat production, (2) Heat exchanger station and (3) Distribution system

has been experienced by the Reykjavik DHS where the Laugarnes low temperature area has been utilized for hot water production since 1930 [3].

For modelling purposes, the physical DHS is decomposed into three primary subsystems as shown schematically in Figure 2: (1) The geothermal heat production, (2) the heat exchanger station, and (3) distribution system. A flow diagram detailing each subsystem as sets of reference flows is provided in Figure 3-Figure 5.

Temporally, the life cycle inventory (LCI) includes the construction and operation life cycle stages of the system but excludes the maintenance and end-of-life. The system boundaries of the life-cycle study are depicted in Figure 6. Although the research would ideally encompass the entire life-cycle of the DHS, the availability of data necessitates the exclusion of some physical components and the maintenance and decommissioning life-cycle phases

The LCI for the construction phase estimates the amount of resources (materials, energy, electricity, fuel, et. al.) consumed during major construction processes such as earthwork (excavation and backfill), drilling, or concrete pours. The LCI also includes estimates of the transportation of materials or products to the construction site and to landfill for disposal.

The LCI for the operation phase includes resource consumption by equipment during maintenance tests as well as electricity consumption for continuous operation of mechanical equipment.

Background processes, such as the production of electricity, materials or products, and transportation are based on secondary data from the ecoinvent 2.2 database [11]. In contrast, foreground processes are based on primary data collected from the DHS owner and engineering consultancy in charge of its design.

General Assumptions

As previously mentioned, Stykkishólmur's DHS is considered 'state-of-the-art,' implying that modern

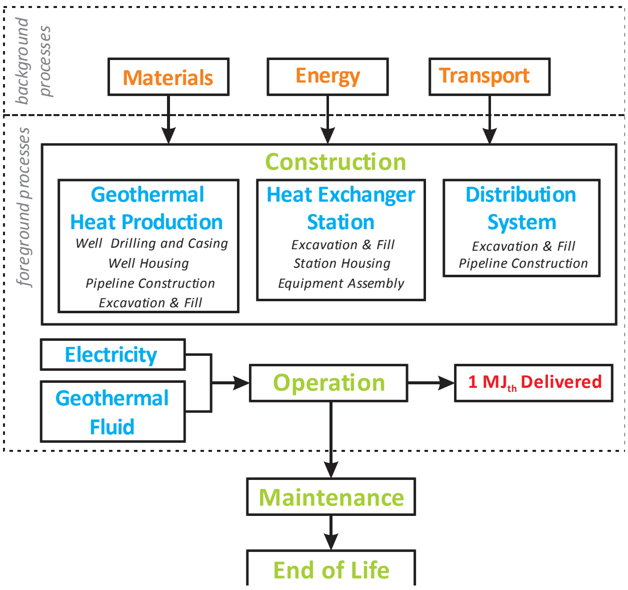

Figure 6. Life-Cycle Boundaries of the LCA case study. The maintenance and end-of-life phases are excluded, but the construction and operation phases are included. Production of materials, energy, and transportation are background processes and based on existing LCAs.

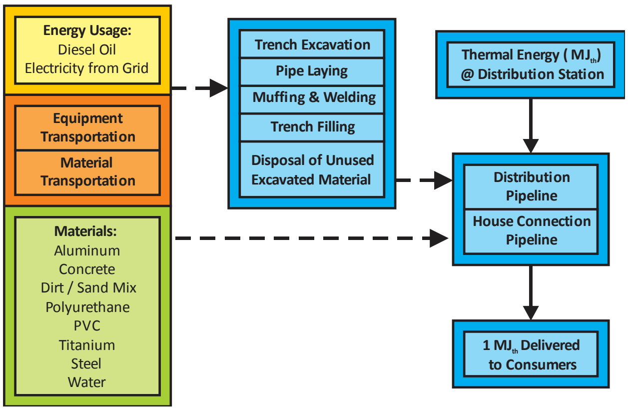

Figure 3. Flow Diagram for Geothermal Heat Production

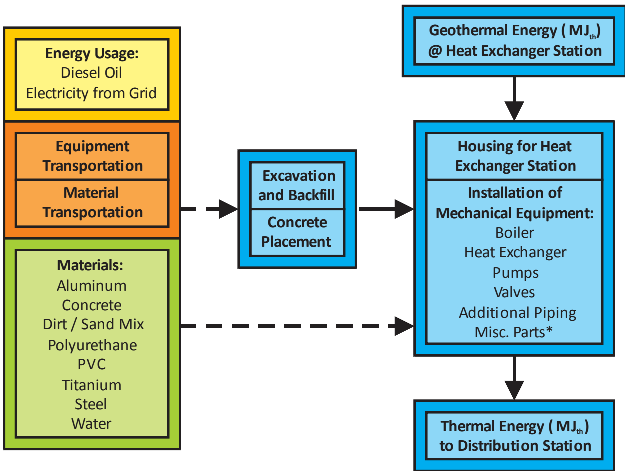

Figure 4. Flow diagram for the Heat Exchange Station.

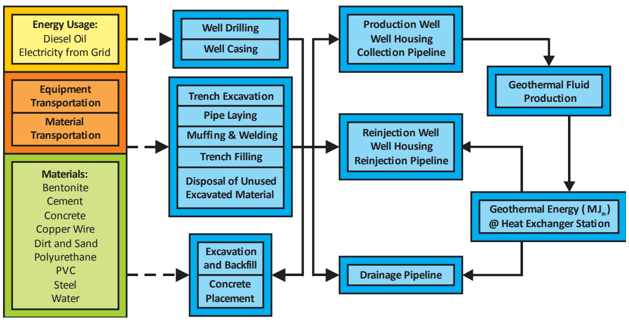

Figure 5. Flow diagram for the Distribution System.

construction techniques, equipment, and part specifications or standards were assumed when estimating material and energy quantities (e.g. standard pipe and trench dimensions).

If no primary data is available, estimations of diesel fuel consumption are based on the braking power of typical equipment used for construction processes (e.g. concrete pumping, assumed to be 80 horsepower).

Following the same assumptions as an LCA study conducted on geothermal energy systems at Argonne National Laboratory [12], a fuel consumption rate of 0.06 gallons per horsepower-hour is assumed. The impacts of earthwork were estimated with ecoinvent v. 2.2 data [11].

For all earthwork construction processes (excluding drilling), it is assumed that any backfill processes reuses excavated material before using virgin materials. Virgin materials such as sand are assumed to be local (50 km from the construction site), and any unused exaction materials are dumped to a local landfill (30 km from the construction site). Finally, steel rebar requirements for concrete housing structures are estimated to be 2% of concrete by volume and based on NREL's LCI Database [13].

Mechanical Equipment Assumptions

Estimations for the mechanical equipment (both production and operation) were included based on data availability, assumed substantial contribution to material demand (steel), and a site inspection of Stykkishólmur's district heating station. Since material data sheets were not readily available for some equipment, the nominal performance and size specifications were used to select similar equipment for which data sheets were available. Transportation estimates include shipping the equipment overseas from Hamburg, Germany (the assumed manufacturer's shipping origin) to Reykjavik, followed by ground transportation to the site of installation.

Exclusion and Additional Equipment

Many smaller pieces of equipment used by the wells and heat exchanger stations are omitted from the material estimations. These include the pressure control vessels, nitrogen tanks, the deairator and its heat exchanger, electrical equipment, and any additional pipes required for connections. Thus, an additional 1% of the distribution system's weight for steel, insulation, and PVC were added to the LCI to compensate for the weight of excluded equipment. This is a reasonable assumption since the total steel weight of all included equipment is nearly 2 orders of magnitude smaller than that of the distribution pipeline system. Thus the small addition is more than sufficient. No roadwork is currently included in the LCI.

RESULTS

To assess the environmental impacts of 1 MWh_{th} of heat delivered to users from the Stykkishólmur geothermal DHS, the LCI was modelled in SimaPro software v. 7.3.3. The life cycle impact assessment (LCIA) methods chosen are cumulative energy demand (CED) v. 1.08 to calculate the accumulated non-renewable and renewable primary energy demand per delivered heat and the CML 2 baseline 2000 v. 2.05 to calculate the global warming potential (GWP) as well as other impact categories widely assessed in LCA studies. The LCIA results are listed in Table 1 and each impact category is discussed shortly below according to definitions given in the SimaPro Database Manual describing the chosen LCIA methodologies [14].

Abiotic depletion potential (ADP) is related to extraction of minerals and fossil fuels on a global scale and presented in kg antimony equivalents (kg Sb-eq). *Acidification potential* (AP) represents impacts of acidifying substances at a local or continental scale due to emissions to air and expressed in kg SO2 eq.. *Eutrophication potential* (EP) evaluates impacts on a local or continental scale due to emissions of nutrients to air, water and soil and is given in kg PO4 eq. *Global warming potential* (GWP100) addresses climate change related to emissions of greenhouse gasses. It is expressed in kg CO2 eq. and the scope of impact is on a global scale during a time horizon of 100 years. *Ozone layer depletion potential* (ODP) takes into account the emission of different gasses and their effect on stratospheric ozone depletion on a global scale, expressed in kg CFC-11 eq. *Human toxicity* (HT) represents the effects of toxic substances on the human environment on a global or local scale, expressed in kg 1,4-dichlorobenzene eq. *Fresh water aquatic eco-toxicity* (FAETP), *marine eco-toxicity* (MAETP) and *terrestrial eco-toxicity* (TETP) refer to the impacts of toxic substances to air on either fresh water, marine or terrestrial ecosystems on a global, continental, regional or local scale. It is expressed the same way as human toxicity. Photochemical oxidation potential (POF) addresses the formation of ozone and other reactive substances that affect human health and ecosystems, often known as summer smog, It represents impacts on a local or continental scale and is expressed in kg ethylene eq (kg C2H4 eq).

The cumulative energy demand method calculates the accumulated energy use over the life cycle of the

Table 1 Life cycle impact assessment (LCIA) results calculated from the CML 2 baseline 2000 v. 2.05 and Cumulative Energy Demand (CED) v. 1.08 using SimaPro LCA software

Impact category	Acronym	Unit	Total
Abiotic depletion	ADP	kg Sb eq	0.048
Acidification	AP	kg SO2 eq	0.029
Eutrophication	EP	kg PO4 eq	0.011
Global warming	GWP100	kg CO2 eq	5.8
Ozone layer depletion	ODP	kg CFC-11 eq	4.6,E-07
Human toxicity	HTP	kg 1,4-DB eq	11.9
Fresh water aquatic ecotox.	FAETP	kg 1,4-DB eq	3.6
Marine aquatic ecotoxicity	MAETP	kg 1,4-DB eq	4990
Terrestrial ecotoxicity	TETP	kg 1,4-DB eq	0.063
Photochemical oxidation	POF	kg C2H4 eq	0.0023
Non-renewable energy	NRE	MJ	101
Renewable energy	RE	MJ	9841

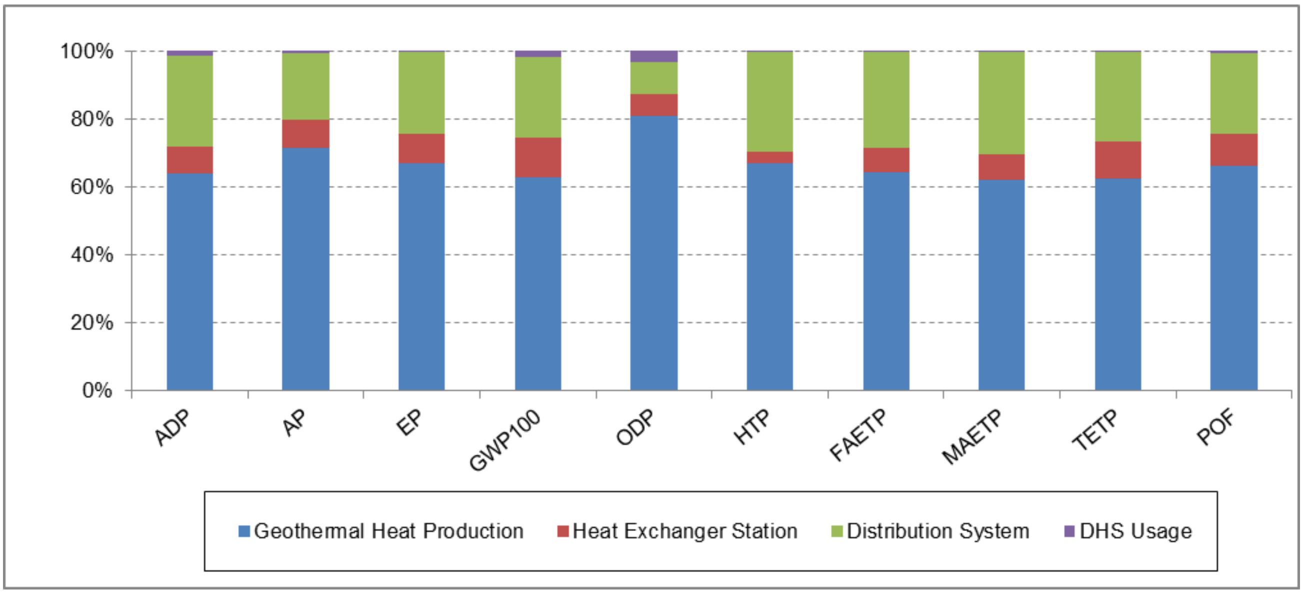

Figure 7 Relative contributions of the construction stage of different subsystems and life cycle stage for the overall DHS to the CML impact categories.

product system. The results are given in six different impact categories: (1) Non-renewable, fossil, (2) non-renewable, nuclear, (3) non-renewable, biomass, (4) renewable, biomass, (5) renewable, wind, solar and geothermal and (6) renewable water and described in the SimaPro Database Manual [14]. These impact categories are tabulated as total sums of the different non-renewable and renewable cumulative energy demand categories and presented in Table 1. Since special focus was given to the primary energy demand and carbon emissions of the delivered heat from Stykkishólmur's geothermal DHS, these values are given in and expressed both in terms of MWh_{th} and MJ delivered heat from the system.

DISCUSSION

To interpret the results of the LCIA, the relative contribution of the construction of the three sub-systems of the DHS as well as the operation life cycle stage is shown in Figure 7. The results suggest that the geothermal heat production system (including the wells and large diameter pipelines transporting geothermal fluid to and from the heat exchanger station) contributes 60% to 80% of all the impact categories in the CML 2 baseline method. The process responsible for most of the contribution of the heat production system is the production of steel used in many components within the system, especially in the pipelines. As well, the use of diesel fuel for drilling the geothermal wells is the largest contributor to the AP and contributes also heavily to EP and GWP100. Bentonite, clay commonly used during drilling of wells, is responsible for considerable portion of the AP and ODP due to its processing.

The distribution system accounts for 10-30% of the overall impacts, where steel production for the pipelines is the major contributor for all of the impacts. Copper wire, used in the district heating pipelines, contributes to the EP and MAETP impact categories while PVC plastic used for pipe cladding contributes to ADP and GWP100. Diesel used for excavation and transport of materials to site affects the ODP and polyurethane used as insulation in the DH pipes contributes to the POF.

The heat exchanger station and the operation stage of the entire system do not contribute heavily to the overall impacts. The heat exchanger station includes machinery and structural housing, but the extensive material and fuel use required for constructing the geothermal heat production and distribution systems, the impacts incurres by the station are small in comparison. During the operational phase, the main inputs to the system are geothermal fluid and electricity from renewable resources, which do not affect the overall environmental impacts evaluated in this study. However, the use of light fuel oil for testing the backup boiler, which is used to backup heat production if needed, has a small impact on some of the impact categories analysed.

For the primary energy demand, calculated with the CED method in SimaPro and presented in Table 2, the use of primary geothermal energy within the geothermal fluid dominates the renewable energy

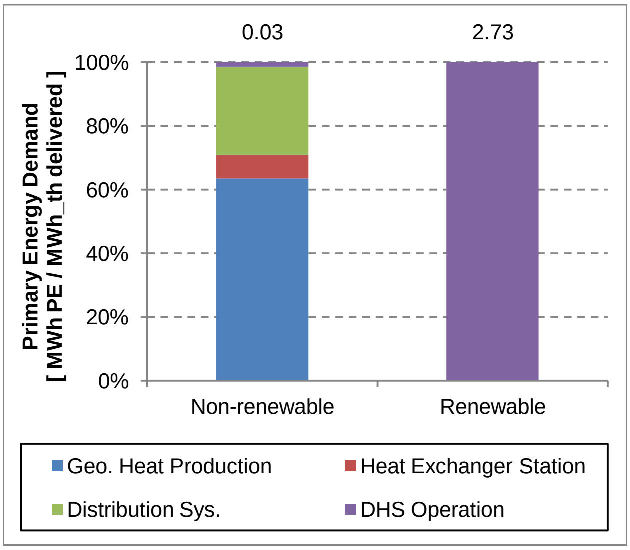

Figure 8. Contribution of Construction and Operation life-cycle phases to Primary energy consumption.

Table 3. Consumption of non-renewable energy resources during the construction phase, separated by subsystem and major subsystem components. The results displayed show the total energy consumed from each major component as an absolute value, a percent of its respective subsystem, and the overall DHS.

Subsystem	Unit	Total	% of Subsystem	% of Total	Main Contributor
Geothermal Heat Production	**MJ**	**64.0**	**100%**	**64%**	
Production Well	MJ	7.9	12%	8%	Diesel, drilling
Reinjection Well	MJ	13.6	21%	14%	Bentonite
Collection Pipeline	MJ	17.3	27%	17%	Steel production
Reinjection Pipeline	MJ	15.2	24%	15%	Steel production
Drainage Pipeline	MJ	7.8	12%	8%	Steel production
Housing Construction	MJ	2.2	3%	2%	Reinforcing steel
Distribution System	**MJ**	**27.9**	**100%**	**28%**	
Distribution Pipe Sys.	MJ	19.6	70%	20%	Steel production
House Connection Pipe Sys.	MJ	8.3	30%	8%	Steel & PVC production
Heat Exchanger Station	**MJ**	**7.4**	**100%**	**7%**	
Structural Housing	MJ	6.6	88%	7%	Reinforcing steel
Mechanical Equipment	MJ	0.9	12%	1%	Steel production

demand. The renewable primary energy demand is 9842 MJ or 2.73 MWh_{th} of geothermal energy to for the delivery of 1 MWh_{th} (~3600 MJ) of district heat to the consumer. Large amount of the primary geothermal energy demand is due to heat losses to the environment in the various sections of the DHS, both from the geothermal fluid side and the distribution side. Also, inefficient heat exchange in the heat exchanger station result in large heat losses from the system.

The non-renewable primary energy demand originates from various processes within the DHS, as seen in Figure 8. Table 3 further explains the origins of the non-renewable primary energy demand. The major contributor is the geothermal heat production system, mostly due to the production of steel for the pipelines but also due to the burning of diesel oil and the processing of bentonite used during drilling of the geothermal wells. The distribution system also contributes to the non-renewable primary energy demand due to production of steel and PVC plastic.

To put the LCIA results into perspective, an attempt to compare them with other LCA studies focusing on district heating is made. The studies on the Swedish district heating system, including pipe production [5], construction of the district heating pipe network [6] and the use of the system [7] conclude that the use phase dominates the contributions to most of the environmental impacts assessed in the study. The functional unit of that study is 100 m of pipe network, making it difficult for direct numerical comparison with the current study. Also, the use phase is modelled with two heat generation scenarios, both very different from that addressed in this study. On the other hand, for the construction of district heating pipes and the district heating system, similar results are found between the studies in that the main contributor to the environmental impacts associated with these processes are the production of materials needed for pipe production and the diesel used in equipment for the laying of pipes in trenches.

For heat production alone, the results can be compared to the study by Ghafghazi et al [8], where different base load heat sources for district heating are analysed while excluding the distribution part of the district heating system. For comparison purposes, the LCIA for Stykkishólmur was recalculated using the IMPACT 2002+ method, which was also used by Ghafghazi et al [8]. The results show that the heavy material burdens on geothermal district heat production, if long pipelines are required to transfer the geothermal fluid from wells to district heat utilization site, can result in greater environmental impacts of geothermal district heating than other base load systems evaluated in the Ghafghazi study. The impacts that were higher for Stykkishólur geothermal DHS than the baseload systems evaluated in [8] were carcinogens, mineral extraction and terrestrial ecotoxicity, all due to the steel production demand pipes within the DHS. Also, aquatic euthrophication and non-renewable energy demand was higher for the Stykkishólmur DHS in all cases except for the natural gas baseload system, mainly due to the use of steel but also PVC plastic, copper and bentonite in the geothermal heat production system. However, geothermal heat production at Stykkishólmur

Table 2 The primary energy demand and CO2 equivalent emissions from delivering 1 MWh_{th} of district heat from the Stykkishólmur geothermal DHS

Environmental impact	Unit	Non-renewable	Renewable	Total
Primary energy demand	MJ PE / MWh_{th}	101	9841	9942
	MWh_{th} PE / MWh_{th}	0.03	2.73	2.76
CO2 equivalent emission	kg CO2 eq/ MWh_{th}			5.8

had less CO2 equivalent emissions than all of the baseload cases explored in [8].

OUTLOOK

Further LCA of the different geothermal district heating systems is needed to fully understand the life cycle environmental impacts of such systems. In Iceland, a comparison can be made between single- and double distribution systems as well as comparing the different geothermal utilization alternatives for district heating, namely; (1) Direct use of geothermal fluid from low temperature areas, (2) Indirect use of geothermal fluid from low temperature areas and (3) Indirect use of geothermal fluid from high temperature areas where heat production takes place in combined heat and power plants.

CONCLUSIONS

The calculated primary energy demand for the Stykkishólmur geothermal district heating system is 9942 MJ/MWh$_{th}$ (~2.76 MWh$_{th}$/MWh$_{th}$) of district heat delivered. Thereof, 101 MJ/MWh$_{th}$ (~0.03 MWh$_{th}$/ MWh$_{th}$) originates from non-renewable sources. The primary energy demand takes into account the energy for constructing and operating the geothermal DHS and also accounts for the heat losses in the heat production system, heat exchanger station and distribution system. The heat losses account for a large part of the primary energy demand, and thus, to improve over all energy efficiency of the system, measures could potentially be made in order to reduce this primary energy loss. The main contributor of the use of non-renewable energy resources within the systems life cycle is the production of steel used in the various pipes within the system, both for heat production and district heat distribution. Also, the use of bentonite in geothermal well drilling contributes to the use of non-renewable primary energy due to its production process.

For the impact of climate change, the Stykkishólmur geothermal DHS is responsible for emitting 5.8 kg CO2/ MWh$_{th}$ of district heat delivered to its customers. The origins of the emissions are the production of steel and the use of diesel while drilling the geothermal wells. To conclude, the shorter the distances between the geothermal wells and the users of geothermal district heat, the less carbon emissions and non-renewable primary energy demand is imposed upon the delivered heat. The distance between geothermal resources suitable for utilization and the sites that utilize district heat varies greatly in Iceland and thus, different geothermal DHS will have different environmental burdens.

The extensive data collection and LCIA results of this study can further facilitate similar studies on other geothermal district heating systems in Iceland as well as other countries. The results show that environmental impacts of mechanical equipment and structural housing are minor while data collection efforts on these components are large. Thus, recommendations can be given to focus data gathering on the well drilling and material use in the pipe system along with energy use during network construction. However, energy use during operation of the system should be collected for the mechanical components if energy analysis defined as one of the goals of the study, especially if the energy use is from non-renewable sources.

ACKNOWLEDGEMENTS

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PRIMARY ENERGY ANALYSIS OF THE COLD PRODUCTION FOR CENTRALIZED AND DECENTRALIZED TRIGENERATION SYSTEMS

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ABSTRACT

The reduction of the primary energy demand for supplying process energies such as heat, electricity and cooling can be achieved with the efficient supply structure of trigeneration systems. The simultaneous supply of these process energies offers a further potential to decrease the overall primary energy demand. The conversion of primary energy is subject to specific component related efficiency constraints.

A methodology for evaluating the potential for decreasing the primary energy demand of energy supply systems can provide structure parameters which determine the size of drawbacks and benefits. A sensitivity analysis of the selected factors shows the impacts that the individual components can have on the overall primary energy efficiency.

A special focus will be based on centralized and decentralized trigeneration systems and the operating points inside the operation field. Depending on the supplied amount of process energies, especially at the operation limits, the potential amount of the total primary energy saving can be estimated.

INTRODUCTION

The efficient supply of process energies such as heat, electricity and cooling is subject to a cost-effective and sustainable energy infrastructure with a low resource demand. In times of climate change primary energy efficient solutions with low/none CO_2-emissions must be identified, implemented and evaluated. Despite technological improvements and energy efficient solutions the overall primary energy demand of industrialized countries and countries of the global south keeps on rising due to factors like life style, increasing population, increasing welfare standard, etc [1]. Further the primary energy demand related to cooling is also constantly increasing due to a rising percentage of installed glass facades in new buildings, higher cooling demands in the residential and commercial sector, excess heat sources and heat accumulation in cities, etc [2]. Cooling has become a non avoidable section of the current energy infrastructure even in regions of the northern hemisphere.

A trigeneration system providing the process energies heat, electricity and cooling can play a key role for reducing the overall primary energy demand and therefore the related CO_2-Emssions. In the last decades the installation of small to middle scale Combined Heat and Power (CHP) units has been been enforced through different legislations aiming at reducing the overall primary energy demand. The german government has decided to increase the contribution of electricity produced in CHP units to the total electricity generation up to 25% by 2020 [3]. From a legislative point of view the implementation of trigeneration systems into the legislation is an essential and fundamental basis for providing investment security and targeting a sustainable energy infrastructure with a low resource demand. A methodology for evaluating the primary energy efficiency of trigeneration systems can assist the legislative transition process and provide engineers/investors with an evaluation tool.

There are various methods for evaluating trigeneration systems, such as normative methods of the German Heat and Power Association AGFW [4] or energetical and exergoeconomic methods as in [5, 6]. A short overview is given in [7]. The methodology described in the coming pages provides a structural overview of the dimensionless groups of efficiencies in such a way that the correlation between primary energy demand and supply of process energies is clearly shown. Depending on the regarded system layout the primary energy demand of a system can be described with a single equation by taking all component related conversion losses into account. Next to a reference system a centralized and decentralized trigeneration system will be used for comparison and evaluating the influence of each system structure and the introduced structure parameters onto a possible primary energy saving.

Apart from the discussion of these structure parameters a sensitivity analysis is used for discussing further the influence of each parameter in respect to the primary energy saving. A more quantitative evaluation is given by a characteristic operation field that can be used for identifying operation boundaries and optimal operating conditions.

SYSTEM DESCRIPTION

For the supply of a building or a property (B) with electrical energy, heat and cooling primary energy is needed. In a reference system electrical energy (W^{iv}) from the electricity grid (EG) and heat (H^{i}) from a district heating system (DH) is supplied to the building (see Fig. 1). Part of the electrical energy ($W^{i\text{-}iii}$) is needed for the supply of cooling (C) and the operation of the reject heat device (RHD). The cooling is provided mainly by a conventional compression chiller (CC), a fraction ξ is provided by the principle of free cooling (FC), avoiding the operation of a compression chiller in times of low ambient air temperatures.

In the following two systems characterized by a centralized and decentralized trigeneration structure the systems will be compared to the reference system. A thermal driven (ad- or) absorption chiller (AC) is providing a fraction γ of the total cooling C needed, excluding the cooling provided by free cooling C^i. Cooling provided by a compression chiller is characterized by C^{ii}, for a thermally driven chiller by C^{iii} For γ equals zero the system is reduced to the reference system. The total cooling C provided to the building can be expressed as in (1):

$$\begin{aligned} C &= C^i + C^{ii} + C^{iii} = \\ &C \cdot \left(\xi + (1-\xi) \cdot \left((1-\gamma) + \gamma\right)\right) \end{aligned} \qquad (1)$$

In a centralized system the needed heat in order to drive the chiller H^{ii} is provided by a district heating system, increasing the overall heat demand and decreasing the demand of electricity (see Fig. 1, system A). In a decentralized system heat from a combined heat and power plant (CHP) H_1^{ii} is used primarily to drive the chiller and provide excess heat to the building (see Fig. 1, system B). The CHP decreases the supply of electrical energy W^{iv} and heat H^i from the electrical grid or a DH system respectively.

The primary energy demand of each system ($PE_{tot,ref}$, $PE_{tot,A}$, $PE_{tot,B}$) is dependent from the supply of the process energies W, H and C. Further the structure of the energy supply systems and the efficiencies of all energy converting units are determining the primary energy demand. While the primary energy needed for the external supply of electrical energy and heat is determined by the efficiency of the total electrical generation system η_{EG} and the primary energy factor f_{DH} of a DH system, the primary energy for the supply of cooling is further dependent from the efficiencies of chillers or alternative cooling devices and the fractions γ and ξ. For the decentralized system the total primary energy is further dependent from size of the CHP unit and its contribution of electrical and thermal energy.

The total primary energy for each system ($PE_{tot,ref}$, $PE_{tot,A}$, $PE_{tot,B}$) can be described as a function of the various efficiencies and factors for the conversion of primary, electrical and thermal energy, the fractions of free cooling and thermal cooling and the process energies W, H and C. For the reference system the total primary energy needed consists of the primary energy for the supply of the external electrical energy W^{iv}, which can be expressed as a sum of needed electrical energies, and the heat H:

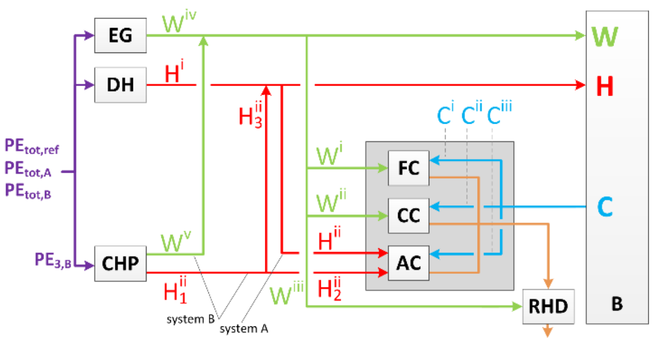

Fig. 1 Energy structure of the ref. system, system A and B

$$PE_{tot,ref} = \frac{W + W^i + W^{ii} + W^{iii}}{\eta_{EG}} + H \cdot f_{DH} \qquad (2)$$

As in (2) the equation of the total primary energy of the system A and B can be further simplified after implementing the defining equations for the energy terms $W^{i\text{-}iii}$, W^v, $C^{i\text{-}iii}$ and H_3^{ii} shown in Table 1.

The efficiencies of the mentioned cooling devices (in other words the Coefficient of Performance) describe the ratio of provided cooling to its driving energy (electrical/thermal). It is assumed that the efficiency of the reject heat device is equal to the efficiency of the free cooling unit. The electricity produced by the CHP W^v is the product of the used fuel (low heating value) and the electrical efficiency of the CHP unit η_{el}. Excess heat H_3^{ii}, ie. the difference between the gained heat of the co-generation process H_1^{ii} and the driving heat of the sorption chiller H_2^{ii}, can be further used to cover the heat load of the building or be supplied to a DH system. Processes such as extraction, treatment, conversion, transport and distribution prior to utilizing primary energy are taken into account with the primary energy factor of the used fuel f (see Table 3).

STRUCTURE PARAMETERS

With the defining equations from equation 2 and the analogue equations for the systems A and B can be simplified in such a way that the total primary energy is structured according to the primary energy needed of the CHP $PE_{3,B}$ and the process energies W, H , C. The primary energy demand of the ref. system and the system A/B is described with eq. (3)-(4):

$$\begin{aligned} PE_{tot,ref} &= \frac{W}{\eta_{EG}} + H \cdot f_{DH} + \\ &C \cdot \left[(1-\xi) \cdot \frac{1}{\varepsilon_C \cdot \eta_{EG}} + \frac{1}{\varepsilon_{co} \cdot \eta_{EG}} \cdot \left(\xi + k_{co,ref} \cdot (1-\xi)\right) \right] \end{aligned} \qquad (3)$$

$$\begin{aligned} PE_{tot,A/B} &= \frac{W}{\eta_{EG}} + H \cdot f_{DH} + \underbrace{PE_{3,B} \cdot \left(1 - \frac{\eta_{el}}{\eta_{EG} \cdot f} - \frac{\eta_{th} \cdot f_{DH}}{f}\right)}_{\text{for system } A \to 0} + \\ &C \cdot \left[(1-\xi) \cdot \left(\frac{1-\gamma}{\varepsilon_C \cdot \eta_{EG}} + \frac{\gamma \cdot f_{DH}}{\varepsilon_A} \right) + \frac{1}{\varepsilon_{co} \cdot \eta_{EG}} \cdot \left(\xi + k_{co} \cdot (1-\xi)\right) \right] \end{aligned} \qquad (4)$$

Eq. (4) contains further for systems A/B a differentiated structure of the efficiencies related to cooling and a term for the primary energy $PE_{3,B}$ for the CHP of system B (for system A this term is neglected). Due to the co-production latter term provides the information of an increasing or decreasing primary energy demand $PE_{tot,B}$ for constant efficiencies and a fuel dependent primary energy factor *f*. As a result of expressing the total primary energy demand of system B as a function of the primary energy $PE_{3,B}$ (possible also as a function of the produced electricity W^{v}) the primary energy efficiency of this system can be evaluated directly. The parameters $k_{co,ref}$ and k_{co} account for the necessity of heat rejection to the environment for the reference system and the systems A/B:

$$k_{co,ref} = 1 + \frac{1}{\varepsilon_C} + \underbrace{\gamma \cdot \left(\frac{1}{\varepsilon_A} - \frac{1}{\varepsilon_C}\right)}_{for\,reference system \to 0}$$

The relative primary energy saving $pee_{A/B}$ is defined by eq. (5):

$$pee_{A/B} = \frac{\left(PE_{tot,ref} - PE_{tot,A/B}\right)}{C} \quad (5)$$

For values below 0 the primary energy demand of the system A or B is higher than the reference system. Embedding eq. (4) into eq. (5) leads to a summarized equation for the primary energy demand of both systems:

$$pee_{A/B} = \gamma \cdot (1-\xi) \cdot (k_1 - k_2) + \underbrace{\frac{PE_{3,B}}{C} \cdot k_3}_{for\ system\ A \to 0} \quad (6)$$

The structure parameters k_1, k_2 and k_3 are defined as follows:

$$k_1 = \frac{1}{\eta_{EG} \cdot \varepsilon_C} - \frac{f_{DH}}{\varepsilon_A} \quad (7)$$

$$k_2 = \frac{1}{\eta_{EG} \cdot \varepsilon_{co}} \cdot \left(\frac{1}{\varepsilon_A} - \frac{1}{\varepsilon_C}\right) \quad (8)$$

$$k_3 = \frac{\eta_{el}}{\eta_{EG} \cdot f} + \frac{\eta_{th} \cdot f_{DH}}{f} - 1 \quad (9)$$

The primary energy saving of the system A and B is linear proportional to the fraction of the thermal driven chiller γ and further to the utilized primary energy $PE_{3,B}$ of the CHP in system B. As a result the primary energy saving of a decentralized system (system B) can always be higher than a centralized system (system A). In case (k_1- k_2) and/or k_3 become negative the systems A or B have a higher primary energy demand than the reference system.

The primary energy efficiency for the supply of cooling is described by the structure parameter k_1, while the structure parameter k_2 takes into account the primary energy demand for rejecting heat of the cooling process. The structure parameter k_3 describes further the primary energy efficiency of a CHP extended system.

Table 1 Definition of equations for various energy terms

	defining equation	**system**	**description**
W^{i}	$K \cdot \xi \cdot \frac{1}{\varepsilon_{co}}$	A,B ref	driving energy FC
W^{ii}	$K \cdot (1-\xi) \cdot \frac{(1-\gamma)}{\varepsilon_C}$		driving energy CC
W^{iii}	$K \cdot (1-\xi) \cdot \frac{k_{co}}{\varepsilon_{co}}$		Driving energy RHD
H^{ii} or H_2^{ii}	$K \cdot (1-\xi) \cdot \frac{\gamma}{\varepsilon_A}$	A,B	driving heat AC
W^{v}	$PE_{3,B} \cdot \frac{\eta_{el}}{f}$	B	produced electricity CHP
H_3^{ii}	$PE_{3,B} \cdot \frac{\eta_{th}}{f} - K \cdot (1-\xi) \cdot \frac{\gamma}{\varepsilon_A}$	B	excess heat CHP

Structurally seen these parameters influence the primary energy saving $pee_{A/B}$. From a quantitative point of view the absolute primary energy saving is determined by the fraction γ or the contribution of the co-generation unit.

SENSITIVITY ANALYSIS

In the following the influence of each parameter in respect to the primary energy saving will be analysed with a sensitivity analysis.

Relative differential sensitivity

The formation of differential quotients for each parameters allows an analytical assessment of the sensitivity of the relative primary energy saving $pee_{A/B}$. The differential quotient $pee'_{A/B,i}$ describes the partial derivative of the relative primary energy saving $pee_{A/B}$ to a parameter *i* as shown by eq. (10) and (11):

$$pee'_{A,i} = \frac{\partial pee_A}{\partial i} = \gamma \cdot (1-\xi) \cdot \frac{\partial (k_1 - k_2)}{\partial i} \quad (10)$$

$$pee'_{B,i} = \frac{\partial pee_A}{\partial i} + \frac{PE_{3,B}}{C} \cdot \frac{\partial k_3}{\partial i} \quad (11)$$

In order to compare the differential quotients for each parameter more closely the relative change of a parameter $\partial i/i$ is taken into account in eq. (12)-(13):

$$pee'_{A,i,\%} = \frac{\partial pee_A}{\partial i / i} = \gamma \cdot (1-\xi) \cdot \frac{\partial (k_1 - k_2)}{\partial i / i} \quad (12)$$

$$pee'_{B,i,\%} = \frac{\partial pee_A}{\partial i / i} + \frac{PE_{3,B}}{C} \cdot \frac{\partial k_3}{\partial i / i} \quad (13)$$

In Table *2* the resulting relative differential quotients for both systems are listed. The differential quotient of the parameters related to cooling (ε_C, ε_A, ε_{co}) are identical.

The sensitivity of system A is dependent from the fraction of sorption cooling $\gamma \cdot (1-\xi)$, whereas in system B the ratio of primary energy of the CHP to the total cooling ($PE_{3,B} / C$) is further an influencing factor. Although these weighting factors influence quantitatively the primary energy saving, they are subject to operation boundaries and hence not arbitrary.

The partial derivative of the relative primary energy saving to the primary energy factor f_{DH} for system A shows that only the structural parameter k_1 and thus the primary energy efficiency for the supply of cooling is linear proportional to a change. The differential quotient $\partial pee_A / (\partial f_{DH} / f_{DH})$ is negative due to the decrease of the primary energy saving with an increasing primary energy factor f_{DH}. Table 2 shows that the relative differential quotients for the efficiencies of the DH system and the electricity grid influence further the co-generation of heat and electricity of the CHP unit

Table 2 Relative differential quotients of the relative primary energy saving for system A and B

	system A and B			system B
i	$\frac{\partial k_1}{\partial i/i}$	$\frac{\partial k_{12}}{\partial i/i}$	$\frac{1}{\gamma \cdot (1-\xi)} \cdot \frac{\partial pee_A}{\partial i/i}$	$\frac{PE_{3,B}}{C} \cdot \frac{\partial k_3}{\partial i/i}$
η_{EG}	$\frac{-1}{\eta_{EG} \cdot \varepsilon_C}$	$-k_2$	$k_2 - \frac{1}{\eta_{EG} \cdot \varepsilon_C}$	$-\frac{PE_{3,B}}{C} \cdot \frac{\eta_{el}}{\eta_{EG} \cdot f}$
f_{DH}	$\frac{-f_{DH}}{\varepsilon_A}$	-	$-\frac{f_{DH}}{\varepsilon_A}$	$\frac{PE_{3,B}}{C} \cdot \frac{f_{DH} \cdot \eta_{th}}{f}$
f	-	-	-	$-\frac{PE_{3,B}}{C} \cdot (k_3 - 1)$
η_{el}	-	-	-	$\frac{PE_{3,B}}{C} \cdot \frac{\eta_{el}}{\eta_{EG} \cdot f}$
η_{th}	-	-	-	$\frac{PE_{3,B}}{C} \cdot \frac{f_{DH} \cdot \eta_{th}}{f}$
ε_C	$\frac{-1}{\eta_{EG} \cdot \varepsilon_C}$	$\frac{1}{\eta_{EG} \cdot \varepsilon_{co} \cdot \varepsilon_C}$	$\frac{-1}{\eta_{EG} \cdot \varepsilon_C} \cdot \left(1 + \frac{1}{\varepsilon_{co}}\right)$	-
ε_A	$\frac{f_{DH}}{\varepsilon_A}$	$\frac{-1}{\eta_{EG} \cdot \varepsilon_{co} \cdot \varepsilon_A}$	$\frac{1}{\varepsilon_A} \cdot \left(f_{DH} + \frac{1}{\varepsilon_{co} \cdot \eta_{EG}}\right)$	-
ε_{co}	-	$-k_2$	k_2	-
$PE_{3,B}$	-	-	-	$\frac{PE_{3,B}}{C} \cdot k_3$

In comparison to system A the partial derivative $\partial k_3 / (\partial f_{DH} / f_{DH})$ is positive due to an increase of the primary energy saving of system B with higher values for the primary energy factor f_{DH}. As a result the potential for increasing the primary energy saving increases with higher primary energy factors f_{DH}. At an efficient operation of the CHP ($k_3 > 0$) the external supply of heat and electricity is substituted.

The relative differential quotients of the structure parameters $\partial(k_1-k_2) / (\partial i/i)$ and $\partial k_3 / (\partial i/i)$ from eq. (12) and (13) are shown in Fig. 2. The reference parameters of Table 3 are taken into account. For the efficiency of the electricity generation the german primary energy factor for electricity mix is assumed ($f_{EG}=1/\eta_{EG}=2{,}8$ [8]). Further a primary energy efficient DH system with a high fraction of biogenic fuels is regarded ($f_{DH}=0{,}16$), f_{DH} is 75% below the average efficiency of district heating in Germany [9]. The remaining efficiencies of the cooling units represent energy efficient conversion units.

For the decentralized system a relative change of the efficiency of the conventional chiller ε_C has the highest impact on the relative primary energy saving pee_A followed by a relative change of the efficiency of a thermal driven chiller ε_A. Changing the efficiency of the electricity generation η_{EG} is of high influence as well, except that the efficiency is dependent from the overall improvements in the electricity generation or an increase of the contribution of electricity from renewable energies. Changes in the efficiency of reject heat devices and in DH system show approx. the same impact on their relative differential quotients.

For the system B the partial derivative of the relative primary energy saving pee_B is dependent from the used fuel. With low primary energy factors (biogenic fuels) of the used fuel a relative change of the parameters (η_{EG}, f, f_{DH}, η_{th}, η_{el}) shows a much higher potential for a primary energy saving than with high primary energy factors (fossil fuels). A change of the electrical efficiency of the CHP unit (η_{el}) or the electricity generation (η_{EG}) has a higher influence on the primary energy saving of the system B than a change of thermal efficiency of the CHP unit (η_{th}) or the district heating system (f_{DH}).

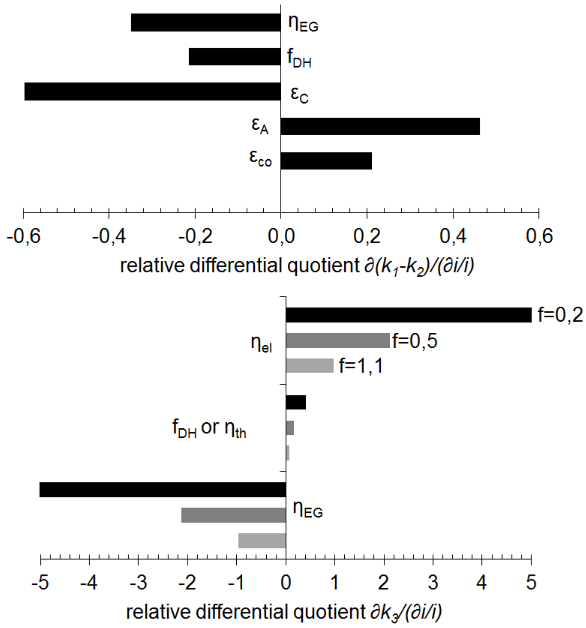

Fig. 2 Relative differential quotients for the system A and B

Relative integral sensitivity

While the differential analysis describes the influence of a parameter variation on the result, the integral sensitivity provides the maximum deviation of the result when varying a single a parameter. For the boundaries given in Table 3 a parameter variation for each component efficiency will be conducted. At the same time all remaining parameters keep their reference value.

The change of the relative primary energy saving pee_A is δ_A. Further the change of the relative primary energy saving in respect to the influence of the CHP unit is δ_B. For the given reference values in Table 3 the relative primary energy saving for system A is $pee_{A,0}$, for varying the parameter i it is $pee_{A,i}$. For system A the integral relative change of the primary energy saving $\delta_{A,i}$ results as follows:

$$\delta_{A,i} = \frac{pee_{A,i} - pee_{A,0}}{\left|pee_{A,0}\right|} \tag{14}$$

Implementing eq. (6) into eq. (14) leads to:

$$\delta_{A,i} = \frac{(k_{11}-k_{12})_i - (k_{11}-k_{12})_0}{\left|(k_{11}-k_{12})_0\right|} = \frac{(k_{11}-k_{12})_i}{\left|(k_{11}-k_{12})_0\right|} - 1 \tag{15}$$

For system B only the influence of the CHP unit is taken under consideration. The integral relative change of the primary energy saving $\delta_{B,i}$ that is influenced by the variation of a parameter i is solely in relation to the co-generation. $\delta_{B,i}$ is expressed as follows:

$$\delta_{B,i} = \frac{(pee_B - pee_A)_i - (pee_B - pee_A)_0}{\left|(pee_B - pee_A)_0\right|} \tag{16}$$

Implementing eq. (6) into eq. (16) leads to:

$$\delta_{B,i} = \frac{(k_{13})_i - (k_{13})_0}{\left|(k_{13})_0\right|} = \frac{(k_{13})_i}{\left|(k_{13})_0\right|} - 1 \tag{17}$$

For eq. (15) to (17) the primary energy saving increases when the difference of the relative primary energy saving between varied parameter and reference parameter (for system A: $(pee_{A,i}–pee_{A,0})$ and for system B $(pee_B\text{-}pee_A)_i\text{-}(pee_B\text{-}pee_A)_0$ respectively) is higher than zero. Since the structure parameters k_1, k_2 and k_3 can become negative, the absolute value of the denominator in eq. (15) to (17) is considered. For values $\delta_{A,i}$ and $\delta_{B,I}$ higher than zero the primary energy saving increases with a variation of a parameter i.

The variation range must be selected in such a way that the varied efficiencies represent realistic values. The total efficiency of the CHP unit is the sum of the electrical and thermal efficiency $(\eta_{ges}= \eta_{el} + \eta_{th})$ and stays constant. As a result the thermal efficiency η_{th} is varied in the counter direction of the electrical efficiency η_{el}. The efficiency of the electricity generation differs nationally due to the different national energy supply structures. For the efficiency η_{EG} in Germany it is assumed that in the following years the contribution of renewables energies to the total electricity production along technological improvements will result in an increase of η_{EG}. The integration of CO_2-capture in the electricity production or a phasing out of nuclear energy can lead to overall efficiency decreases. Nonetheless these aspects are of minor importance and do not affect the overall increase of η_{EG}. The lowest efficiency of 0,2 accounts for countries of the global south with possible low efficiencies in the electricity production. For multistage absorption chillers a maximum COP of 1,2 is assumed.

Table 3 Values for the reference parameters, variation range and threshold values

I	variation range ref	min	max	threshold value	unit
η_{EG}	0,36	0,20	0,77	0,58	kWh_{el} / kWh_{pe}
f_{DH}	0,16	0	0,50	0,26	kWh_{pe} / kWh_{th}
η_{el}	0,38	0,15	0,66	0,35	kWh_{el} / kWh_{fuel}
η_{ges}	0,88	0,88	0,88	-	kWh / kWh_{fuel}
ε_C	5	2	10	6,5	kWh_{co} / kWh_{el}
ε_A	0,75	0,30	1,20	0,6	kWh_{co} / kWh_{th}
ε_{co}	15	6	40	9,2	$kWh_{co/th}$ / kWh_{el}
f	0,2/0,5/1,1(biogenic solid/gas fuels +fossil fuels) [9]				

The threshold values in Table 3 describe the value for which the primary energy saving of system A is zero $(pee_A=0)$. For example system A leads to no primary energy savings when a compression chiller with a COP of 10 is implemented. Assuming a primary energy factor for a used fossil fuel of 1,1 the co-generation reaches a primary energy saving of zero for the threshold values η_{el}=0,35 or η_{th}=0,55. For these threshold values the structure parameter k_3 becomes zero.

Fig. 3 shows the results of the parameter variation. Each curve shows the relative change in primary energy saving for the varying a parameter i within the given variation range of Table 3. For a decrease of the primary energy saving of more than 100%, for which the value of the relative change of primary energy saving is $\delta_{A,i}<-1$, the variation of the parameter i leads to a higher primary energy demand than the reference system. As a result the threshold value for the varied parameter i can be found at $\delta_{A,i}=-1$.

As already shown in Fig. 2 the potential for a primary energy saving is increased by a factor of 5 or 8 for decreasing efficiencies of the electricity generation $(\eta_{EG} \rightarrow 0,2)$ or the compression chiller $(\varepsilon_C \rightarrow 2)$. The reduction of η_{EG} leads to a higher primary energy demand for the supply of electricity from the grid, so that system A benefits stronger than the reference system. In a similar way the reduction of ε_C leads to a higher primary energy demand of the reference system. The potential for a primary energy saving increases for lower primary energy factors of the DH system f_{DH} due to the higher primary energy efficiency of the cooling with thermal driven chillers.

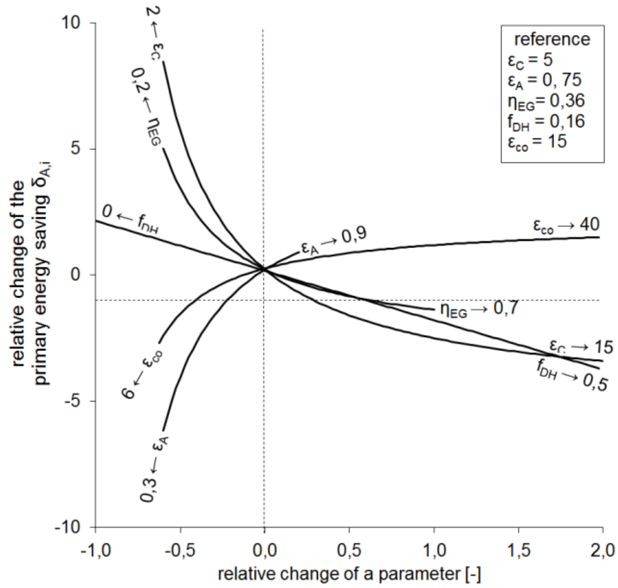

Fig. 3 Influence of each parameter on the integral relative primary energy saving of system A

While the influence of the district heating efficiency is linear, a variation of the remaining *parameters* (η_{EG}, ε_A, ε_C, ε_{co}) shows an asymptotic curve.

Fig. 4 shows the influence of a parameter variation on the relative change of primary energy saving for the CHP unit. In contrast to system A and similar to Fig. 2 the potential for primary energy saving of system B increases slightly for higher primary energy factor f_{DH} Analogue increases of the primary energy saving are achieved with a decreasing efficiency of the electricity generation ($\eta_{EG} \rightarrow$ 0,2) or an increase of the electrical efficiency ($\eta_{el} \rightarrow$ 0,7) of the CHP unit. The variation of the primary energy factor for the used fuel *f* has the same impact on the primary energy saving as the efficiency of the electricity generation η_{EG}.

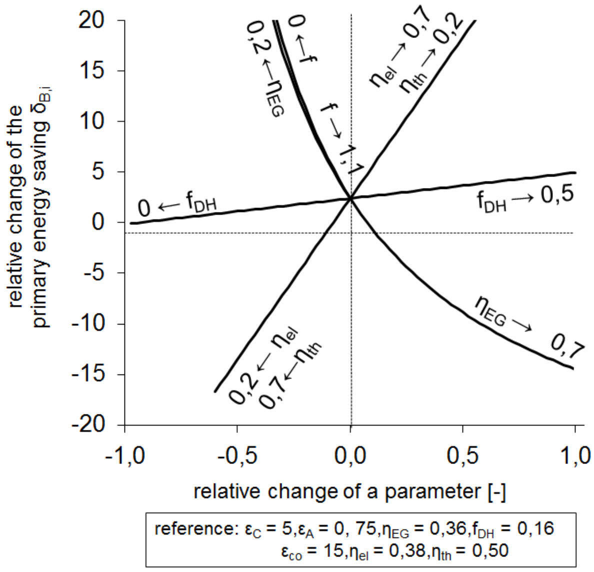

Fig. 4 Influence of each parameter on the integral relative primary energy saving of the CHP unit

Both Fig. 3 and Fig. 4 show that a variation of some parameters can easily result in a doubled primary energy saving or even an increased primary energy demand for system A or B. While the primary energy factors and the efficiency of the electrical generation are quite known and therefor normative, the remaining efficiencies for the cooling (ε_C, ε_A, ε_{co}) are subject to the design of the system, the commissioning and the operating point of the energy converting units.

CHARACTERISTICS OF THE OPERATION FIELD

A quantitative evaluation of the systems A and B for known process energy demands *(W, H, C)* gives a further insight into process and supply related boundaries and the overall achievable primary energy saving.

Since in system A the driving energy for the thermal driven chiller is heat from a DH network the electricity supply for providing cooling via a compression chiller is reduced. Assuming constant structure parameters k_1 and k_2 eq. (10) shows that the primary energy saving pee_A is linear proportional to the contribution of the sorption chiller. The fraction ξ is neglectable since it is assumed to be equal in all systems. As a result the primary energy saving in system A can be described with an operation line $pee(\gamma)$.

Due to the primary energy demand of the CHP unit in system B an operation field $pee(\gamma, PE_{3,B})$ describes any primary energy savings that are subject to low and high boundaries. While the efficiencies and the known process energy demands are kept constant in the operation field, the following ratios are varied:

- fraction of the total cooling provided by an (ad- or) absorption chiller γ (excl. free cooling)
- primary energy demand of the CHP unit $PE_{3,B}$

The ratio of the CHP supplied electricity to the total electricity demand x_W ($x_W = W^v / (W+W^i+W^{ii}+W^{iii})$) is directly linear coupled with $PE_{3,B}$ and is a more common known parameter. Similar the ratio x_H describes the contribution of the generated heat to the total heat demand ($x_H = H_1^{ii} / (H+ H_2^{ii})$). Fig. 5 shows in grey colour qualitative a three-dimensional operation field that is described by γ, $pee_{A/B}$ and x_W. This field is formed by $\overline{AEX_2X_3}$ and is part of the plane $\overline{AX_1X_2X_3}$. The inclination of the operation field and its plane towards the relative primary energy saving $pee_{A/B}$ describes the cooling efficiency due to thermal driven chillers and is given by the difference of the structure parameters k_1-k_2 (see $\sphericalangle X_1AX_{01}$ in Fig. 5). The operation line for system A is given by $\overline{AX_1}$. With increasing values for the difference k_1-k_2 the inclination of the operation line for system A (and consequently operation field for system B) gains, so that the relative primary energy saving $pee_{A/B}$ increases.

Independently from the fraction *γ* the inclination of the operation field towards the fraction x_W describes the primary energy efficiency of a CHP expanded system (see ∢ X_3AX_{10} in Fig. 5). The partial derivative of the relative primary energy saving of system B to the primary energy demand $PE_{3,B}$ is expressed by the differential quotient $\partial pee_B / \partial PE_{3,B}$. This quotient shows the ratio of the structure parameter k_3 to the total cooling *C* and evaluates the potential for a primary energy saving with a decentralized trigeneration system. In Fig. 5 a ratio of electricity demand *W* to heat demand *H* to cooling demand *C* of 1:1:1,2 is taken into consideration.

In the following the various operation conditions will be described.

District heating for the thermal driven chiller

The operation line $\overline{AX_1}$ shows the quantitative influence of the increasing fraction *γ* on the relative primary energy saving for system A. Starting from point A a linear increase of the relative primary energy saving of up to 0,16 can be achieved (point X_1) if all cooling is provided by an (ad- or) absorption chiller. As shown in the following the effect of a centralized trigeneration system is no comparison to a decentralized system.

Heat from CHP for covering the building heat demand

A higher relative primary energy saving can be reached through a higher contribution of the CHP unit to the totally needed electricity or heat. On the operation line $\overline{AF}$ the CHP unit covers only the heat and electricity demand of the building, demonstrating in such an operation mode a singular decentralized co-generation system. In this case the cooling is provided similar to the reference system solely by a compression chiller. In point B the total heat demand of the building is covered by the CHP unit *(x_H=100%)* and a relative primary energy saving of 0,31 can be achieved.

For higher inputs of primary energy for the co-generation unit $PE_{3,B}$ and an export of the generated heat into a DH system the total electricity demand of the building is covered in point F *(x_W=100%)*. If generated heat cannot be exported or fed into an existing DH network then only by means of a thermal driven chiller and increasing fraction of *γ* is a further use of the heat from the CHP unit possible. With an increase of $PE_{3,B}$ from point B and a further conversion of the excess heat into cooling (increasing *γ* fraction) the relative primary energy saving of system B can rise according to the line $\overline{BC}$. Point C describes the operation condition in which both the electricity and heat demand of the building is covered by the CHP unit *(x_H=100%, x_W=100%)*. A relative primary energy saving of 0,39 can be reached.

Heat from CHP for driving the sorption chiller

The CHP unit provides solely heat for driving the sorption chiller according to the line $\overline{AD}$ or $\overline{ADE}$. Starting from point A and with an increasing fraction *γ* a relative primary energy saving of 0,50 can be achieved in point D (ending for *γ=1* with pee_B of 0,62 in point E, x_W=125%). In point D the thermal driven chiller covers approx. 80% of the total cooling demand of the building, while the generated electricity of the CHP unit can cover the total electricity demand of the building *(x_W=100%)*. Similar to the operation line $\overline{AF}$ and for higher inputs of primary energy for the CHP unit $PE_{3,B}$ the provided (ad- or) absorption cooling, driven further with excess heat from the co-generation, can cover the total cooling demand of the building (point E, *γ=1*). The relative primary energy saving is increased further to 0,62. The line $\overline{DE}$ describes operating points with a surplus of the CHP produced electricity that can be fed in a similar way into an external electricity network.

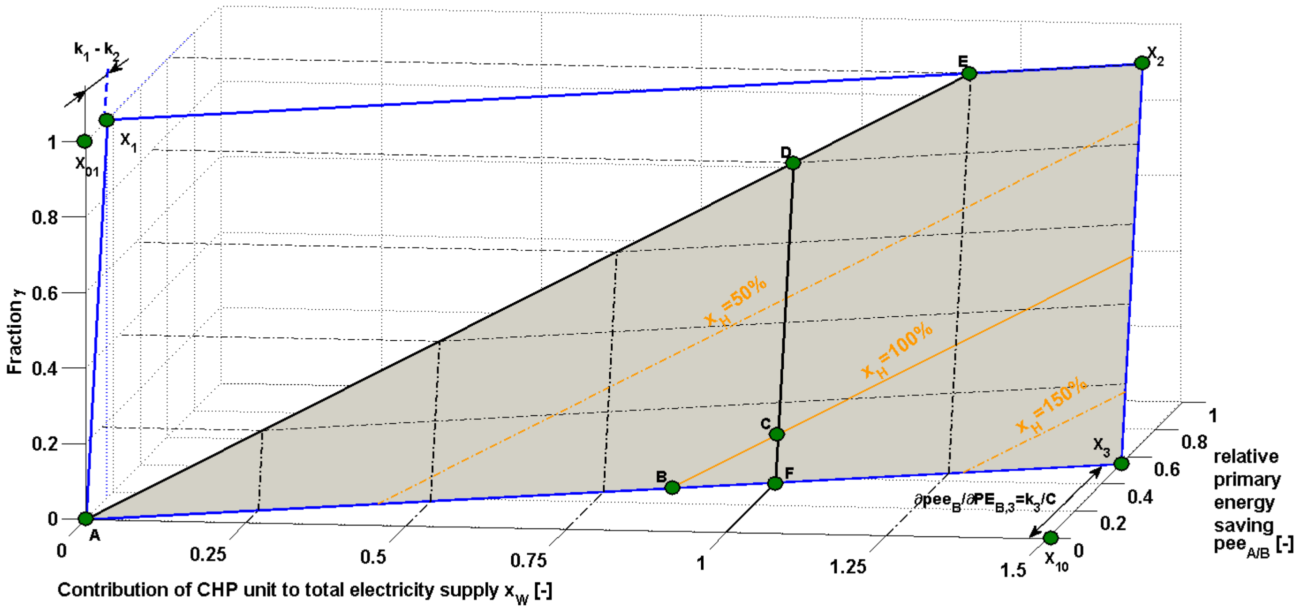

Fig. 5 Relation of *γ*, $pee_{A/B}$ and x_W for various operating points of the CHP unit (used parameters: *f=0,5*, ε_{co}*=20*, ε_C*=3*, remaining reference parameters taken from Table 3)

Combined supply of heating and cooling

The line $\overline{AE}$ describes operating conditions for which the generated heat from the CHP unit is completely utilized by an (ad- or) absorption chiller. The further heat demand of the building *H* is supplied with heat from a district heating network. By increasing the primary energy demand of the CHP unit $PE_{3,B}$ at a constant fraction γ the primary energy demand associated to the supply of DH is reduced. At the same time due to higher fractions x_H and x_W the supply of electricity from the electricity grid is also minimized. As a result of higher fractions x_H the operation of the decentralized trigeneration system is shifted away from the operation line $\overline{AE}$ into the grey operation field. Dashed lines parallel to the line $\overline{AE}$ describe operation points with a constant heat fraction x_H.

The plane $\overline{ABCD}$ shows an operation field for system B where no energies leave the system boundaries. A co-generation system with the assumed parameters could achieve a maximum relative primary energy saving of 0,31 (point B). If this system is expanded by an (ad- or) absorption chiller the relative primary energy saving can be increased by 62% to 0,5 (point D). The extension of a CHP system into a trigeneration system is essential for reaching higher primary energy efficiencies. A further potential for primary energy savings can result from the export of heat and electrical energy into external networks.

While the utilization of excess heat from decentralized trigeneration systems in DH networks is uncommon, the supply of excess electricity at high (ad- or) absorption cooling fractions γ especially in peak cooling seasons can benefit the utilization and strengthen the economic feasibility of trigeneration systems.

CONCLUSION

The introduced methodology for evaluating the potential for primary energy savings of centralized and decentralized systems allows a simple and compact overview of the structure of such systems primary energy demand and their conversion losses. A sensitivity analysis and the formation of differential quotients show the influence of each efficiency parameter on the primary energy saving. Further a parameter variation for a given variation range gives a qualitative insight into the potential for a primary energy saving.

The primary energy efficiency of a centralized system with an (ad- or) absorption driven by heat from a district heating system is strongly dependent from the cooling efficiency and the primary energy related efficiency of the district heating system. For decentralized systems the overall primary energy efficiency is influenced strongly by the contribution of the CHP unit to the provided process energies and the used fuel.

The primary energy saving can be described quantitatively by an operation field for system B or an operation line for system A. For a single co-generation system the limiting factor for achieving high primary energy saving is often the heat demand. On the other hand a decentralized trigeneration system can increase the relative primary energy saving of a single co-generation system compared to classical reference systems by 60%. Depending of the operation conditions relative primary energy saving up to 0,5 are possible. Higher efficiencies can be reached when process energies such as electricity, heat and/or cooling can be exported to external networks. Also thermal storages (at low/high temperature level) for decoupling heat/cold demand and load can increase the fraction of (ad-) or absorption cooling and contribute to a further increase or primary energy savings.

The introduced methodology provides the possibility of evaluating systems with heat pumps and/or thermal storages. Moreover an assessment in respect to CO_2-emissions or investment costs can assist in the evaluation of such systems from an economical or ecological point of view.

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SESSION 12

Key elements in District Heating and Cooling systems

CYCLIC LATERAL SOIL RESISTANCE ON DISTRICT HEATING PIPES

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ABSTRACT

The soil resistances in axial and lateral direction strongly affect the behavior of earth-buried district heating pipes under variable operating temperatures. The state of knowledge regarding these resistance forces is summarized, and it is shown that almost now information exists regarding the cyclic effects on lateral soil resistances. A numerical model with an advanced material law for the stress-strain characteristics of sand is presented. Results gained from this model are compared to results from an experimental test with cyclic lateral loading of a pipe. The investigations give a first insight into the behavior of cyclic laterally loaded district heating pipes. One important result is that the un- and reloading curves in a deformation-controlled test are almost independent of the absolute displacement limits, but only dependent on the cyclic displacement amplitude. It is shown that the developed numerical model is capable of reflecting the main features of the complex system behaviour.

INTRODUCTION

District heating (DH) pipes are in most cases buried in soil. Due to the varying temperature loading of the pipes during operation, the pipe tends to elongate and shorten permanently. This causes a strong interaction of the pipe with the surrounding soil, since the movement of the pipe is hindered by friction forces and – if a lateral movement occurs – by lateral bedding forces.

The varying operation temperatures cause a cyclic movement of axial as well as lateral deformations. Therefore, the soil resistances under loading and unloading have to be distinguished, and the change of the resistances with cyclic loading, i.e. with the number of load cycles, has to be taken into account in the prediction of the pipe behavior.

One effect of the change of the friction forces with cyclic loading is, for instance, that the pipe deformation measured at an arc section, i.e. at the end of a straight pipe section, tends to increase with time. Fig. 1 shows measurement results from a district heating pipe in operation. The observation over 2 years shows that the displacement under the maximum operation temperature of 110°C increases significantly. The reason for this behavior is a reduction of friction forces in the straight pipe section due to cyclic un- and reloading.

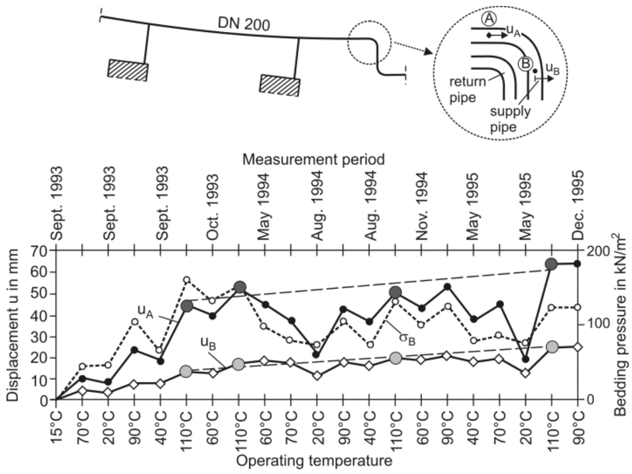

Fig. 1 Measurement results for deflections and bedding pressures in an arc section of a DH pipe [1]

Fig. 1 also shows the results of earth pressure measurements in the arc section directly beneath the pipe. Due to the variation of the lateral deflection with the operating temperature, also the bedding pressures vary. However, although the maximum deflection increases with time, the maximum bedding pressure tends to be constant or even to decrease slightly.

The behavior of the pipe-soil system is of course affected by the features of both soil resistances, i.e. friction forces and lateral resistances. The cyclic features of the friction forces have been subject of a number of investigations in the past ([1]-[4]). In contrast, cyclic lateral soil resistances have not been investigated so far.

In a research project funded by the German Federal Ministry for Economic Affairs and Energy, the cyclic features of lateral soil resistances on pipes are investigated. Herein, experimental tests and numerical simulations are carried out.

This paper firstly outlines the state of knowledge regarding the friction forces and lateral resistances acting on district heating pipes. Then a numerical model for the calculation of lateral soil resistances under monotonic and cyclic loading is presented. Finally, the first results of experimental tests, which shall be used for calibration and validation of the numerical model, are shown.

STATE OF KNOWLEDGE

Friction forces

It is well known from experimental investigations that the friction force acting on a district heating pipeline is not constant, but is dependent on the operating temperature, i.e. the temperature of the heat-transporting medium. The reason for this is the increase in the radial earth pressure due to the radial expansion of the pipe induced by the temperature increase. Additionally, the friction forces for the first loading or movement of the pipeline are different from the friction forces for repeated loading and unloading.

Fig. 2 gives experimental results for friction forces on pipes of nominal widths DN 150 and DN 250 (Gietzelt et al. [5]). A temperature-induced increase of the friction forces for first loading and an even more pronounced temperature-dependence of the friction forces for unloading and reloading were observed.

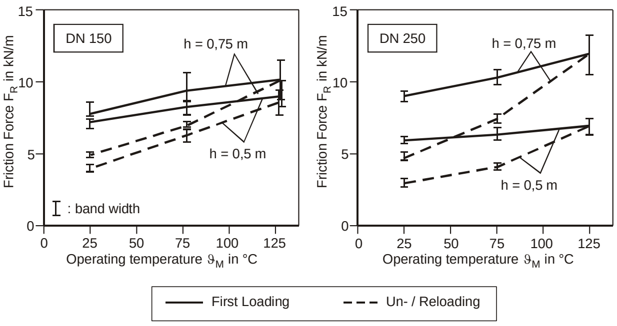

Fig. 2 Experimentally determined friction forces on plastic jacket pipes DN 150 and DN 250 for first loading and un-/reloading [5]

Weidlich [4] investigated the reduction of friction forces on pipes under cyclic axial displacements. Results of experimental tests are shown in Fig. 3. The reduction factor D_F indicates the maximum friction force with respect to the friction forces measured in the first cycle, i.e. under monotonic loading. In the example of a DN 65 pipe with an overburden height of 42 cm given in Fig. 3, both for medium and dense sand a decrease of the friction forces of almost 50% after the first 10 cycles was observed. In [4], recommendations are given for the determination of the reduction factor dependent on relative overburden height.

Lateral soil resistances

The system under consideration and the denominations are depicted in Fig. 4. The problem to be dealt with is to predict the lateral resistance force F_B or the average bedding pressure p dependent on the lateral deflection v.

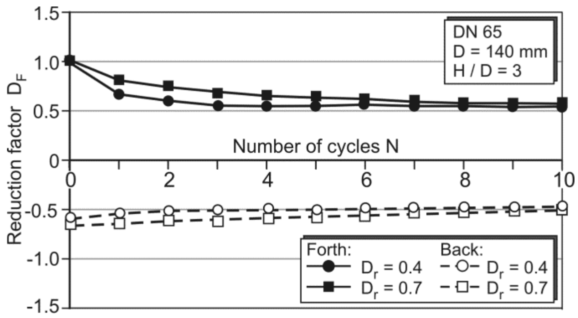

Fig. 3 Experimental results on the decrease of friction forces with cyclic axial displacement [4]

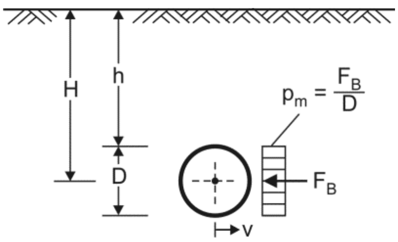

Fig. 4 System and denominations for the problem of lateral soil resistances

Experimental investigations regarding the lateral soil resistance acting on pipes under monotonic loading were carried out by Audibert & Nyman [6] and also by Trautmann & O'Rourke [7].

Exemplary results from [6] are shown in Fig. 5. For loose sand, a monotonic increase of the resistance force with lateral deflection was observed until a maximum value is reached. The maximum value is strongly dependent on the overburden height h. In dense sand, a peak value is reached after a relatively small deflection, followed by a softening which becomes more pronounced for increasing overburden heights. The deflection at which the peak value is reached is also dependent on overburden height.

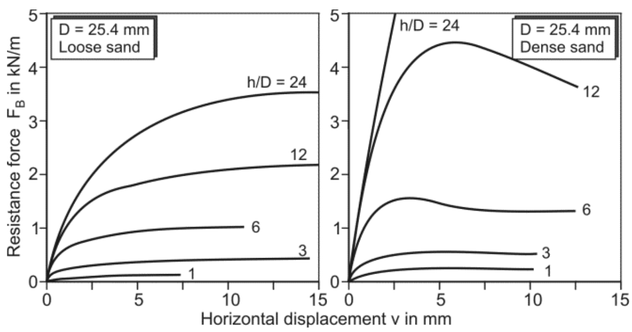

Fig. 5 Experimental results for monotonic loading [6]

For a dimensionless representation of the maximum bedding resistance force F_{Bu} a bearing capacity factor N_u is defined as follows:

$$N_u = \frac{F_{Bu}}{\gamma(h + D/2)D} \quad (1)$$

Here γ is the unit weight of the soil.

Results from [6] and [7] for the bearing capacity factor are shown in Fig. 6. In both investigations, a dependence of the bearing capacity factor on the relative overburden height h/D and on the friction angle of the soil (or the relative density, respectively) was observed. However, the magnitudes of the determined factors were slightly different, with the higher values observed by Audibert & Nyman.

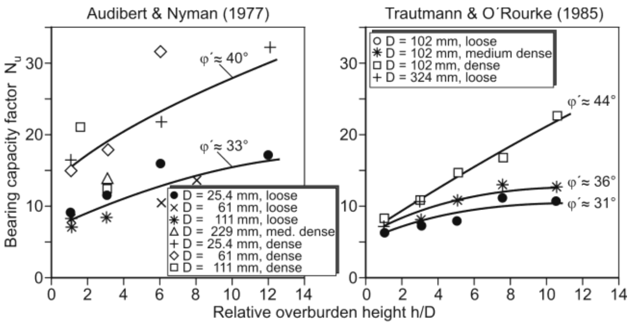

Fig. 6 Experimentally determined bearing capacity factors

Achmus [2] showed by numerical simulations that the reason for the observed deviations were probably the different pile diameters considered in the two studies. The numerical results indicated a decrease of the bearing capacity factor with an increase in absolute pile diameter. Since Trautmann & O'Rourke [7] investigated in most cases larger pile diameters than Audibert & Nyman [6], they got smaller bearing capacity factors.

The approach to calculate the bedding pressure-deflection curve in the standard DIN EN 13941 [8] uses the following equations:

$$p_u = \gamma\left(h + D/2\right)N_u \tag{2}$$

$$\frac{p}{p_u} = \frac{v/v_u}{0.15 + 0.85 v/v_u} \tag{3}$$

The second input parameter besides the bearing capacity factor is the displacement v_u at which the maximum bedding resistance is reached.

According to DIN EN 13941, the bearing capacity factors shall be taken from the diagram in Fig. 7 dependent on relative overburden height and friction angle of the soil. Indicative values for the displacement v_u are also given in DIN EN 13941. For dense sand, v_u = 0.02 (h+D/2) is recommended for a pile diameter of 120 mm and v_u = 0.015 (h+D/2) shall be taken for pile diameters greater than 300 mm.

Regarding the development of lateral bedding resistances on pipes with un- and reloading and with repeated (cyclic) loading, the authors are not aware of any investigation. It is generally known that foundations or structures in soil under cyclic loading can exhibit an accumulation of displacements. With un- and reloading an hysteresis loop is observed, and the un- and reloading stiffnesses may change with the number of load cycles.

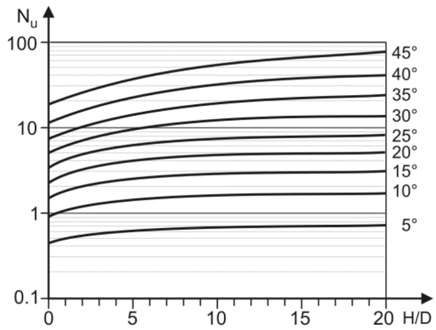

Fig. 7 Bearing capacity factor according to DIN EN 13941

By trend, the resistance-displacement curve might look similar to the curve given in Fig. 8. However, at the time being, for cyclic lateral displacements of piles an accurate prediction of the bedding resistance is not possible.

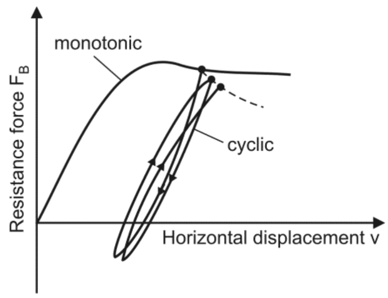

Fig. 8 Qualitative sketch of a bedding resistance-deflection curve under cyclic loading

NUMERICAL MODELING

A finite element model was established in order to simulate the system behavior of a pipe under monotonic and cyclic lateral movement buried in sand. A two-dimensional system under plane strain conditions was considered. The finite element programme PLAXIS-2D [9] was applied.

An example for a finite element mesh used in this study is shown in Fig. 9. A single rigid pipe in a homogeneous sand soil was considered. Interface elements were defined between the pipe and the soil to account for limited frictional stresses between soil and pipe. The width and depth of the soil domain and the mesh fineness was chosen such that a further increase of the domain or the number of elements did not lead to a significant change in calculation results.

The loading was applied deformation-controlled, i.e. the deformations of the nodes of the rigid pipe section were prescribed. As a system response, the resultant load, necessary to cause the deformation, was recorded.

A crucial point for the quality of simulation results of soil-structure interaction problems is of cause the material law used for the soil. The stress-strain behavior of soil is already very complex for monotonic loading paths, and it becomes even more complex for cyclic loading. Here, an advanced material law termed ‘hypoplasticity with intergranular strain’ was applied.

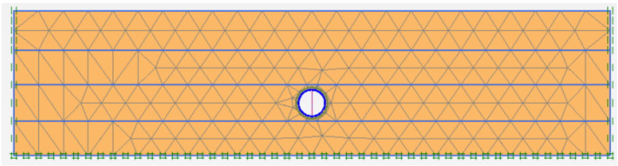

Fig. 9 Example for a finite element mesh used in the simulations

The hypoplastic material law is a rate-type model which accounts for the complex non-linear soil behavior by just one (rather sophisticated) tensorial equation (see e.g. [10]). In its original form, the hypoplastic material law needs 8 parameters. It uses the stress state and the void ratio of a non-cohesive material as state variables and accounts for stress-dependence of soil stiffness and soil strength, thereby reflecting contractancy or dilatancy of soils under shearing in a realistic manner.

The material law in the original form was found to overestimate the accumulation of soil deformations under cyclic loading. Therefore, the intergranular strain concept was developed (see [11]), which cares for a realistic simulation of the behavior under cyclic loads. However, another 5 parameters are necessary to define the behavior with consideration of intergranular strain.

Details on the material law can be found in [10], [11] and [12]. Fig. 10 shows a comparison of experimental and numerical results for an oedometer test with cyclic un- and reloading given in [12]. The agreement is not perfect, but at least for stresses smaller than 1000 kN/m^2 the material law is obviously capable to reflect the soil behavior with sufficient accuracy.

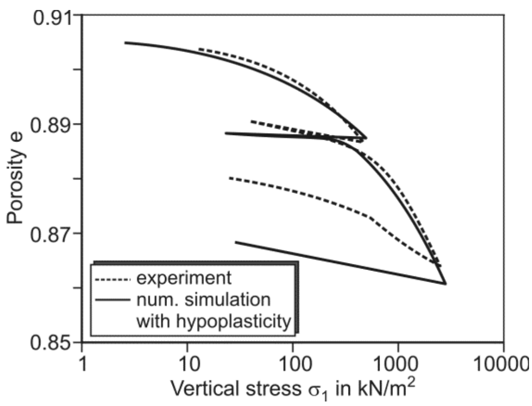

Fig. 10 Comparison of numerical and experimental cyclic oedometer test results [12]

The hypoplastic parameters used in the simulations presented here are given in Table 1. These parameters were derived from a comprehensive laboratory programme with a medium sand with portions of fine sand.

The maximum shear stress in the interface was determined by the contact friction angle $\delta = 24°$, i.e. the coefficient of friction was $\mu = \tan 24° = 0.45$.

The modeling process consisted first of the placing of a sand layer below the pipe. Here initial stresses were generated, using a k_0-value of 0.59. Then the soil layer with the pipe in the center, extending 5 cm both to the top and the bottom of the pipe, was generated. Afterwards, the upper layers were generated layer by layer in a ‘staged construction’ procedure. To reach an overburden height of 0.8 m, two upper layers with widths of 35 cm and 40 cm were generated. In the final stages, the prescribed deformations of the pipe were applied.

Table 1 Hypoplastic material parameters

Parameter	Value
Granular stiffness h_s	6,000 MPa
Critical friction angle φ_c	31.4°
Critical void ratio e_{c0}	0.912
Maximum void ratio e_{d0}	0.458
Minimum void ratio e_{i0}	1.090
Compression exponent n	0.3
Pycnotropy exponent α	0.13
Pycnotropy exponent β	1.0
Maximum intergranular strain R	0.000045
Factor m_R	6.7
Factor m_T	3.4
Exponent β_r	1.5
Exponent χ	0.7

NUMERICAL RESULTS

Results for monotonic loading

Numerically determined load-deformation curves for monotonic loading are shown in Fig. 11. As an example, results for a pipe diameter of D = 0.27m, an overburden height of h = 0.8m and different initial void ratios of the sand are presented. The void ratios between 0.54 and 0.59 cover the range of dense to very dense sand. Therefore, the results are compared to the DIN EN 13941 approach for angles of internal friction φ’=37° and φ’=40°.

Very good agreement of the numerical results with the DIN approach can be stated with regard to the maximum resistance. However, the DIN approach predicts a much stiffer behavior, since the displacement v_u necessary to reach the peak state is just 14 mm (1.5% of h+D/2, see above).

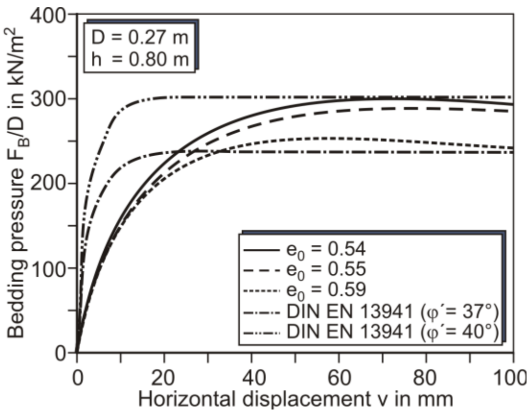

Fig. 11 Numerical results for D=0.27m, h=0.8m with variable initial void ratio

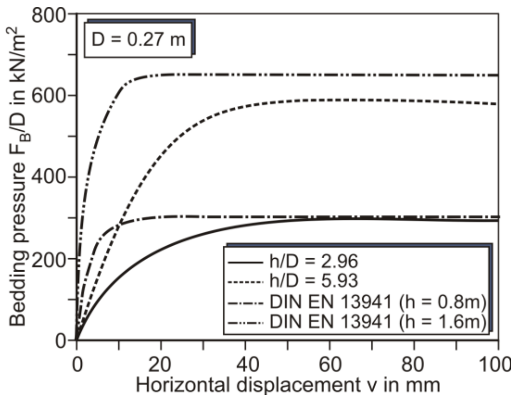

Fig. 13 Results for variable overburden heights (D=0.27m, e_0 =0.54/ φ'=40°)

The numerically determined deformation pattern of the soil at reaching the peak state is shown by a vector plot in Fig. 12. A large passive zone occurs in front of the pipe, with a failure wedge displaced in horizontal and upwards direction. Above the pipe almost no deformation occurs, and behind the pipe an active zone with downwards directed deformations occurs. This general deformation pattern with a passive, a neutral and an active zone was also observed by Audibert & Nyman [6] in their experimental tests.

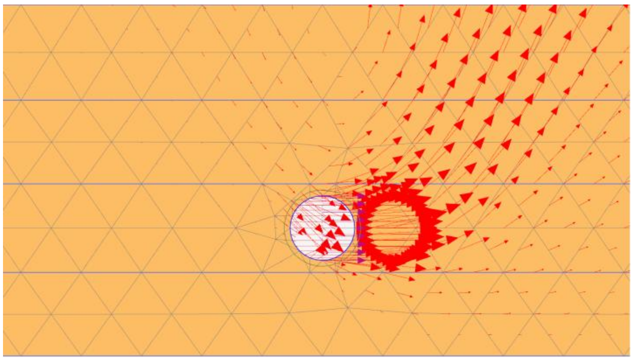

Fig. 12 Displacements at peak state

Fig. 13 compares numerical and DIN EN 13941 results for two different overburden heights. In the DIN approach, the ultimate resistance is assumed to be linear dependent on the overburden height with respect to the pile center (see Eq. 1). Evidently, this approach overestimates bedding resistances at large overburden heights.

Results for cyclic loading

Two simulations were carried out with cyclic loading. In both cases, a pipe with D=0.27m and h=0.8 m in dense sand (e_0=0.54) was considered.

In practice, a relatively large deformation (dependent on the length of the adjacent straight pipe sections and the magnitude of friction forces) is induced in an arc section with the first heating of a pipeline. In the following un- and reloading steps, only a portion of this deformation is reversible, i.e. the absolute deformation always remains positive (see Fig. 1). To simulate such loading patterns, the displacements were once varied between 0 and 2 cm and once between 2 and 4 cm.

Fig. 14 shows that in both cases very similar hysteresis loops occur. After the first un- and reloading cycle, the maximum bedding pressure is considerably decreased compared to the monotonic loading curve. The un- and reloading stiffnesses for the following cycles are very similar, which means that the stiffness seems to be almost independent of the absolute maximum displacement, but only dependent on the cyclic deformation amplitude. The maximum bedding pressure decreases only slightly with the number of load cycles. Even after the first cycle, the magnitude of the maximum (negative) bedding pressure after unloading (acting on the left side of the pipe) is almost identical to the maximum pressure after reloading (acting on the right side). This means that the bedding resistances at both sides of the pipe become equal, although the resultant deformation with respect to the initial state is always directed to the right side.

After 20 cycles, the deformation was further increased to simulate a post-cyclic failure test. In both cases the same residual resistance (after very large displacements) is reached, which is almost the same as the monotonic ultimate resistance. However, for the case with larger cyclic displacements, a slightly greater peak load occurs.

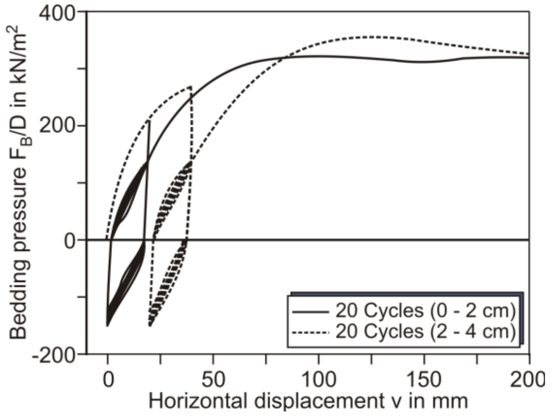

Fig. 14 Results for cyclic loading (D=0.27m, h=0.8m, e_0=0.54)

Fig. 15 shows the deformation pattern in the soil after cyclic loading with N=20 load cycles, which is remarkably different from the deformation pattern after monotonic loading. Now, passive zones and a heave of the soil surface occur on both sides of the pipe, and above the pile a considerable settlement is predicted. Evidently, the cyclic loading leads to significant rearrangements of soil particles and strong effects on the deformation pattern in the soil around the pipe.

The first results shown here give an impression of the system behavior to be expected under cyclic loading. However, such complex numerical simulations urgently need validation by experimental testing.

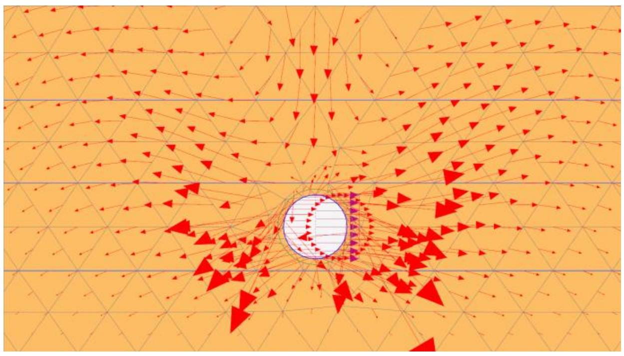

Fig. 15 Displacement after cyclic loading with N=20

EXPERIMENTAL RESULTS

Experimental tests will be carried out in the ongoing project and shall be used for the calibration and validation of the numerical model. A few tests have already been carried out and shall be presented here.

A sketch of the test device is shown in Fig. 16. The test pit is about 2.04 m wide, 1.57 m deep and 2.96 m long. A rigid pipe (steel pipe filled with concrete, 2m long) is horizontally displaced by a steel rod. The load can be applied either deformation- or force-controlled.

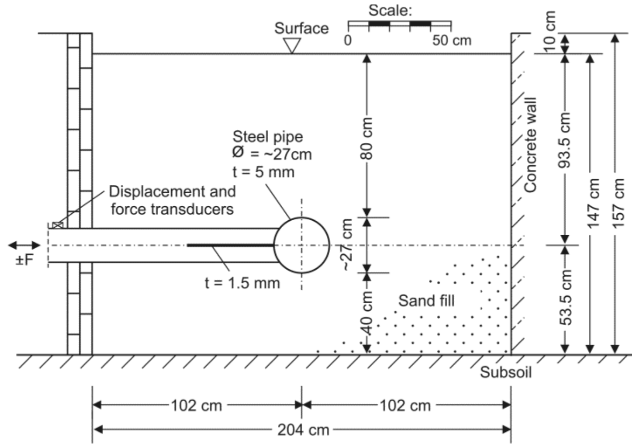

Fig. 16 Sketch of the testing device

The pipe is buried in a medium sand with portions of fine sand (mS, fs). The compaction of the sand is realized in layers such that a degree of compaction of $D_{pr} = \rho_d/\rho_{Pr} \approx 98\%$ is reached, with ρ_d = dry density and ρ_{Pr} = proctor density of the soil. This degree of compaction coincides with a dense state of the sand.

Results of two tests under identical boundary conditions with monotonic loading are shown in Fig. 17 and compared to results from a numerical simulation and the DIN EN 13941 approach. The experimental curves differ considerably, in particular in the initial part, i.e. in stiffness. The reason for these differences shall be investigated in further tests. However, good qualitative agreement with the prediction curves can be stated. It should be noticed that the predictions refer to an infinite trench width, whereas in the experiments the trench width is limited. It is of course planned to carry out numerical simulations also for the geometry in the experimental tests. However, this has not been done yet.

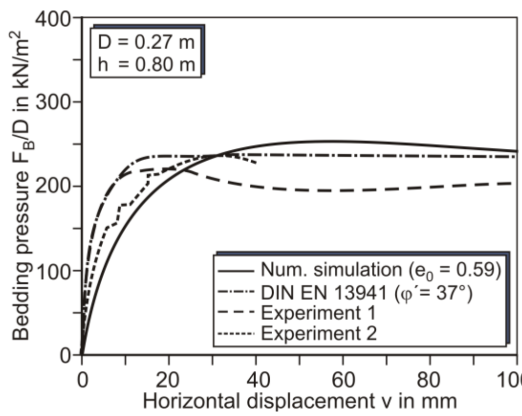

Fig. 17 Results of monotonic experimental tests in comparison to DIN EN 13941 and numerical simulation predictions

The results of the first experimental test with cyclic displacement-controlled loading are presented in Fig.

18. The horizontal displacement was specified with the amplitudes of $\Delta v = 2.5$ cm from 2.5 cm to 5.0 cm, 3.0 cm to 5.5 cm, 3.5 cm to 6.0 cm and at last 4.0 cm to 6.5 cm. For each of these prescribed displacement limits, 10 cycles were executed.

Fig. 18 top shows that the bedding pressure at maximum displacement decreases only slightly in each cyclic loading phase. An increase of the maximum displacement after a cyclic phase regains the initial maximum bedding pressure, which is almost identical with the residual bedding pressure in a monotonic test.

The (negative) maximum bedding pressure on the left side of the pipe first increases with the number of load cycles, until almost the same value as on the right side is reached. In subsequent cycles, the maximum bedding pressure remains constant or increases slightly, as it does on the right side of the pipe.

A direct comparison of the experimental results with the numerical simulations (in which an infinite trench width was assumed) is yet not possible. However, the experimental results in Fig. 18 are qualitatively quite similar to the numerical results shown in Fig. 14. The numerical model seems thus capable to properly describe the main features of the system behavior.

The status of the soil surface after the above mentioned experimental cyclic load test is pictured in Fig. 19. A large heave with macro cracks in the soil occurred in front of the pipe in loading direction. Also a heave, but with smaller magnitude, was observed behind the pipe. In contrast, above the pipe a large settlement occurred. This is also in good qualitative agreement with the findings from the numerical simulations depicted in Fig. 15.

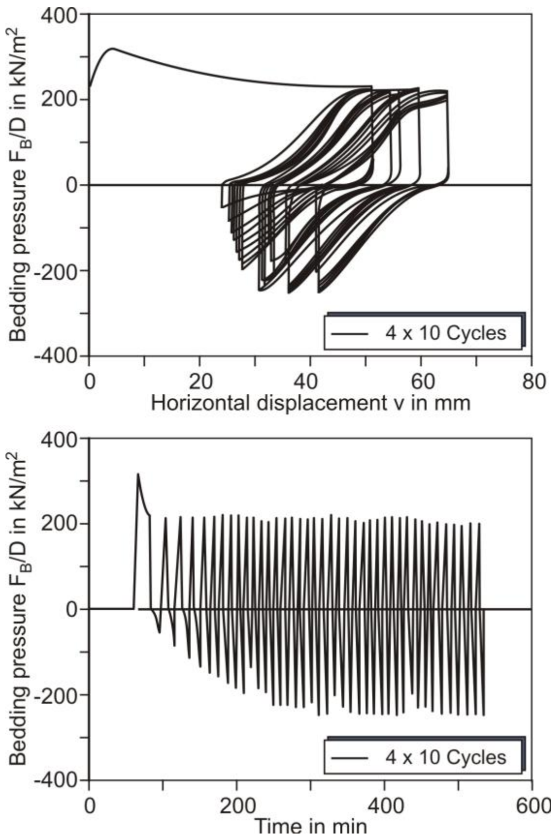

Fig. 18 Results of cyclic experimental tests

Fig. 19 Photographic picture of the soil surface after a cyclic test with 40 cycles and lateral deformations between 2.5 and 6.5 cm

CONCLUSIONS AND OUTLOOK

The overview on the state of the art regarding soil reaction forces on district heating pipes shows that cyclic loading effects on friction forces was already subject of investigations, whereas the effect of cyclic loading on the lateral bedding resistance forces is widely unknown.

A numerical model with an advanced material law was developed, which predicts the behavior of a cyclic laterally loaded pipe buried in sand soil. First results derived with this model are compared to results from an experimental test in which cyclic lateral displacements were applied on a pipe section. Good agreement regarding the basic features of the system behavior was observed. This shows that the model is capable of reflecting the main features of the complex system behavior.

Both the numerical simulation and the experimental test show that the cyclic loading significantly changes the behavior of the system. After 40 cycles of alternating displacements, large deflections and in particular differential settlements occur at the soil surface above the pipe, which could of course severely affect the integrity of a pavement located there.

The numerical and the experimental investigations presented here will be continued. A main target of this research is the development of an approach for the determination of non-linear spring stiffness curves for the bedding resistance dependent on the main influence parameters (e.g. pipe nominal width, overburden height, soil density). Such 'load transfer'-curves could be used in a calculation model shown conceptually in Fig. 20 to predict the displacements and stresses of a district heating pipeline depending on operation parameters, i.e. the course of operating temperatures. This would be an important step towards a more accurate prediction of the pipe behavior in operation and with that to an optimized design of such pipelines.

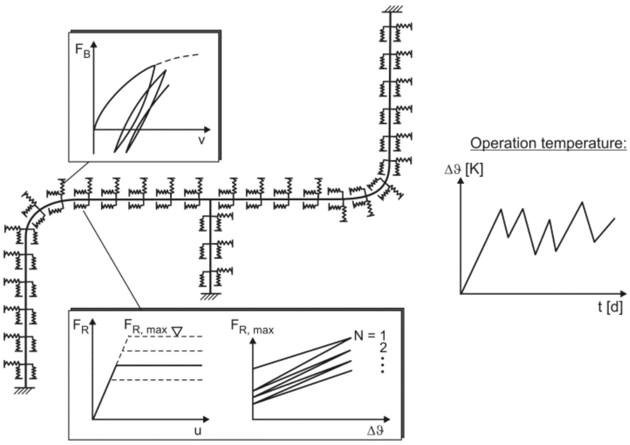

Fig. 20 Schematic drawing of a calculation model for the determination of displacements of district heating pipelines

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THERMAL CONDUCTIVITY COEFFICIENT OF PUR INSULATION MATERIAL FROM PRE-INSULATED PIPES AFTER REAL OPERATION ON DISTRICT HEATING NETWORKS AND AFTER ARTIFICIAL AGEING PROCESS IN HEAT CHAMBER

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ABSTRACT

Preinsulated pipelines, because of foam polyurethane (PUR) lifetime, are designed for 30 years of operation. During operation insulating foam is subject to natural process of ageing, resulting in changing of its basic thermal and mechanical properties. Main destructive factor for insulation is temperature of steel pipe, which depends on heat carrier. Foam moisture also accelerates this process. As a result of ageing, an increase (worsening) of insulation thermal conductivity coefficient λ follows. Unfortunately, because of lack of data, or they are not published, the information concerning changes of this coefficient in time are unavailable. Laboratories usually proceed with measurements concerning new products or artificially aged ones.

Because of increasing importance of energy efficiency for District Heating Network (DHN), the Research Laboratory in Heat-Tech Center (LB HTC) from Dalkia Warsaw has started a research project, which aim is to determine actual values of thermal conductivity coefficient of pipe insulations, changing over time, under real operating conditions. Knowledge of the value of the thermal conductivity coefficient of new insulation and aged insulation allows the determination of conductive heat and anticipation of change in the future.

Laboratory also performs in parallel studies on insulation of preinsulated pipes after ageing process according to norm EN 253. First pipes are heated in heating chamber and then the λ coefficient for aged product is determined. According to norm, obtained result is the value of thermal conductivity coefficient of pipelines insulation, which would be functioning in soil for 30 years with the temperature of heating medium 120°C.

The publication presents the results of the tests of thermal conductivity of PUR foam insulation of the pre-insulated pipe ageing in natural and artificial environments.

INTRODUCTION

One of the reasons for the ageing of polyurethane insulation is the phenomenon of diffusion of gases. The atmospheric gases - oxygen and nitrogen penetrate into the PUR foam and replace the cell gas - cyclopentane and carbon dioxide (CO_2), what causes the deterioration of the insulation, i.e. the increase of the thermal conductivity of the foam.

Diffusion is caused by different partial pressure of gases (also called expanding or foaming agents, which are used to produce foamed materials with closed cells) arising during the production of insulation.

Because the period of estimated life expectancy of the pre-insulated pipelines working in different temperature values of the factor is estimated to be approx. 30 years, a phenomenon of diffusion of gases (fig. 1) and the gradual deterioration of the insulation thermal insulation properties are important from the point of view of a district heating network operating costs and emissions of pollutants into the environment. Changing the thermal conductivity causes that over time the use of the network to grow heat losses through infiltration. In the case of the pre-insulated pipe system oxygen penetration by penetrating pipe also leads to:

- degradation of the insulation cells,
- permanent deformation under load insulation,
- decrease the compressive strength in radial direction,
- decrease the axial strength, whereby reducing its adhesion to the leading pipes, and consequently mechanical integrity of the pre-insulated set decreases [1, 2, 3].

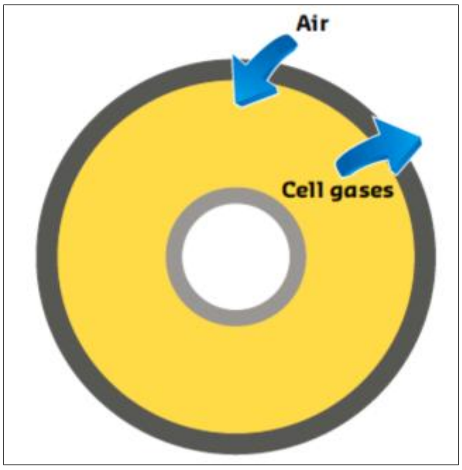

Fig. 1 Diffusion of gases from and into the PUR foam [3]

The speed of diffusion of gases in the pre-insulated pipes depends on:

- the type of foaming agent, namely the size of the gas molecules contained in closed insulation cells. CO_2 molecules are relatively small, so its diffusion will be much faster than the diffusion of cyclopentane-gas of much larger molecules,

- the temperature of the heat-carrier - the higher the temperature, the faster the diffusion process is,
- the thickness of the casing - the thinner the casing, the faster the diffusion will be, which means that the insulation of small diameter pipe will have a worse thermal insulation properties than insulation from large pipe diameters (thickness of the casing is rising with the increase in nominal diameter),
- the method of production.

The pre-insulated pipes are produced by three methods. Method:

- The TRADITIONAL, most common, involves the injection of polyurethane foam in the space between the service pipe and casing pipe. It is used by many producers in the production of the pre-insulated pipes of nominal diameter from DN20 up to DN1200. The casing is made of polyethylene pipe of properties specified in EN 253.

  The casing pipe, at the production stage, can be additionally equipped with an additional layer, the so-called diffusion barrier (e.g. three-layer pipes produced by ZPU Jońca Company from Poland, five-layer pipes produced by RADPOL Company from Poland - fig. 2).

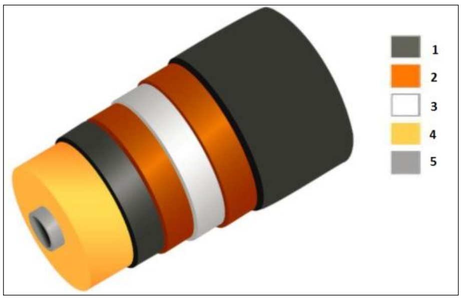

Fig. 2 The pre-insulated pipe with five-layer HDPE (1)/ adhesive layer (2)/ EVOH (3)/ adhesive layer (4)/ HDPE(5) [3]

- CONTI – continuous production, which involves the simultaneous formation of insulation and the extrusion of the casing with diffusion barrier. This is a very difficult method of production, applied according to knowledge of the authors of this publication, only by two pre-insulated pipe producers in Europe (LOGSTOR and ISOPLUS Companies). This method is limited to nominal diameters DN20 ÷ DN250.
- OPTI - semi-continuous production, involves the formation of foam on steel pipe, and then - after removing the mould, winding the casing or aluminium film, as a diffusion barrier (fig. 3) on the insulation. They are produced in diameters above DN200.

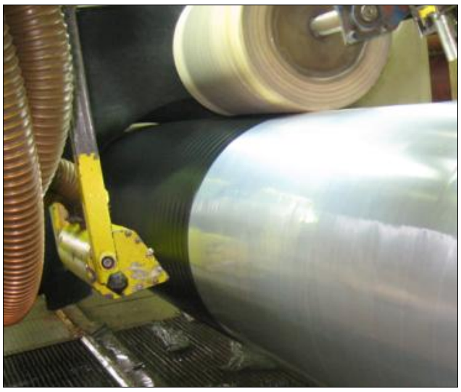

Fig. 3 Winding of the casing of HDPE on the diffusion layer [4]

STATE OF THE ART [2]

The tests carried out by the independent Swedish research institute Chalmers Technical University (ChTU) have shown that in the thermal conductivity coefficient depends on the type of used foaming agent and method used for pipe production.

ChTU's results are shown in figure 4.

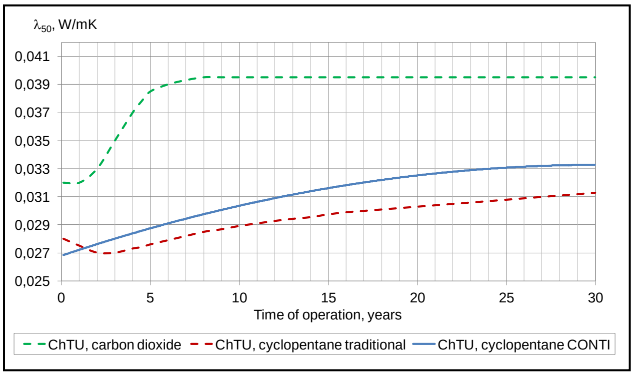

Fig. 4 Change of the thermal conductivity coefficient λ_{50}, W/mK in time (polyurethane insulation foamed with CO_2 and cyclopentane (TRADITIONAL and CONTI method)).

In the case of the pre-insulated pipe produced by the traditional method with the insulation foamed with CO_2, during the first 5 years the thermal conductivity coefficient increases sharply and after about 6 years it reaches the limit value of λ_{50}= 0,0395 W/mK. This means increase of $\Delta\lambda_{50}$ = 28%.

In the case of pipes with insulation foamed with cyclopentane, there is a difference between the pipes produced in the traditional way, and pipes produced by CONTI method.

For pipes with cyclopentane, produced by the traditional method, at the time of production, the value of the thermal conductivity coefficient of PUR foam is approx. λ_{50} = 0,028 W/mK. Then after 2 years is decreases to approx. λ_{50} = 0,027 W/mK and after 30 years it increases to a value of λ_{50} = 0,0312 W/mK. This means increase of $\Delta\lambda_{50}$ = 13,4 %.

For pipes produced by CONTI method, the thermal conductivity coefficient λ changes from initial value λ_{50} = 0,027 W/mK to λ_{50} = 0,033 W/mK, which represents increase by $\Delta\lambda_{50}$ = 22,4 %.

METHODOLOGY

The result of polyurethane insulation ageing is a change of the thermal conductivity coefficient. Its value changes significantly with the density of the insulation, and depends on the raw material (the nature and the composition of the gases in closed cells) and on the test method.

LB HTC has been involved in the tests of the thermal conductivity for more than a dozen years. It is carried out on the pipe apparatus (fig. 5), constructed in accordance with EN ISO 8497. Since 2003, the test method has been accredited by the Polish Centre for Accreditation (PCA), which means that the test requirements are carried out according to the valid standards, in this case with the standard EN 253.

Fig. 5 The test stand SB-6 "pipe apparatus"

The laboratory caries out the tests of thermal conductivity of new pipes, disassembled pipes after operation, and insulation after artificial ageing.

LB started the project on the thermal conductivity coefficient tests of pre-insulated pipe produced in traditional method by different producers that had been dismantled from the pre-insulated pipelines of DN50 and DN80 after varying periods of operation.

In the years 2006 ÷ 2008 there **were the tests of pre-insulated pipes with PUR foam foamed with CO_2**. Samples - the sections of the pre-insulated pipes - were taken from Warsaw heating system. In total, 8 samples, operated during the period from 5 to 15 years, were tested.

Since 2008, LB **has tested the thermal conductivity coefficient of the pre-insulated pipes insulation foamed with cyclopenthane.** Thanks to the cooperation with the Polish district heating companies, 16 samples from the pre-insulated pipelines from different places in Poland, which operated from 4 to 14 years, were tested. The results of the pipes operated over 11 years were rejected due to a lack of clear information on the type of the expanding agent.

In January 2011, LB **started the heating chamber** (fig. 6) **for artificial ageing of the pre-insulated pipes.** According to the EN 253:2009 artificial ageing before the tests of the thermal conductivity means heating of the pipes system at a temperature of t = 90°C for 150 days.

Fig. 6 The heating chamber for ageing of samples

In each case LB HTC investigate the thermal conductivity coefficient together with density and compressive strength of PUR foam, according to EN 253, EN ISO 845 and EN 826.

RESULTS

RESULTS OF THE TESTS OF THERMAL CONDUCTIVITY COEFFICIENT AFTER NATURAL AGEING

Figure 7 shows the value of thermal conductivity coefficient λ_{50}, W/mK of the insulation foamed with CO_2 of the supply pipeline and return pipeline depending on the time of operation.

Figure 8 shows the value of thermal conductivity λ_{50}, W/mK of the insulation foamed with cyclopenthane of the supply pipeline and return pipeline depending on the time of operation.

Figure 9 compares the value of the thermal conductivity λ_{50}, W/mK of the insulation of the supply pipelines and the return pipeline foamed with cyclopenthane and CO_2 depending on the life of the test samples.

The average content of cyclopenthane in % (*v/v*) as determined by the gas chromatography method in the Institute of the Industrial Chemistry (IChP) in Warsaw, Poland, in samples of the operated pipes was as follows:

- up to 10 years, supply: 6 ÷ 26, return: 5 ÷ 35
- above 10 years, supply: 1,6 ÷ 26, return: 1÷ 10.

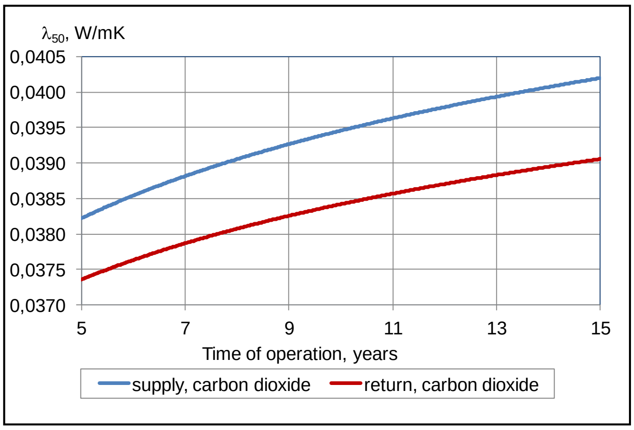

Fig. 7. The thermal conductivity coefficient λ_{50}, W/mK, depending on the time of operation of pipelines system (supply, return) with the insulation foamed with CO_2.

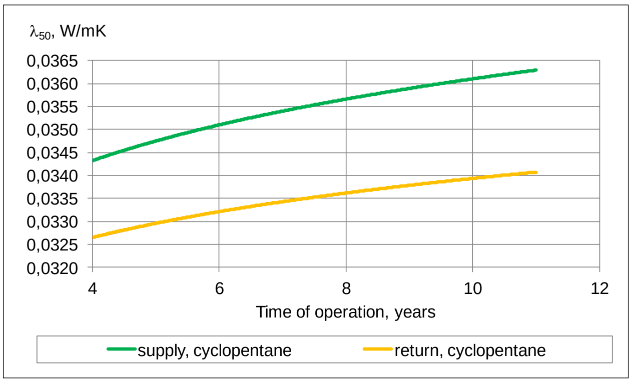

Fig. 8. The thermal conductivity coefficient λ_{50}, W/mK, depending on the time of operation of pipelines system (supply, return) with the insulation foamed with cyclopenthane.

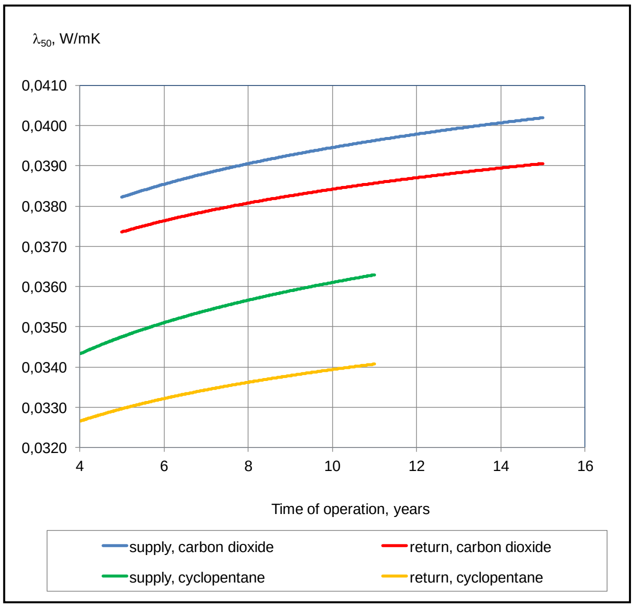

Fig. 9. The thermal conductivity coefficient λ_{50}, W/mK, depending on the time of operation of the pre-insulated pipelines system (supply, return) with the insulation foamed with CO_2 and cyclopenthane.

On the basis of the experience of the laboratory it was assumed that mean values of thermal conductivity coefficient in the pre-insulated pipes produced in traditional method were:

- λ_{50} = 0,032 W/mK for new insulations foamed with CO_2,
- λ_{50} = 0,028 W/mK for new insulations foamed with cyclopenthane.

It was found that thermal conductivity coefficient increases for the insulation foamed with CO_2:

- after the first 5 years of operation by 19% (supply) and 17% (return),
- from 6 to 15 years, from 0,4% to 1% per year.

and for the insulation foamed with cyclopenthane:

- after the first 4 years of operation by 23% (on supply) and 17% (on return),
- from 5 to 11 years by 1% per year.

Thermal conductivity coefficient values increase $\Delta\lambda_{50}$ for both types of insulation is shown in figure 10.

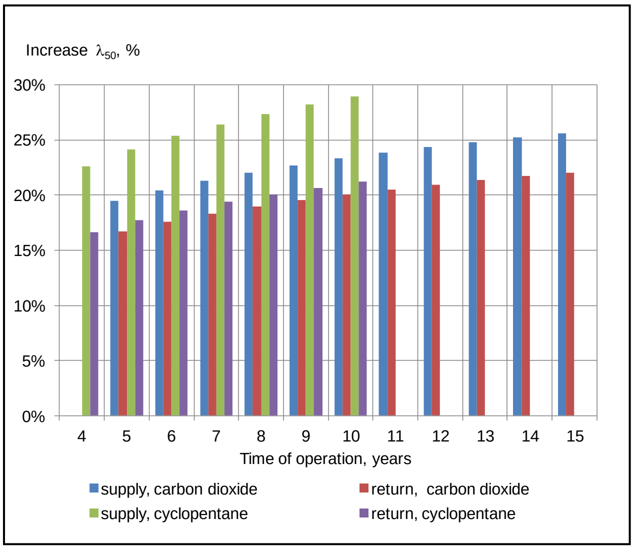

Fig. 10. Thermal conductivity coefficient values increase depending on the life of piping system foamed with CO_2 and cyclopenthane.

As a result of the tests of the pre-insulated pipes aged in the natural conditions, the thermal conductivity coefficients of the insulation foamed with CO_2 and cyclopenthane have changed in a different way.

Figure 11 compares the expected change of value (the average of the supply and return pipeline) of the thermal conductivity of the insulation foamed with CO_2 and cyclopenthane in 30 years of operation. The value of the thermal conductivity in the periods up to 4 years and 12 ÷ 30 years (cyclopenthane) and up to 5 years and 16 ÷ 30 years (CO_2) were specified by the method of extrapolation.

As initial values (the thermal conductivity coefficient of new insulation) the following was assumed:

- in the case of cyclopenthane λ_{50} = 0,028 W/mK (average of the tests carried out in the laboratory) and λ_{50} = 0,029 W/mK (requirements of the standard EN 253:2009),

- in the case of CO_2 λ_{50} = 0,032 W/m (average of the tests carried out in the laboratory) and λ_{50} = 0,033 W/mK (requirements of the standard EN 253:2003).

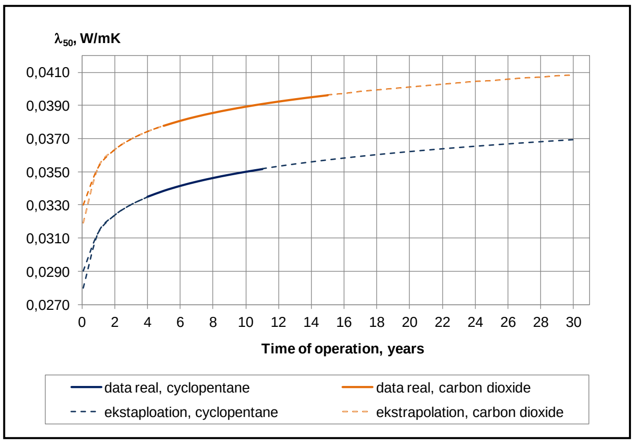

Fig. 11 Change the thermal conductivity coefficient λ_{50}, W/mK (average value - supply + return) of the insulation of PUR foam foamed with CO_2 and cyclopenthane.

During the project, a new edition of the standard EN 253 (EN 253:2009) was issued, which by the change of the maximum value of thermal conductivity coefficient (from $\lambda_{50} \leq 0{,}033$ W/mK to $\lambda_{50} \leq 0{,}029$ W/mK) has imposed the use of cyclopentane as the foaming agent in PUR foams used in the pre-insulated pipes.

RESULTS OF THE TESTS OF THERMAL CONDUCTIVITY COEFFICIENT AFTER ARTIFICIAL AGEING

Table 1 presents the results of the tests of the thermal conductivity coefficient after artificial ageing of the insulation foamed with cyclopenthane of the pre-insulated pipe produced in TRADITIONAL method, from different producers.

In the case of the pipes produced by the traditional method after artificial ageing of the pre-insulated pipes from different producers with insulation foamed with cyclopentane, an increase in thermal conductivity coefficient by an average of 5,7 % occurs.

LB has made the tests of pre-insulated pipes with antidifusion barrier produced in CONTI and TRADITIONAL method, too.

The results of tests of the pre-insulated pipes with the diffusion barrier were very promising. Due to the too low number of samples, the results are not representative, but confirm the correct course of action taken by the producers.

Table 1. The results of the tests of the thermal conductivity coefficient of the pre-insulated pipe after artificial ageing by EN 253.

Sample number	λ_{50}, W/mK before ageing	λ_{50}, W/mK after ageing	DN/ D_c*
1.	0,0273	0,0311	50/125
2.	0,0271		
3.	0,0283	0,0302	50/140
4.	0,0281		
5.	0,0287		
6.	0,0268	0,0288	50/125
7.	0,0265		
8.	0,0264		
9.	0,0272	0,0303	50/125
10.	0,0282	0,0300	50/125
11.	0,0279	0,0291	50/125
average	**0,0281**	**0,0297**	**-**

* DN/ D_c – nominal diameter/ nominal outside diameter, mm

RESULTS OF THE TESTS OF DENSITY AND COMPRESSIVE STRENGHT

The results of the tests of density ρ and compressive strength σ of the insulation were from pipes with the insulation:

<u>after natural ageing:</u>

foamed with CO_2:

- ρ_{av} = 80 kg/m^3 (71 kg/m^3 ÷ 90 kg/m^3),
- σ_{10av} = 0,41 MPa (0,33 MPa ÷ 0,48 MPa),

foamed cyclopenthane:

- ρ_{av} = 85 kg/m^3 (67 kg/m^3 ÷ 103 kg/m^3),
- σ_{10av} = 0,49 MPa (0,32 MPa ÷ 0,74 MPa),

<u>before artificial ageing:</u>

foamed cyclopenthane:

- ρ_{av} = 67 kg/m^3 (59 kg/m^3 ÷ 76 kg/m^3),
- σ_{10av} = 0,28 MPa (0,16 MPa ÷ 0,34 MPa),

<u>after artificial ageing:</u>

foamed cyclopenthane:

- ρ_{av} = 68 kg/m^3 (66 kg/m^3 ÷ 72 kg/m^3),
- σ_{10av} = 0,28 MPa (0,15 MPa ÷ 0,38 MPa).

Figures 12 and 13 show the results of the tests of the average density and the average compressive strength.

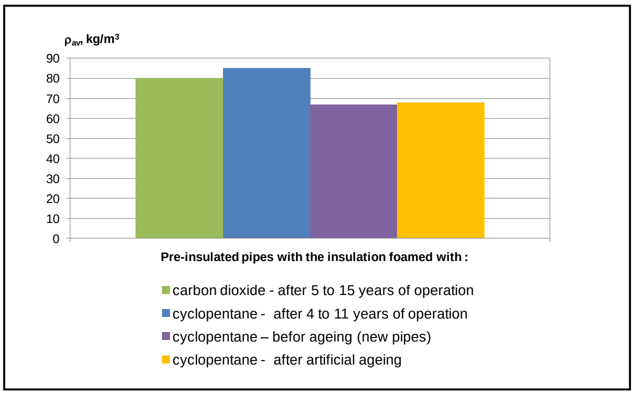

Fig. 12 Average density ρ, kg/m^3

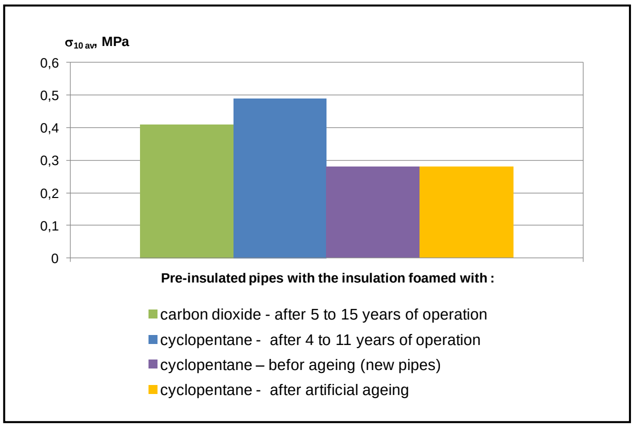

Fig. 13 Average compressive strength σ_{10}, MPa

DISCUSSION - THERMAL CONDUCTIVITY COEFFICIENT

The first series of tests of lambda value which were performed in Poland were carried out on samples of dismantled heating pipelines after a couple/few years of operation. In the case of the Swedish units, on samples of likely artificial process of ageing in the laboratory conditions (in the source material, there is no description of the method).

Figures 14, 15, 16 and 17 show thermal conductivity coefficient of the insulation foamed with CO_2 and cyclopentane after the natural ageing (HTC) and after artificial ageing (ChTU) of pre-insulated pipe produced in traditional method.

Thermal conductivity coefficient of the insulation foamed with CO_2 (fig. 14) after operation (HTC) and after artificial ageing (ChTU) in the range of 5 to 15 years are similar and difference is from -1,9% to + 0,3%.

Figure 15 shows thermal conductivity coefficient of the insulation foamed with CO_2. In case of HTC's results of the tests of the thermal conductivity coefficient in the periods up to 5 years and 16 ÷ 30 years were specified by the method of extrapolation.

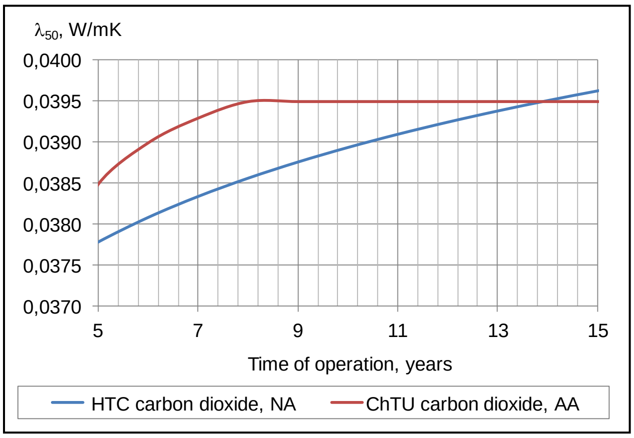

Fig. 14 Thermal conductivity coefficient of the insulation foamed with CO_2 after artificial (AA) and natural ageing (NA).

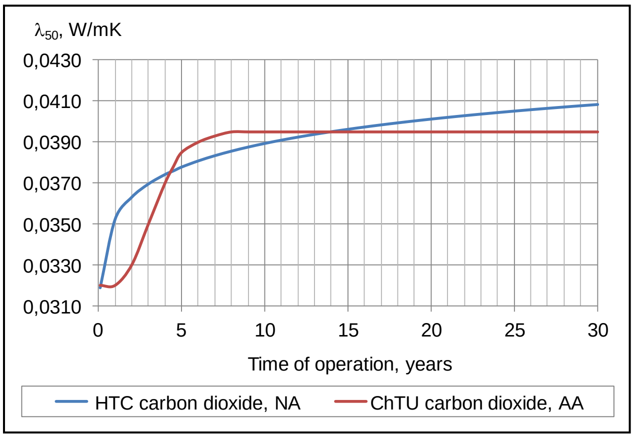

Fig. 15 Thermal conductivity coefficient of the insulation foamed with CO_2 after artificial (AA) and natural ageing (NA).

Thermal conductivity coefficient of the insulation foamed with cyclopentane (fig. 16) after operation (HTC) and after artificial ageing (ChTU) in the range of 4 to 11 years are very different from 20,9 % to + 22,7%.

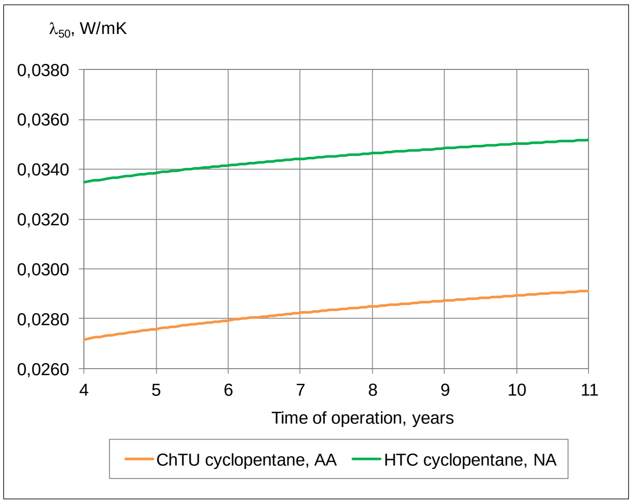

Fig. 16 Thermal conductivity coefficient of the insulation foamed with cyclopentane after artificial (AA) and natural ageing (NA).

Figure 17 shows thermal conductivity coefficient of the insulation foamed with cyclopentane. In case of HTC's results of the tests of the thermal conductivity coefficient in the periods up to 4 years and 12 ÷ 30 years were specified by the method of extrapolation.

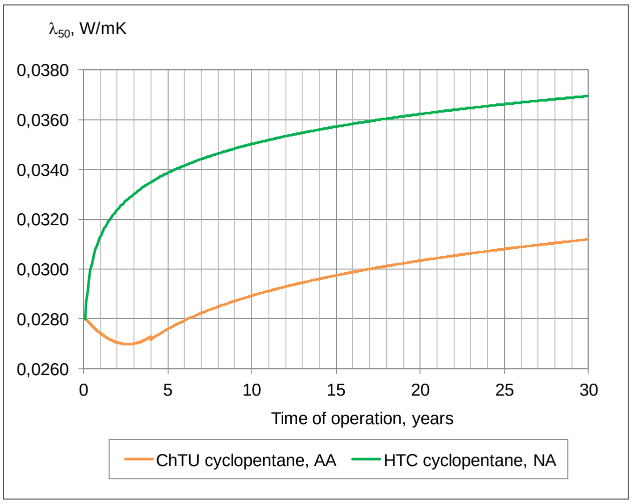

Fig. 17 Thermal conductivity coefficient of the insulation foamed with cyclopentane after artificial (AA) and natural ageing (NA).

The second series of tests of lambda value which were performed in Poland were made on samples after artificial ageing.

Figure 18 compares the anticipated thermal conductivity coefficient of the insulation foamed with cyclopentane after artificial (LB HTC, ChTU) and natural ageing after 30 years of operation (extrapolation) (LB HTC).

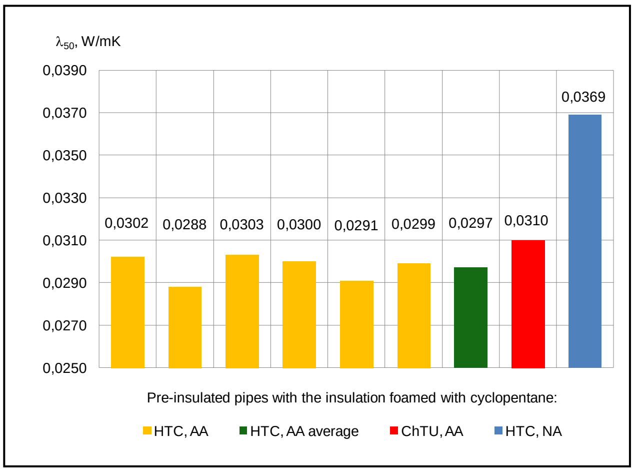

Fig. 18 The anticipated thermal conductivity coefficients of the insulations foamed with cyclopentane after artificial (AA) and natural ageing (NA) after 30 years operation.

Figure 18 shows that the thermal conductivity coefficient of foam foamed with cyclopentane after artificially ageing and after natural ageing after 30 years of operation are quite different.

DISCUSSION - DENSITY AND COMPRESSIVE STRENGHT

The lower density of the insulation, the lower the value of the thermal conductivity coefficient but also lower compressive strength. Not all producers are able to match the foam density so that both the parameters requiring by the standard EN 253 were preserved at a time ($\lambda_{50} \leq 0{,}029$ W/mK and σ_{10} = min 0,3 MPa). The lower density of the insulation leads to greater savings on the raw material system for pipes producers, but also causes a greater probability of failure and shorter lifetime of the product, and hence causes higher costs for operators of DHN. The problem is due to loophole in the standard EN 253:2009, which at the type tests requires to provide values of thermal conductivity coefficient with the density, cell size and composition of gas in the cells, but does not require to provide the value of compressive strength.

OUTLOOK

The possibility of increased knowledge on the value of the heat conduction coefficient of the insulation after ageing in the natural conditions, it is necessary to continue the tests of PUR foam of operated pre-insulated pipeline sections.

The study of samples after artificial ageing should be continued.

CONCLUSIONS

1. The tests results of the thermal conductivity coefficient of the insulation of the pre-insulated pipes aged in the natural conditions confirm, that during the operation of the pre-insulated district heating pipeline the insulation properties of PUR foam degrade in time.
2. The tests results of the thermal conductivity coefficient of the insulation foamed with CO_2 of the pre-insulated pipes aged in the natural conditions, carried out on samples of 8 operated in district heating pipelines in various operation periods are similar with the anticipated changes in this coefficient after artificial ageing.
3. The tests results the thermal conductivity coefficient of the insulation foamed with cyclopentane of the pre-insulated pipes aged in the natural conditions, carried out on samples of 14 operated in district heating pipelines in various operation periods do not coincide with the anticipated changes in this coefficient after artificial ageing in the heating chamber.

4. The results of test of thermal conductivity coefficient after artificial ageing performed in different laboratories are similar.
5. The difference of the thermal conductivity coefficient after artificial ageing and natural ageing of the insulation could mean the need to verify the parameters of the artificial ageing specified in standard EN 253.
6. Because of requirements of norm EN 253 regarding the maximal value of thermal conductivity coefficient of PUR foam before the aging, the insulations foamed with cyclopentane should be the main target of tests.
7. In order to preserve the correct insulation parameters, it is recommended to consider via CEN the change in the standard EN 253 for the tests type, for which it should be required to provide thermal conductivity coefficient with the density, cell size and composition of the gas as well as the compressive strength.

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- District heating companies from Poland which performed excavation of pipelines and provided for us samples for tests,
- Pre-insulated pipe manufacturers, who give us their products for tests,

and Veolia Group for financing our research conducted within Reliable DH project.

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[9] EN ISO 845 Cellular plastics and rubbers - Determination of apparent density

[10] EN 826 Thermal insulating products for building applications - Determination of compression behaviour

QUALITY CONTROL OF JOINT INSTALLATION IN PRE-INSULATED PIPE SYSTEMS

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ABSTRACT

A three-step quality control method was developed and applied to more than 70 joints in pipes installed on behalf of a Dutch district heating supplier. Multiple joint types were visually examined, tested for leak tightness, and dismantled for further examination. Each type of joint (except for welded joints) comprised three water barriers to prevent groundwater and rain water from entering the interior of the joint.

Various installation errors were found. For example, tape had been incorrectly applied, the PE casing had not been sufficiently abraded, PUR foam had destroyed the PIB water barrier, water had become trapped inside the joint and insulation shells were cut off too short or were not straight.

The results show the importance of foolproof jointing systems in obtaining high-quality joints in the field. Moreover, it is recommended that the installer's staff training be improved.

INTRODUCTION

A district heating pipeline consists of different parts. Figure 1 shows a schematic of a typical district heating pipe. For pipes manufactured in accordance with EN 253 [1], it is important that the steel service pipe be protected from water to prevent corrosion. Water will also degrade the polyurethane (PUR) foam. If water enters the area around the hot service pipe it will heat up, accelerating the degradation and hydrolysis of the PUR foam.

The weak spots in plastic piping systems generally occur at the joints, since these are often made in situ [2]. This is also the case for pre-insulated pipe systems. Since the applications of pre-insulated pipe systems include district heating, district cooling and LNG transport, joints need to be made in a variety of (often harsh) environments.

In the Netherlands, this harsh environment is mostly a wet one, which arises as a result of high groundwater levels and weather conditions.

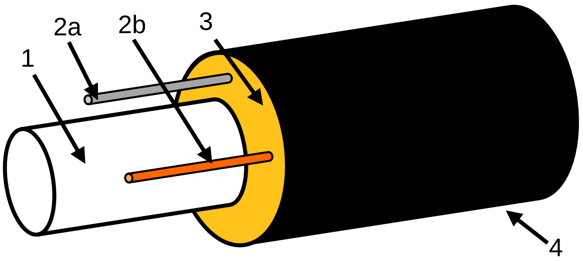

Figure 1. Schematic view of the end of a district heating pipe where a joint has to be made. (1) Service pipe (steel), (2) Leak detection ((2a) tinned copper, (2b) copper), (3) Insulation (PUR) and (4) Casing (PE).

Because joints may need to be made in wet conditions, they are a critical component in pre-insulated district heating systems. The edges of the joints are particularly susceptible to water ingress. Multiple water barriers are therefore used to prevent water entering the system.

If the water barriers fail and water enters the joint, heat losses in the district heating system will result in a less effective system. The leak detection system will warn the district heating supplier, so that the joint can be repaired. The service pipe can stay in place, meaning that the supply of hot water need not be interrupted.

However, if action is not taken quickly enough, the service pipe may corrode. If the service pipe fails, the escaping hot water may cause extensive damage to the surrounding area. Repairs will then include replacing part of the service pipe, resulting in an interruption to service, which will leave end users without a hot water supply. Aside from the inconvenience caused to end users, the repair costs will be high. This is especially so in the case of larger diameter pipes. District heat suppliers must therefore always remain alert. However, since prevention is better than cure, special care should be taken when making pipe joints.

Jointing systems that comply with EN 489 [3] are designed to withstand ground forces and remain leak tight throughout a technical life of at least 30 years. Joint installation on site must be done by specially trained personnel following the instructions given by the manufacturer in accordance with EN 13941 [4]. This means that the quality of the water barriers is largely dependent on the competence of the installer, but also the attention paid to the leak tightness of the joint during installation.

To ensure that the joints and their water barriers are properly made by the pipeline installer, a Dutch district heating supplier commissioned a quality control procedure for joints. This paper describes the results of this investigation. The goal of the operation was threefold:

1. To check the quality of the joints made by the pipeline installer. This also enables the district heating supplier to call the pipeline installer to account if mistakes are made, or even to withdraw the right to work for the district heating supplier.
2. To learn which mistakes are made when making joints, resulting in better on-site supervision by the district heating supplier.
3. To improve the work of the pipeline installer, simply by letting them know they are being checked. Not every joint is inspected, but the pipeline installer never knows which joints will be tested.

MATERIALS

Over 70 joints made on pipes installed on behalf of a district heating supplier in the Netherlands were completely removed from the system immediately after installation by the pipeline installer. These joints were then tested in the laboratory of Kiwa Technology. Multiple types of joints of various diameters were investigated. These joint systems are produced by Logstor (Løgstør, Denmark), German Pipe (Nordhausen, Germany) and Isoplus (Rosenheim, Germany).

This paper discusses three types of joints: PEX shrink joints, PE shrink joints and welded joints. The shrink joints are installed with three water barriers.

A general schematic cross-section of a joint is given in Figure 2.

PEX shrink joint

After welding the steel service pipe (*1* at position *4* in Figure 2), two insulating PUR foam shells are placed around the service pipe. The shells are wrapped in a shrink film with mastic (*3* in Figure 2). Because the film is also attached to the polyethylene (PE) casing of the district heating pipe (*5* in Figure 2), it forms the first barrier against groundwater.

A cross-linked polyethylene (PEX) shrink sleeve (*7* in Figure 2) is placed over the shrink film to form the second water barrier.

A third barrier is created by applying two shrink collars (*6* in Figure 2) over the ends of the PEX shrink sleeve.

Because insulating shells are used, no subsequent foaming is needed. Therefore, no holes need to be made in the shrink sleeve and film to add foam, nor are water barriers needed to cover the plugs that would be required to seal such holes.

PE shrink joint

After welding the steel service pipe (*1* at location *4* in Figure 2) and coating the casing of the district heating pipe with a primer (*5* in Figure 2), a PE shrink sleeve (*7* in Figure 2) is used to connect the two pipes. No shrink film is used; instead, a polyisobutylene (PIB) tape is applied beneath the PE sleeve to act as the first water barrier.

The annular space between the service pipe and the PE sleeve is subsequently filled with PUR foam. To accomplish this, two holes are drilled in the sleeve: one for adding the foam, the other to allow the release of air during the foaming process. These holes are later closed with a plug (not drawn in Figure 2).

Butyl rubber is applied over the plugs and at the ends of the PE sleeve (*6* in Figure 2). This forms the second water barrier.

Densolen® tape N8 (*6* in Figure 2) is applied over the butyl rubber at the ends of the sleeve and at the plugs to form a third water barrier. The Densolen® tape N8 is mechanically protected by black Denso foil (*6* in Figure 2).

Welded joint

After welding the steel service pipe (*1* at position *4* in Figure 2), two insulating PUR foam shells are sometimes placed around the service pipe. A polyethylene (PE) sleeve (*7* in Figure 2) is welded to the casing (*5* in Figure 2) using copper wires (not drawn in Figure 2). Other types of welded joints don't use PUR foam shells but are instead filled with PUR foam after the welding process. In this case, two holes are drilled in the sleeve. These are subsequently closed with a plug.

A second water barrier is created by applying two shrink collars (*6* in Figure 2) over the ends of the weld sleeve. This type of joint does not have a third water barrier.

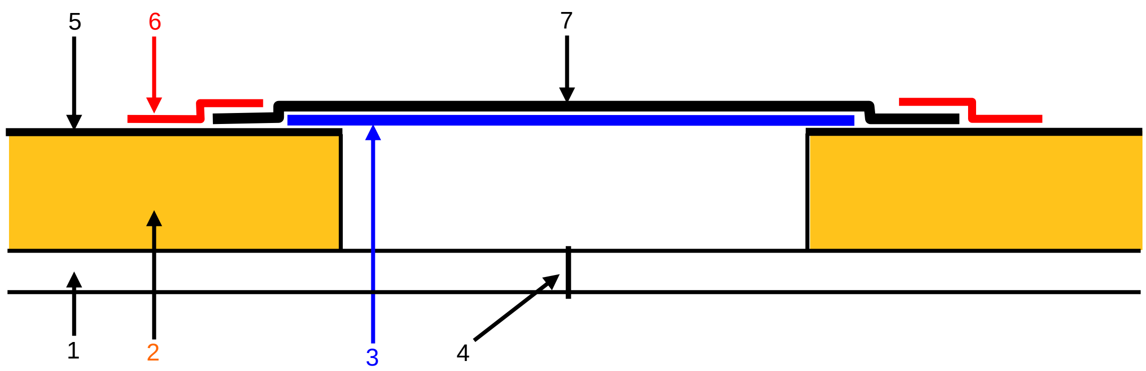

Figure 2. Cross-section of a joint (schematic). (1) Service pipe (steel), (2) Insulation (PUR), (3) Optional shrink film, (4) Weld in the steel pipe, (5) Casing (PE), (6) Shrink collar (PEX) or tapes (butyl rubber, Densolen N8 and black Denso foil) and (7) Shrink sleeve (PEX or PE) or welded sleeve (PE).

METHODS

The purpose of the laboratory testing method is to assess the quality of the joint. The water barriers in the joints were therefore carefully inspected. If any part of the water barrier in the joint is not applied as prescribed, the joint will be more susceptible to future leaks.

A practical testing method, consisting of three steps, was devised.

Non-destructive investigation

Firstly, the joints were inspected non-destructively by:

- Measuring the resistance of the leak detection wires (*2* in Figure 1). The leak detection wires of the pipe ends need to be properly connected across the joint. Without proper connections, any leaks cannot be detected. This renders the leak detection system useless.
- Checking whether the work instructions had been followed correctly. This involved a visual inspection of the outside of the joint in order to determine whether the pipe had been properly abraded before the joint was made, whether the primer was visible, whether the tapes had been correctly applied, whether the sleeves and collars were correctly centred, etc.

Leak tightness

Secondly, the leak tightness of the intact joint was verified. This leak tightness test was specially developed for this joint quality control inspection. Air pressure was applied between the outer casing and the PUR foam or shells. To obtain a good connection between the air supply and the outer casing, two short PE rods were welded onto the casing (Figure 3). A small hole was subsequently drilled through each PE rod and the casing into the PUR foam. One connection was for the air supply, of which the flow was measured, while the other was for measuring the pressure (Figure 4).

By pressurising the joints, the weakest point – or indeed any leaks – can be found. Initially, a relatively high pressure, sometimes as high as 0.5 bar(g), is needed to overcome the bond between the shrink sleeve or shrink film and the PUR foam or shells. This is necessary so that air can flow inside the joint towards the water barriers.

The measured air flow indicates whether or not a leak has occurred. If there is virtually no air flow, then there are no leaks. If a high air flow is measured, leak detection fluid (e.g. a soap solution) is used to find the leak. If no leaks are found, the pressure is increased and the air flow is monitored. For quality control purposes the pressure is not increased beyond 1.5 bar(g), since at higher pressures the procedure becomes a strength test.

Figure 3. Connections to a district heating pipe joint using two hollow PE rods to perform the leak tightness test.

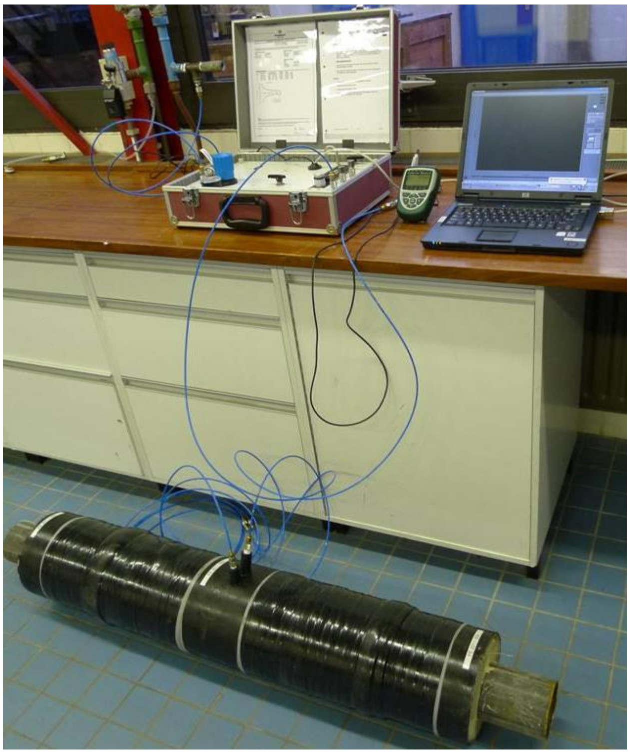

Figure 4. A district heating pipe joint is pressurised; the pressure and flow are measured.

Destructive examination

Finally, the joints were dismantled for further examination. Four strips were cut from the joint, including the collars, for all joint types. The collars were manually peeled away from the casing and the sleeve while the strength of the bonding was continuously assessed. The sleeve was manually peeled away from the casing. The bonding of each part was then examined visually. The PUR foam or shells and PIB tape (if relevant) were also inspected. Finally, the primer was analysed using Fourier transform infrared spectroscopy (FTIR) in order to check whether any differences in bonding of the tape might be due to the use of a different (i.e. other than prescribed) primer.

RESULTS

Non-destructive investigation

In one of the 58 joints inspected, one of the leak detection wires (*2* in Figure 1) was not correctly connected across the joint. Although only one broken connection was found, this is a major fault, as explained earlier.

A situation in which the tinned copper wires were connected to the copper wires was observed more often. The wires were thus not connected to the same type of wire (tinned copper to tinned copper and copper to copper), but to the other type of wire. Although this is not in itself incorrect, it makes the leak detection surveillance diagram more complex.

The PE casing was not properly abraded in more than 50 % of the joints. In some cases the casing had only been lightly abraded, while in others this had not been done at all. Sometimes the casing had been abraded in the axial direction, resulting in potential leak paths under the sleeve.

Furthermore, folds or wrinkles in the sleeve or collar of several PEX shrink joints were found (Figure 5 and Figure 6).

Signs of insufficient heating, such as the absence of mastic next to the collars, were observed in about 10 % of the joints.

Tape had been wrongly applied to more than 50 % of the PE shrink joints. Tapes require special attention when applied, as they must be wrapped tightly over the joint.

The (small) mistakes were therefore mainly due to sloppiness: folds, air inclusions and tape endings halfway were observed (Figure 7). Tape was also found to have been applied separately over the sleeve ends and the plugs, while it should have been applied in one piece (Figure 8). Although these are not major mistakes, they do introduce unnecessary weak points in the water barrier of the system. The resulting reduction in the leak tightness of the joint is out of proportion to the extra effort required from the pipeline installer in order to apply the tape correctly.

Figure 5. Fold in PEX shrink sleeve.

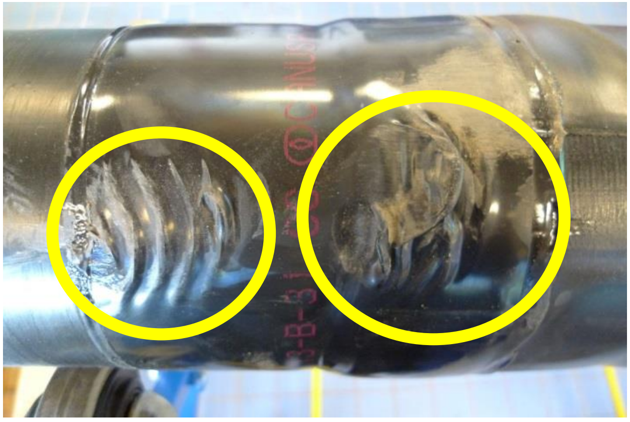

Figure 6. Wrinkles in the collar of a PEX shrink sleeve.

Figure 7. A tape ending halfway across the taped area. This causes a weak spot in the system.

Figure 8. The left side has two separate tape sections. This leads to unnecessary extra possible entry points for water and points at which the tape may detach. Tape applied correctly in one piece can be seen on the right-hand side.

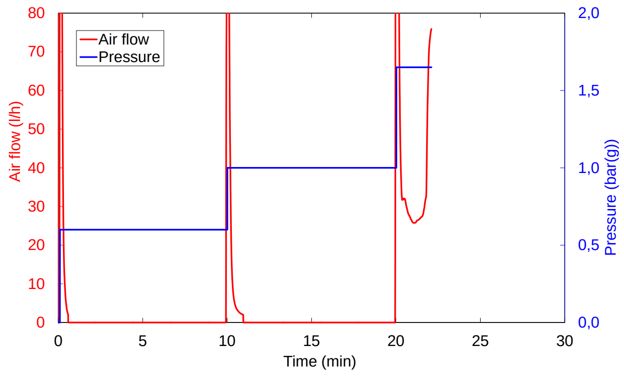

Figure 9. Air flow (lower trace, red) and pressure (upper trace with steps, blue) during a pressure test with air until failure of the PE shrink joint. Below 1 bar(g) the air flow is 0 l/h after an initial peak as the pressure increases. At 1.5 bar(g) the air flow increases considerably, indicating a leak.

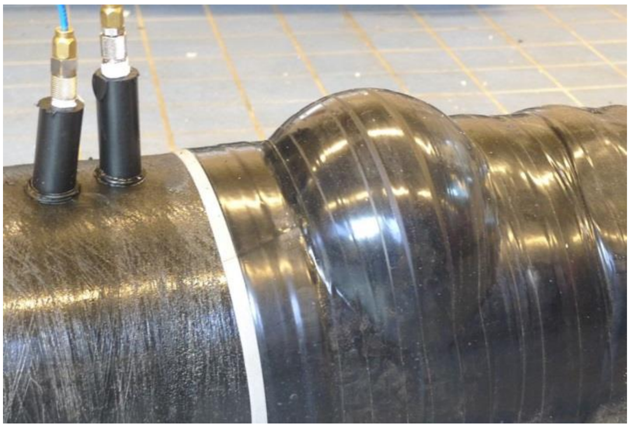

Figure 10. Failed joint after being pressurised up to 1.5 bar(g).

Leak tightness

Five of the 20 PE shrink joints failed during the leak tightness test (Figure 9 and Figure 10). None of the other joint types failed.

The five defective PE shrink joints all failed at the plugs. In one of the five cases, the butyl rubber and Densolen tape were strong enough to withstand the pressure; the tape thus blew up like a balloon. In the other four cases the tape did not have enough adhesive strength; this created a leak path. The poor adhesion was confirmed during destructive inspection.

Destructive examination

Destructive examination was carried out in order to visually examine the performance of the water barriers.

In more than 50 % of the PE shrink joints, one or more tape strips could be peeled away from the casing and/or PE shrink sleeve (compare Figure 11 with Figure 12). It was often found that the pipe ends and PE sleeve were not properly abraded. Improper abrading can therefore result in a low bonding strength of the tape, which decreases the quality of this water barrier and thus increases the possibility of water entering the joint.

Figure 11. A poorly abraded joint, resulting in a low tape bonding strength. The tapes were easily peeled away from the PE casing and shrink sleeve manually. The quality of this water barrier is therefore low.

Figure 12. These tapes were strongly bonded to the PE casing. The edge on the right side shows unsuccessful attempts to detach the tape.

Only about 15 % of the collars in the PEX shrink joints could be peeled away from the casing and/or PEX shrink sleeve manually (Figure 13). In slightly more cases (about 20 %) the PEX shrink sleeve could be peeled away from the casing manually (compare Figure 14 with Figure 16). Insufficient heating, insufficient abrasion and/or contamination, e.g. by sand, of the joined surface are expected to be the principle causes of the poor adhesion. In the other cases the PEX sleeve and shrink film all had strong bonds with the PE casing. In each of these cases considerable force was needed to separate the various components at room temperature.

Surprisingly, over 60 % of the welded joints could also be manually peeled away from the PE casing (compare Figure 15 with Figure 17). In a welded joint, the PE of the casing and sleeve are melted together to form a very strong bond.

Being able to manually peel the sleeve away from the casing is a clear indication that the casing and sleeve have not fused together properly. Welded joints are used in the most severe conditions and for the most important district heating systems. Since this type of joint only has two water barriers (in some cases, even the collars are omitted), a good weld is essential in order to guarantee the quality of the entire joint.

In two PE shrink joints, water was found trapped beneath the PE shrink sleeve (see Figure 18). This could have been caused either by condensation or by rainfall. Regardless of the cause, the pipe and other components had not been properly dried before joining, despite this being specified in the installation instructions. Since water had already passed the water barriers, the risk of joint degradation was increased.

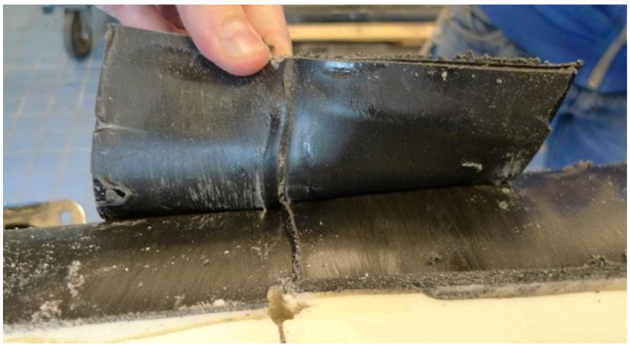

Figure 13. The collar of this PEX shrink joint could easily be detached manually from the casing and the PEX shrink sleeve.

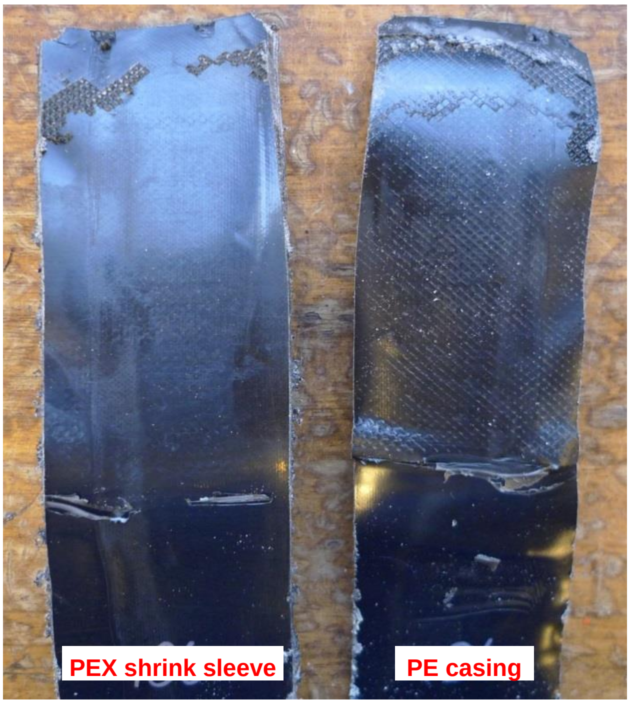

Figure 14. There is no bonding strength between the PEX shrink sleeve and PE casing, probably due to insufficient heating.

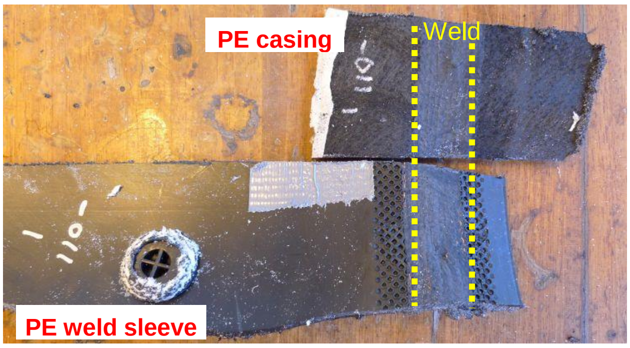

Figure 15. The PE weld sleeve and the PE casing are not properly fused. The PE weld sleeve could therefore easily be manually peeled away from the PE casing.

Figure 16. The bonding between the PEX shrink sleeve and the PE casing is strong enough to withstand manual peeling.

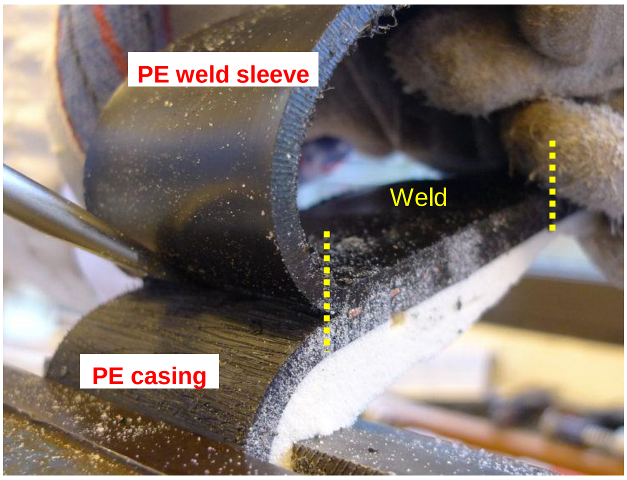

Figure 17. The weld is strong enough to withstand manual peeling.

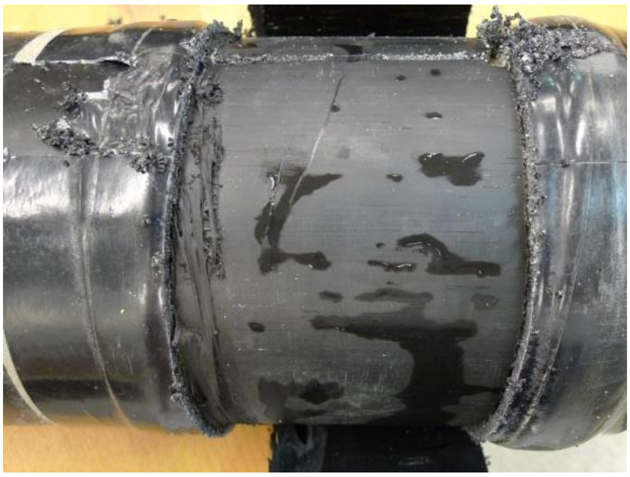

Figure 18. PE shrink sleeve removed to show water trapped in the joint.

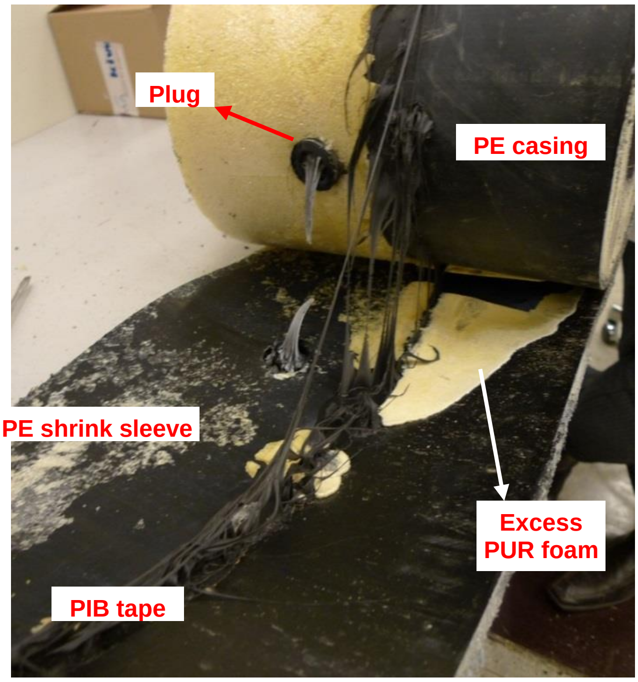

Figure 19. PUR foam has flowed beyond the PIB tape barrier, creating a failure in the first water barrier.

Inspection of the PIB tape in PE shrink joints revealed that in various cases, PUR foam had flowed beyond the PIB tape barrier (Figure 19). After joining the steel pipes, the annular space between the service pipe and the PE sleeve is filled with foam. It appeared that the foam had been able to flow beyond the PIB tape. The PIB tape, which is the first water barrier, was in the process destroyed. This is therefore a very undesirable situation.

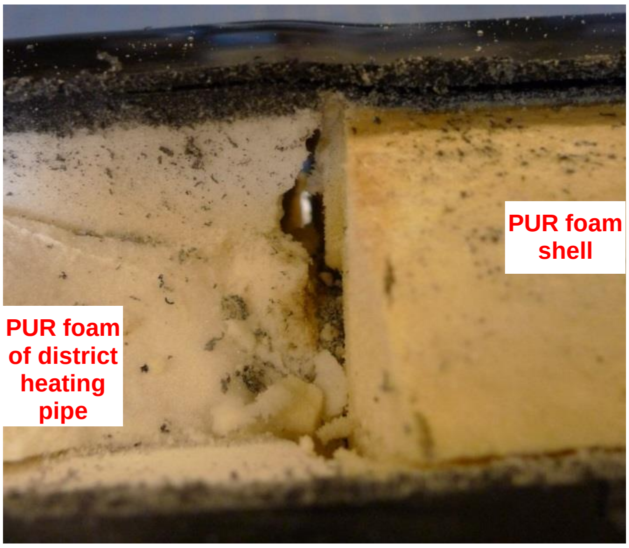

Figure 20. PUR foam is cut very irregularly, so that the PUR foam shell does not fit tightly, which leads to large gaps.

The noted defect is not a result of the pressure test, since the cured PUR foam is a very rigid material and should not therefore be able to flow beyond the PIB tape.

In addition to examining the water barriers, the destructive inspection also examined the quality of the PUR foam shell installation.

In about 10 % of the joints the PUR foam shells were not placed tightly enough against the PUR foam of the district heating pipe (*3* in Figure 1), resulting in large gaps (Figure 20). Such gaps are undesirable as they lead to:

1. Extra heat losses.
2. Heat build-up in the mastic used in the PEX shrink joints, leading to possible movement of the collars and shrink sleeves.
3. Migration of any water that may have entered the joint towards the steel service pipe. The water will heat up and become very hostile to the PUR foam. Hot water can quickly degrade and hydrolyse the PUR foam, thus decreasing the thermal insulation. This will cause the water to heat up still further, etc. If the new joint is subsequently foamed, then this process will occur much less quickly, since the water cannot easily reach the hot service pipe. This in turn means that it will take longer to heat up and attack the PUR foam.

FTIR measurements showed no differences in the primers used. District heating suppliers are nevertheless aware that other primers are used in the field. This therefore remains a potential issue.

DISCUSSION

The three-step quality control method described in this paper was specifically developed in order to ensure that district heating joints and their water barriers are properly made by the pipeline installer. An outer visual inspection gives some indication if errors have been made. These include insufficient or incorrect abrasion, folds and wrinkles in the sleeve and/or collar or insufficient heating of the collar and/or sleeve. However, (manually) peeling these parts away from the PE casing gives a much better indication of the bonding strength, and thus leak tightness, of the water barriers. Although the pressures and loads applied in the leak tightness test and the destructive examination are not comparable with loads in practice, they nevertheless give a good indication of where the weak spots in the system are.

Performing the destructive inspection revealed that about 20 % of the PEX shrink joints were poorly bonded. This was mainly due to insufficient heating. The installation of PE shrink joints is a more laborious process; this resulted in 50 % of the tapes having poor bonding. In this case sufficient abrasion in the tangential direction is an important step in obtaining a good bond. Surprisingly, about 60 % of the welded joints could be separated manually. The reason for this is unclear. Specific research is needed in order to determine which crucial steps failed, thus causing the poor bonding. It is interesting to note the differences in design between welds made in gas and water pipes and in district heating pipes.

Furthermore, it was found that the plugs in the holes used for foaming after installation of the sleeves of PE shrink joints can form weak spots, especially if the tapes have a low bonding strength on the PE casing. The district heating system is designed for a technical life of 30 years. Therefore, weak spots of this nature in a wet environment such as the Netherlands are highly undesirable.

In view of the errors made, it is clear that there is still much room for improvement. The three-step quality control method is not only intended to check the quality of the joints but also so that it is possible to learn from mistakes. On-site supervision could easily prevent errors such as insufficient or incorrect abrasion, folds and wrinkles in the sleeve and/or collar and gaps between the PUR foam of the pipe and the PUR foam shells of the joint. In particular, communicating these mistakes to the various contractors and stressing the importance of high-quality work has already improved the latter. This research therefore assists on-site supervision and indicates at which installation steps the installer’s staff need to improve quality, for example by proper heating of the joint, to obtain high-quality joints with a technical life of at least 30 years.

CONCLUSIONS

A three-step quality control method of three types of joints in district heating pipes revealed various installation errors. Most of these errors were found in PE shrink joints with a PE shrink sleeve and tapes.

Various installation errors were found. For example, tape had been incorrectly applied, the polyethylene casing had not been sufficiently abraded, polyurethane foam had destroyed the polyisobutylene water barrier, water had become trapped inside the joint and insulation shells were cut off too short or were not straight, leading to gaps.

The results show the importance of foolproof jointing systems in obtaining high-quality joints in the field. Moreover, it is recommended that the installer's staff training be improved.

OUTLOOK

Completely extracting the joint from the field, including the steel service pipe, is costly. This is especially so in the case of larger diameter pipes. Therefore, preliminary tests can be performed to examine joints in the field. Although visual inspection is slightly more difficult in the field than in the lab, the three steps (non-destructive, leak tightness and destructive testing) can also be performed in the field.

ACKNOWLEDGEMENTS

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FIELD MEASUREMENT OF SKIN-FRICTION OF TRENCHLESS INSTALLED DISTRICT HEATING PIPES

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ABSTRACT

The presented investigation gives an overview on field measurements of skin friction carried out with DH pipes for trenchless installation in an AGFW research project. Ten district heating pipelines were installed in 2013. The installation process was observed and monitored with high accuracy. Pulling forces during installation were measured. After a certain period single pieces of the district heating pipelines were cut off in a pit. By pushing these pipe segments through the bore hole the skin friction between the surrounding soil, saturated with bentonite suspension, and the district heating pipe was determined.

INTRODUCTION

For the expansion of district heating (DH) networks, smart solutions for construction are needed. An accurate and safe design must be coupled with economic, flexible and innovative pipe laying methodologies. A promising pipe laying technology is trenchless laying. This technology is wide spread for several supply applications, however, not for preinsulated bonded DH heating pipes. The existing scepticism regarding trenchless installation is based on special loads and needs of the DH pipelines. The fact that a hot medium has to be transported, leads to a special design, where skin friction, lateral bedding pressures and cyclic temperature loads have to be taken into account [1]. For an accurate analysis, the contact forces between pipe and soil have to be clearly determined in every case - after installation and during operation. The contact pressure to the pipe coating, and the related friction forces have to be assessed as accurate as possible. The presented investigation gives an overview on first field measurements of skin friction, carried out with DH pipes for trenchless installation in an AGFW research project [2].

STATE OF THE ART

For the design of preinsulated bonded DH-pipes, the friction force in the pipe-coating – soil interface is an important quantity. Stress-strain calculation and the estimation of maximum displacements due to thermal load, depend on the friction force, which partly or fully constrains thermal expansion. According to the Coulomb friction law approach, the friction forces are assumed proportional to the radial contact pressure around the pipe [1]. The ratio between the contact pressure and friction force is defined as the interface coefficient of friction (μ). Although μ can depend on a number of factors including the pipe surface conditions, pipe material, time rate of interface shearing, temperature, and humidity, in most cases, it is assumed to be a constant. The coefficient of friction μ is respected in the commonly used formula for pipe-soil friction according to equation (1).

$$F_R = \mu * \frac{D}{2} \int_0^{2\pi} \sigma_{avg} d\phi \qquad (1)$$

Where F_R=friction force, μ=coefficient of friction between pipe and backfill, D=pipe diameter, σ_{avg}=average contact pressure, $d\phi$=increment of pipe perimeter angle

Skin friction in the pipe-soil interface may thus be described by the coefficient of friction. As a conventional trench refill according to EN 13941, a coarse grained material with a percentage of fines with a diameter <0.075 mm less than 10% is recommended [1]. For the contact with the pipe coating of preinsulated bonded DH-pipes, according to O'Rourke et al. (1990) [3], μ may be estimated in the range of 0.43 – 0.57 for a coarse material with an internal friction angle of φ'=35°-45° according to equation (2) [1].

$$\mu = \tan\left(\frac{2 * \varphi'}{3}\right) \qquad (2)$$

Where μ=coefficient of friction between pipe and backfill, φ'=internal friction angle

Trenchless pipe installation deals with the in situ soil. For friction reduction during installation, bentonite slurries are generally used in the borehole (see below). First laboratory investigations of the friction between polyethylene of high density and mixtures of sands and bentonite slurries are shown in [4]. However, no experience is reported concerning the skin friction of district heating pipes after trenchless installation under full scale field conditions.

METHODOLOGY

The credibility of theories, laboratory analysis and design procedures is increased by field tests. Because of this, field measurements of skin friction are carried out with DH pipes for trenchless installation in an

AGFW research project. The field tests have to be seen as an important part of the AGFW investigations on trenchless technology for the district heating sector. Three major field activities were done and monitored with high accuracy:

- Trenchless installation of district heating pipes
- Simulation of real heating conditions
- Recovery of pipes and joints

This paper deals with the first step of activities in the project, namely the trenchless installation and survey of district heating pipes. In the year 2013, ten district heating pipelines were installed under full scale conditions. The investigations were carried out on a testing field at BRUGG-Pipe systems GmbH in Wunstorf, Germany. Nominal diameters from DN25 to DN200 were used according to figure 1.

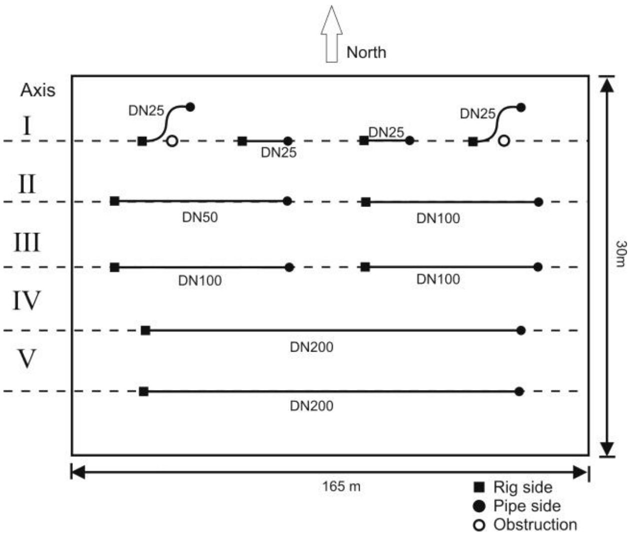

Fig. 1 Arrangement of the test field

Soil investigations are essential for the assessment of the bearing behaviour of trenchlessly installed district heating pipes. According to Eurocode 7, soil investigations are even obligatory. They include continuous coring and penetration tests [5]. The soil conditions of the test field were explored by 8 drillings involving continuous coring, 4 dynamic probing and several laboratory tests. Table 1 shows the different soil types at different depths. The DH pipes were installed in the depth of layer No. 2 and 3.

Table 1, Soil parameters of the underground at the testing field

Layer No.	**1**	**2**	**3**	**4**
Soil	Topsoil	Finesand – middle sand	Sand, Gravel	Lime-stone
Depth [m]	0.0 – 0.5	0.5 – 2.0	2.0 – 6.0	> 6.0
Internal friction angle φ' [°]	30 (estimated)	32.5 – 37.5	35 – 40	25 – 30
Cohesion c' [kN/m²]	-	0	0	0 – 20
Friction coefficient according to Eq. 2	0.36	0.40 – 0.47	0.43-0.50	-
Weight γ/γ' [kN/m³]	11/8 (estimated)	18/10 (estima-ted)	20/10.5 (estima-ted)	21/11 (estima-ted)

The ground water table was registered - 3.0 m below surface.

After drilling along the pipe route, the bore holes were adjusted to the required pipe diameter by an expansion process with back reamers. To reduce the friction between the pipe coating and the borehole walls, bentonite slurries were used. Mainly pure bentonite suspensions were used. Two pipes (DN100 and DN200) were pulled in, with a bentonite suspension containing hardening additives. Furthermore, different methods of trenchless pipelaying were tested. For the smaller pipes with DN25, the installation with soil displacement hammer and the horizontal directional drilling (HDD) with mini drill rigs were used. The bigger pipes from DN50 to DN200 were installed with the conventional normal scale HDD-method. Since the HDD method was identified in the project to be the most important laying method, the main focus was put there.

Using HDD, the pulling forces were measured continuously by a tensile load cell unit between the back reamer and the pipe head. The measuring device is shown in Figure 2.

Fig. 2 Tensile load cell during installation

The development of skin friction after trenchless installation is not known today. It depends on several parameters, of which the presence of ground water seems to play a major role. For many pipe systems, skin friction after the installation is not relevant. However, for district heating pipes it is one of the most important parameter for the design. Because of this, two special friction tests were carried out several months after installation.

In a pit, a pipe segment was cut off and pushed through the borehole. The experimental setup consisted of a hydraulic press, an abutment, a load cell and displacement measurement. In Figure 3 the arrangement is shown.

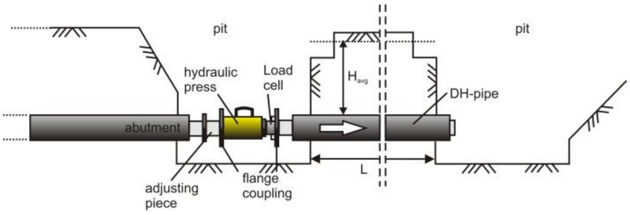

Fig. 3 Experimental set-up for friction tests

Test No. 1 with pipe V.1 is characterized by a length of L=3.72 m of the pipe segment and an average overburden height of H_{avg}=1.8m. A bentonite suspension containing hardening additives was used. In test No. 2 with pipe IV.1 L=3.08m and H_{avg}=2.23 m was measured. A pure bentonite suspension was used. It is planned to carry out two more tests of this kind after the project phase „Simulation of real heating conditions“, which gathers knowledge of the changes in skin friction due to operation.

RESULTS

The monitoring of the installation process was done by a tensile load cell according to figure 2. Maximum pulling forces and average pulling forces are presented in table 2. An equilibrium between the pulling forces and the skin friction around the pipe perimeter during installation was assumed.

Table 2. Results from tensile load measurement during installation

Nominal Diameter / pipe No.	Maximum pulling force [kN/m]	Average pulling force [kN/m]	Target depth [m]
DN25 / pipes I.1-4	-	-	-
DN50 / pipe II.2	0.93	0.24	1.5
DN100/ pipe II.1	0.45	0.27	1.5
DN100/ pipe III.2	0.16	0.08	1.5
DN200/ pipe V.1	0.51	0.36	2.5

Table 2 shows no clear correlation between the measured friction forces, overburden height and diameter. This leads to the conclusion that besides the geometry of the bore hole, local geological boundaries play a major role for the quantity of the friction force. Furthermore, the used bentonite suspension significantly affects the skin friction during installation. The skin friction is reduced to a minimum. After installation, earth pressure leads to a close contact between pipe and soil, which is saturated with bentonite slurry.

There is a lack of knowledge concerning the skin friction for this situation. However, this is the relevant friction force for the design of DH pipes in operation. Because of that, the presented test concept according to figure 3 was developed. The received results from the friction test No. 1 and No. 2 according to the presented scheme included force and displacement measurements. The obtained curves are illustrated in figure 4.

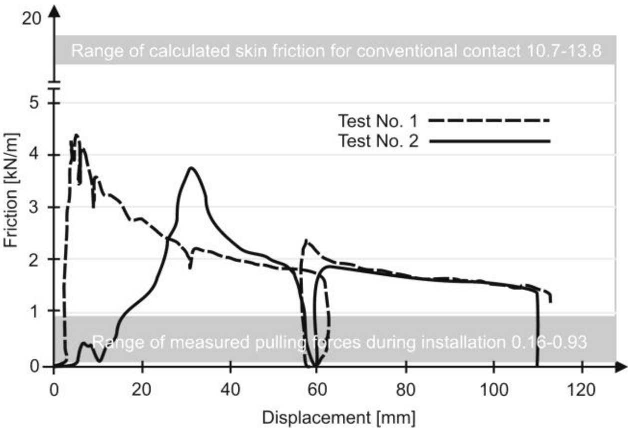

Fig. 4, Skin friction obtained from in situ tests

DISCUSSION

A maximum friction force of 4.33 kN/m was measured in the first test after 5.3 mm. After the peak, a residual friction force of approximately 1.5 kN/m was observed. In the second test, the maximum friction force was 3.72 kN/m at 30.8 mm with the same residual friction force as in the first test. This leads to the evidence, that an exact correlation between shallow target depth and contact pressure after trenchless installation is difficult to obtain. The comparison with the pulling forces during installation showed that there is a kind of ageing effect in the soil-pipe contact zone over time. Ageing is already known as a time dependent phenomena for conventionally installed pipes without friction reducers [6], but it was also evident for trenchless installed pipes.

The hardening additives in the bentonite suspension of test No. 1 resulted in a higher peak friction force, that was achieved after a smaller displacement compared to test No. 2.

Nevertheless, for the same target depth, the friction force for conventional pipe laying in soil 2 and 3 according to Equ. 1 with parameters from table 1 is expected to be 10.73 kN/m to 13.79 kN/m, which is significantly higher than the measured values.

CONCLUSIONS

It is the first time skin friction was measured between district heating pipes and the surrounding soil after trenchless installation. This publication presents important results in comparison with the expected skin friction for conventional pipe laying and the skin friction during installation.

The results showed an ageing effect that led to 3.5 to 4 times higher friction forces, compared to installation forces. Nevertheless, the calculated friction for conventional pipe laying was even higher.

For the trenchless installation of DH pipes, the interaction between installation method, soil, pipe and temperature is not clearly investigated today. So far, the special operation conditions of DH pipes seem to be the biggest barrier, because different recommendations and investigations for the calculation of the initial contact conditions are available – even though the calculation method for trenchless pipe laying serve foremost to estimate the maximum pulling forces on the “safe side”. First steps for a safe design and application of trenchless DH pipe installation are shown here.

ACKNOWLEDGEMENT

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SESSION 14

Resource efficiency and environmental performance

DISTRICT HEATING COMBINED WITH DECENTRALISED HEAT SUPPLY IN HYLLIE, MALMÖ

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ABSTRACT

Hyllie is an area under construction in Malmö, Sweden, targeting to have an energy supply consisting of 100% renewable or recycled energy by 2020. To achieve this, one solution could be to utilise the excess heat from cooling machines (CMs) providing cooling for e.g. offices in district heating networks. Other studies have addressed similar issues. The utilisation of the excess heat from decentralised CMs is however a new research area. The results were mainly developed by simulations in the simulation programme NetSim. The simulations were based on data from 2012 and 2013 and on future plans for the Hyllie area. CM data were mainly obtained from simulations performed by a heat pump manufacturer. The results indicate that by utilisation of the excess heat produced by CMs in Hyllie, a noticeable amount of heat production in more conventional production units could be retained. The results also suggest that the carbon dioxide emitted and primary energy used due to the heating demands in Hyllie could decrease distinctly, especially during the warmer period of the year. This however depends on how the electricity is regarded. It is also important that the excess heat is utilised under the right conditions, to avoid network problems.

NOMENCLATURE

P_{el} = Electricity power (kW)

q = Flow (m^3/s)

q_{pump} = Flow through pump (m^3/s)

P = Heat power (kW)

C_p = Specific heat (kJ/kg,°C)

T_s = Supply temperature (°C)

T = Temperature (°C)

GREEK

ρ = Density (kg/m^3)

η = Efficiency (-)

Δp_{pump} = Pressure difference over pump (kPa)

INTRODUCTION

The aim of the present paper is to investigate incorporation of heat from small consumer owned, decentralised cooling machines (CMs) for simultaneous heating and cooling into the district heating (DH) network in Hyllie in Malmö, Sweden. These customers will be called prosumers as they are both consumers and producers of DH [1]. The main focus is to see how incorporation of such CMs affects the primary energy balance and carbon dioxide emissions of this area.

The world will be facing great challenges if no or too little action is taken to reduce the anthropologically driven climate change [2]. A substantial part of the carbon dioxide reducing work and research focus on cities. Cities are said to be one of the main causes and thus also one of the main solutions to human induced climate change [3]. There is for instance a city in Denmark called Frederikshavn, aiming at becoming a 100% renewable city by 2015 [4]. Such studies show that there is a comprehensive need for climate work in the urban environment. The present study adds another component to this work.

Offices and businesses in Sweden with extensive cooling demands sometimes choose a CM instead of district cooling for their cold supply, as this often is a cheaper alternative [5]. The cooling demand in Sweden is already large in office buildings and is likely to increase in the future [6]. This could facilitate a transition from DH to heat pumps and CMs for these buildings. An alternative could be to instead install CMs and utilise the excess heat from the CMs in the DH network. When the CM produces cold for the building, there is often no use for the excess heat, why this is otherwise deposited to the air. Utilisation of that heat could facilitate mitigation of the climate impact of Malmö and thus also help reducing the present climate change in the world. There is currently a gap in the scientific literature for studies that describe this kind of smart DH systems, which the present study seeks to fill.

The Hyllie area in Malmö is an especially interesting area from an energy point of view. The area is under construction and thus the buildings are and will be energy efficient and adapted to lower temperatures in the DH network. Furthermore, the DH network of Hyllie is attached to the rest of the DH network in Malmö via only one supply and one return pipe. Even if Hyllie is not a delimited low temperature DH network, it is possible to partly treat it like that, due to these properties. This simplifies the introduction of low temperature heat sources. Hyllie is also the focus of a so called "climate contract" that is signed by the City of Malmö, E.ON (the local energy company) and VA SYD (the local water and sewage company). In this contract it is stated that Hyllie is to develop into the most climate smart district of the Öresund region and become a global model for sustainable urban development. One clause also declares that the energy supply is to consist of 100% renewable or recycled energy in 2020 at the latest. The present study suggests a part of the solution to this challenge.

The present study is mainly performed with input data from the local DH company (E.ON) and a heat pump manufacturer (Carrier). The CM used is a standard CM that is designed for simultaneous heating and cooling. The calculations have been carried out in the commercial district energy network simulation programme NetSim, produced by Vitec [7].

STATE OF THE ART

DH is often seen as a usable tool to help reduce the carbon dioxide emissions caused by heating demands in cities [8]. There are great opportunities to introduce renewable energy sources, such as solar collectors [9] and heat pumps [10] in DH networks. Brand and Svendsen [11] for instance evaluate the possibility to lower the DH supply temperature in typical 70s houses in Denmark, which would enable renewable energy sources to be utilised in DH networks to a greater extent. The authors conclude that only a small refurbishment of the house is needed to reduce the maximum DH supply temperature from 78 to 67ºC and even to below 60ºC for 98% of the year.

Regarding excess heat, mostly industrial heat has been examined in different studies, such as potentials for excess heat in Sweden [12]. Persson and Werner point out that excess heat recovery is important to reach the fulfilment of European Union energy and Climate goals [13]. Even if this conclusion focuses on industrial excess heat, it can also be applied on the excess heat in the present study.

Interesting for the present study is also that there is a substantial amount of studies dealing with heat pumps for simultaneous heating and cooling, which shows that this is a current technology with great potential. For instance, Ghoubali et al. perform a simulation of such a heat pump [14] and Fatouh and Elgendy conclude that heat pumps that are used for simultaneous heating and cooling can improve the total energy utilisation efficiency [15]. These studies are however not discussing the possibility of connecting the heat pump/CM to the DH network.

METHODOLOGY

The Malmö DH network is a large DH network that covers the city of Malmö. Hyllie is situated in the south part of Malmö. The hydraulic separations in substations consist of indirect space heating and closed hot water supply and the district heating network provides heat for both domestic hot water and space heating demands.

The results were mainly developed using data from the local DH company and with simulations of CMs and simulations of DH networks in NetSim, a commercial simulation programme for district energy [1]. The basic settings in NetSim were the same as in [1].

Model in NetSim

An existing model of Hyllie in the Malmö DH network in NetSim was updated to fit a future scenario of 20 years from the present. This was done in order to see how the future network would react to the CM prosumers. The network model can be seen in Fig. 1. To see how the heat production by CMs in Hyllie affected the nearby parts of the DH network, the model included also the adjacent areas. The 20 year scenario was anticipated to be the most interesting scenario as the CM solution will probably not be relevant in the near future. The return temperatures and the heat power demand of the existing buildings were based on measured values.

The Hyllie area was updated and built in accordance with the comprehensive plan of the City of Malmö and additional plans from the local DH company. The heat power demands were thereafter calculated with a value of 1000-1100 hours utilisation time and predicted annual heat demand [16], according to data from the local DH company. The return temperatures of these buildings were set to 30°C. This value was based on the DH contracts for the new buildings in Hyllie.

In NetSim it is possible to simulate DH networks in three levels. Simulations in level 3 are simplified and only involve the main pipes. Simulations in level 1 involve the whole DH network including the service pipes. When the Hyllie area was finished in the Malmö DH model (referred to as the Malmö model), the network was divided and a new model was created with only the Hyllie area (referred to as the Hyllie model). This enabled the possibility to conduct simulations in level 1, as this is hardly possible with bigger networks.

Input supply temperatures, pressure maintenance and differential pressures from the Malmö model to the Hyllie model were developed with simulations. The pressure maintenance was set to 587 kPa in the return pipe of the fictitious heat power unit representing the input from the Malmö DH network.

The return temperature and the heat power needed by the buildings are in NetSim depending on the outdoor temperature and regulated with curves developed from measured data. The curves from the Malmö model at level 3 had to be adjusted to level 1 for the Hyllie model.

In the Malmö model, it was not possible to perform simulations for higher outdoor temperature than 13ºC and thus the input data for the higher temperatures to the Hyllie model were estimated.

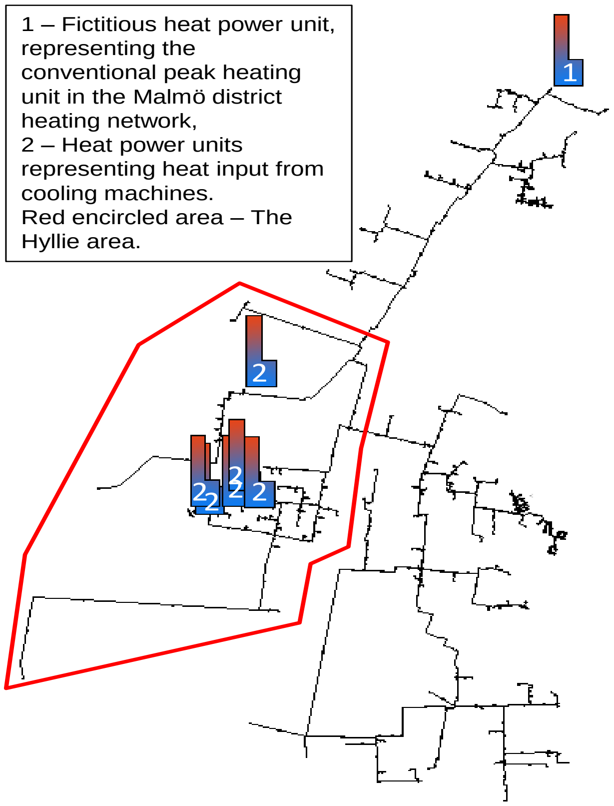

Fig. 1. Hyllie model network layout in NetSim.

Cooling load in Hyllie

First, the maximum cooling loads for the new buildings in Hyllie were calculated. The local DH company provided information about which buildings that would probably have a commercial cooling demand. It was however not possible to know their cooling load. The cooling loads in the new buildings in Hyllie were thus developed by looking at the cooling loads at consumers in the existing DH network in another part of Malmö in 2012. The maximum cooling demand for each consumer was compared to their connected DH heat power, achieved from NetSim. A mean value for this relationship was 0.88. This value was used to calculate a maximum cooling load of the new consumers in Hyllie, based on their connected heat power.

Then, the proportion of the maximum cooling load at different outdoor temperatures was calculated. The cooling loads for all the existing district cooling consumers were added for each hour 2012. These values were thereafter compared to total maximum cooling load of the summarised values and the percentage of how much cooling load of the maximum that was utilised each hour was developed. Each hour was also allocated its outdoor temperature, retrieved from the local DH company. A histogram for temperature intervals of 6°C between the outdoor temperatures of -18°C and 30°C was made. The mean value of the cooling load percentage for each interval was calculated.

To achieve average temperatures for each hour, the temperatures in Malmö the last 9 years (2005-2013) were investigated A similar histogram to the one before, a histogram for temperature intervals of 6°C between the outdoor temperatures of -18°C and 30°C was made. This showed the frequency of each temperature interval during the nine examined years. These percentages were multiplied by the number of hours during a year (8760). By comparing these to the cooling load percentages for 2012, the number of hours during a year could be coupled to the right cooling load percentage. For 2012, there were no temperatures below -18°C or above 30°C, why the cooling load for these temperatures had to be estimated. Under -18°C the cooling percentage was set to the same as for -13°C (the lowest temperature 2012) and over 30 degrees, the cooling percentage was set to the same as for 29 degrees (the highest temperature 2012). The results of these calculations can be seen in Table 1.

Table 1. Results from cooling load calculations.

Temperature interval	**Frequency**	**Hours of a year**	**Cooling percentage**
-18	0.01%	0.67	6.00%
-12	0.04%	3.67	6.20%
-6	1.26%	110.16	6.50%
0	10.57%	925.52	6.70%
6	23.54%	2062.25	6.90%
12	25.75%	2255.89	8,40%
18	26.35%	2308,47	13.60%
24	11.04%	966.87	32.80%
30	1.43%	125.17	62%
>30	0.02%	1.33	99%

Cooling machines

The outline of the CM solution can be seen in Fig. 2. CM data was achieved from Carrier, a heat pump manufacturer. The CM was a standard CM (30HXC080-PH3opt150) made for simultaneous cold and heat production. The refrigerant was R134a and two screw compressors were used. The temperatures to and from the evaporator were 18°C and 12°C and the temperatures from the condenser were 50°C, 55°C, 60°C and 63°C, hereinafter referred to as “supply temperature”. The temperatures to the condenser varied, as no larger temperature difference than 20 degrees was possible to simulate in the CM simulations. The COP and EER should be unaffected by the temperature going into the condenser, according to the Carnot theorem [16]. This does not apply to the flow. This is however regulated automatically in

NetSim, why the heat power outputs were not affected. The investigated cooling power demands were approximately 300, 400, 500, 600, 700 and 800 kW, hereinafter output power level 1-6, where power level 1 represents 300 kW and power level 6 represents 800 kW.

A simulation of a conventional CM that did not have any heat output requirements and with the cooling power output of 433 kW was also made. The CM was a standard CM (30HXC100-PH3) made for only cold production. The refrigerant was R134a and two screw compressors were used. The temperatures to and from the evaporator were 18°C and 12°C and the output temperature from the condenser was 30°C.

The heat power output in relation to the electricity power input is in this study called Coefficient of Performance (COP) and the cooling power output in relation to the electricity power input is in this study called Energy Efficiency Ratio (EER). The EER was achieved in the CM simulations and the COP was calculated from the electricity demand and the heat output of each CM. These values were assumed to be constant for a specific CM power level and supply temperature [17].

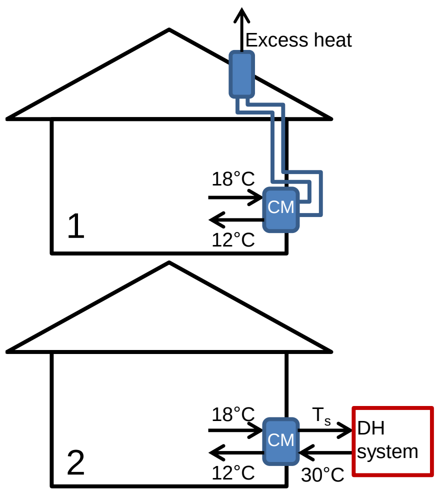

Fig. 2. Conventional CM (1) and a CM connected to the DH network (2).

Carbon dioxide and Primary energy

The following procedure was performed for each outdoor temperature interval and supply temperature. The outdoor temperature used in each simulation was the mean temperature of each temperature interval. The CMs were allocated to the appropriate building in NetSim, according to the maximum cooling power demand of the building, and simulations were made. Simulations without prosumers were also made (reference case). The peak heat producing unit in the Malmö DH network was identified. Thereafter, the difference in output heat power from this unit between the simulations with and without prosumers was calculated. This value was then converted to input heat power in the heat producing unit, by values of efficiencies achieved from E.ON and SYSAV, a company that owns a waste Combined Heat and Power (CPH) plant that delivers heat to the Malmö DH network. If the peak heating unit was a CHP plant, the heat allocation was calculated with the alternative production method [18]. The heat power difference was multiplied by the amount of hours that each temperature interval represented and the total amount of heat saved during a year could be calculated. It was not possible to perform simulations of the supply temperature of 50°C and the temperature intervals of 24-30°C and >30°C or of the supply temperature of 55°C and the outdoor temperature of >30°C. The supply temperature was in these simulations regulated to 60°C.

The carbon dioxide emissions this heat energy difference corresponded to were calculated with carbon dioxide emission rates for the peak heating unit, including the carbon dioxide emitted during the production and transport of the fuel. As the ratio of primary wood fuel and secondary wood fuel was not known in one of the heat units, a 50/50 ratio was assumed. The carbon dioxide emission rates used for the DH were 101 g CO_2 eq/kWh for waste incineration CHP, 247 g CO_2 eq/kWh for natural gas CHP, 37 g CO_2 eq/kWh for primary wood fuel and 16 g CO_2 eq/kWh for secondary wood fuel. The primary energy this heat energy difference corresponded to was calculated similarly, but with primary energy factors (PEFs). The PEFs used were 0.04 kWh/kWh for CHP waste incineration, 1.09 kWh/kWh for CHP natural gas, 1.05 kWh/kWh for primary wood fuel and 0.03 kWh/kWh for secondary wood fuel [18], [19].

The extra electricity needed to raise the excess heat from the CM to the required supply temperature to the DH network was calculated by comparing the electricity need for the CM for simultaneous heat and cold supply with the electricity need for a conventional CM. The total extra electricity this sums up to was thereafter multiplied with different carbon dioxide rates and primary energy factors. The rates and factors used were 969 g CO_2/kWh and 2.9 kWh/kWh, respectively, for worst case marginal electricity (coal condensing power) [18], [19], 258 g CO_2/kWh and 2.23 kWh/kWh for Nordic residual mix electricity, respectively, [20] and 13 g CO_2/kWh and 0.05 kWh/kWh for renewable electricity (wind power), respectively [18], [19]. The electricity needed in the pump raising the flow from the pressure in the return pipe to the pressure in the supply pipe was calculated with (1).

$$P_{el} = (\Delta p_{pump} \cdot q_{pump} / \eta_{pump}) \quad (1)$$

The efficiency of the pump was assumed to be 80%.

Flow and network

To examine how much of the heat load in the Hyllie area (the encircled area in Fig. 1) that was replaced by heat from the CMs, the flow into the area was investigated. As the temperature, the specific heat and the density of the DH water from the Malmö network were the same for the reference case and the prosumer case, the flow ratio represents the replaced heat power (2).

$$P = q \cdot \rho \cdot C_p \cdot \Delta T \quad (2)$$

The results in NetSim were also investigated to see how the technical parameters of the network, such as differential pressure, temperature and velocity were affected.

Bias

Tests were made to investigate the impact the pump efficiency had on the results. The pump efficiency had some impact if the electricity had large carbon dioxide emissions. The magnitude and sign of the results however remained the same. The fact that the conventional CM only was simulated for one cooling power output could be a source of bias. The EERs of the CM made for both heating and cooling however did only vary very little between the different power levels (Fig. 3). The EER is thus probably approximately the same for all power levels for the conventional CM too, why this should not affect the result.

The bias created by the altered supply temperatures from 50 and 55 to 60°C for the highest outdoor temperatures was also investigated. The aim was however to look at the heat power needed and that should be approximately the same, since the heat powers were defined in advance in NetSim. The bias this created was thus mainly a difference in pumping power. This had however negligible impact in test simulations made.

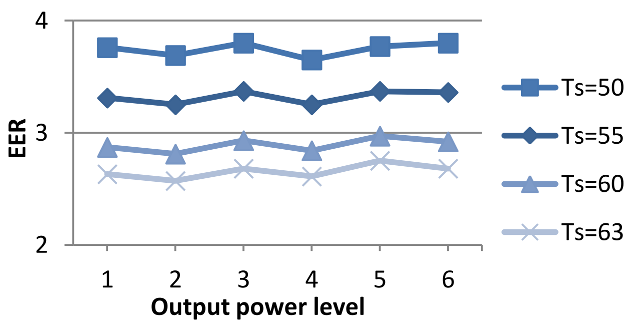

Fig. 3. EER for different output power levels and supply temperatures

RESULTS

Carbon dioxide and Primary energy

The carbon dioxide savings generated by the excess heat from the CMs can be seen in Fig. 4.

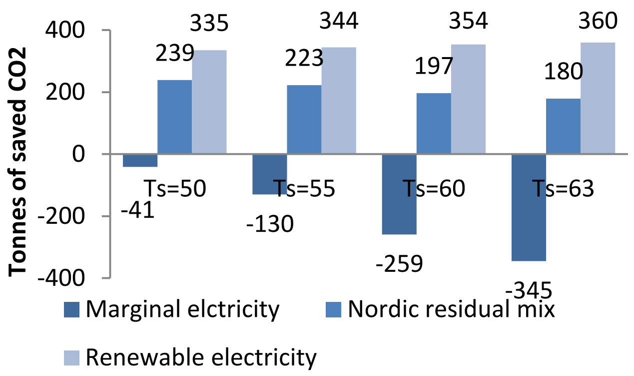

Fig. 4. Tonnes of saved CO_2 for the different scenarios.

When marginal electricity was used, the carbon dioxide savings were negative, i.e. more carbon dioxide was emitted than if conventional CMs were used. When renewable electricity or Nordic residual mix was used, the carbon dioxide emission savings were instead positive. For the case with renewable electricity, the carbon dioxide savings were higher, the higher the supply temperature was. For the case with Nordic residual mix, the carbon dioxide savings were lower, the higher the supply temperature was. For the case with marginal electricity, the carbon dioxide emissions were higher, the higher the supply temperature was. This was because in order to raise the temperature higher, more electricity was needed. More electricity was then transformed into heat, why more heat could be extracted from the CM. This additional heat was however mostly generated by electricity. When the electricity had low carbon dioxide emissions, as in the renewable electricity case, this heat also had low carbon dioxide emissions. But with the other cases, a higher supply temperature from the CMs instead resulted in more carbon dioxide emissions.

For the marginal electricity case, a decrease of carbon dioxide emissions occurred primarily during the cold half-year, when the DH peak heat generation was based on natural gas. For the Nordic residual mix electricity case, a decrease of carbon dioxide emissions occurred all the time except from when the DH peak heat generation was based on biofuels. For the renewable electricity case, a decrease of carbon dioxide emissions occurred for all DH peak heat generation types. The primary energy savings generated by the excess heat from the CMs can be seen in Fig. 5

This diagram is similar to the one for carbon dioxide (Fig. 4). When marginal electricity was used, the primary energy balance was negative and lower the higher the supply temperature was. When Nordic residual mix was used, the primary energy savings decreased with higher supply temperature and were negative for the two higher supply temperatures (60°C and 63°C). When renewable electricity was used, the primary energy savings were positive and higher the higher the supply temperature was. For the marginal electricity case, a reduction of primary energy use occurred primarily during the cold half-year, when the DH peak heat generation was based on natural gas. For the Nordic residual mix electricity case, a decrease of carbon dioxide occurred all the time except from when the DH peak heat generation was based on waste. Waste has a very low PEF since it is regarded as a waste stream [18]. For the renewable electricity case, a decrease of primary energy use occurred for all DH peak heat generation types, as the total PEF for the heat generated in the CM was very low in this case.

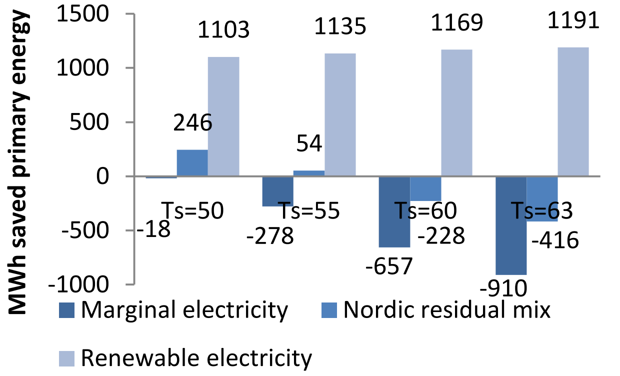

Fig. 5. Retained primary energy for the different scenarios.

Flow and network

The amount of energy in the Hyllie area provided by the prosumers for each temperature interval can be seen in Fig. 6. For the temperature interval of more than 30°C, the amount of energy replaced was more than 100%.

The heat from the CMs also affected the DH network in different ways. The prosumers started to be producers instead of consumers of heat in the temperature interval of 12-18°C. This could cause a number of difficulties. Consumers further away from the CM heat producing unit could for example be reached by water with too low temperature. The highest supply temperature from the CMs (63°C) was needed for the supply temperature to never be below 55°C for any consumer. The supply temperature to the consumers was however still below 60°C, which is the lower limit in the local DH company. Furthermore, the differential pressure and the velocity sometimes became too high at the prosumers and the nearest consumers. The differential pressure should according to the local DH company not exceed 800 kPa. This was exceeded from the temperature interval of 18-24 degrees for the lower supply temperatures and 24-30 degrees for the higher supply temperatures. The velocity should according to the local DH company not exceed 1 m/s in the service pipe, as disturbing noise else might occur. This was exceeded for the lower supply temperatures for some of the prosumers from the temperature interval of 18-24 degrees and for all supply temperatures and almost all prosumers from the temperature interval of 24-30 degrees. Another important aspect was that the energy from the prosumers reached other parts of the DH network than Hyllie from the temperature interval of 24-30°C.

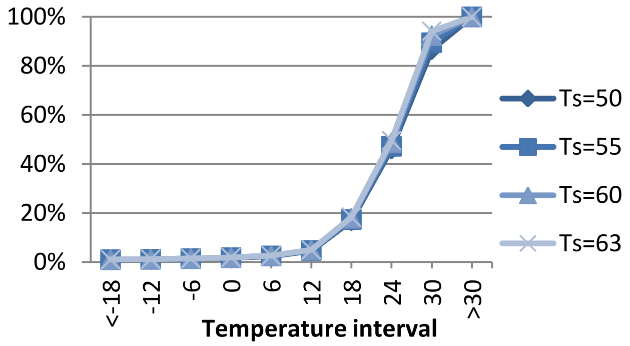

Fig. 6. Energy replaced in Hyllie.

DISCUSSION

As can be seen in the results, the effects of excess heat from CMs on the carbon dioxide emissions and the primary energy balance of the DH network vary a lot. The most important factors are which electricity that is used and what kind of heat source that is replaced in the DH network. If marginal electricity is used it is better to generate heat with conventional DH units. Marginal electricity is often said to be the technologies affected by the small changes in demand [21]. As it is such small changes that have been investigated in the present paper, it might be appropriate to see the marginal electricity case as the most truthful. It is however not as straightforward as that carbon condensate power is always the marginal power [22]. It would then be advantageous to generate heat in the CMs when the marginal electricity is produced by less carbon dioxide intensive sources. The CMs mainly produce heat during the warm half-year, when the electricity demand is lower, especially in northern Europe [23], which proposes the possibility of less carbon dioxide intensive marginal electricity. It is also important to consider the possible changes of the energy system in the future. If there is a higher share of renewable energy in the energy system in 20 years [24], the use of excess heat from CMs in the Malmö DH network would create carbon dioxide and primary energy savings, which can also be seen in the results.

It is also an important matter for the carbon dioxide and primary energy savings which DH network the CMs are placed in. A relatively large amount of the DH in Malmö is based on fossil fuels, which increases the possible carbon dioxide and primary energy savings. If the DH is mainly based on excess heat or biofuels, the possible carbon dioxide and primary energy savings are smaller.

Especially excess heat from for example industries has very little climate impact and PEF, why it would not be advantageous to utilise the heat from CMs in these systems. For primary energy, primary wood fuel have a much higher PEF than secondary wood fuel, why it is important which one is used in the biofuel heating unit. Waste has also a very low PEF, since it is considered a waste stream, why it is not advantageous to utilise heat from CMs in these systems, from a primary energy point of view. It is however hard to predict the future available amount of excess heat from industries and waste, why it could be a good strategy to keep the options open and not invest only in a system which will be difficult to modify.

It is also a possibility in Hyllie to generate local renewable energy and place the system boundaries around only the Hyllie area. Then the DH from the CMs would be regarded as generated with help from renewable electricity. This could help fulfilling the climate contract mentioned in the introduction

Lower supply temperature from the CMs gives higher carbon dioxide and primary energy savings for all cases except for when renewable energy is used. Lower supply temperatures from the prosumers however also create more problems in the network, such as too low supply temperatures to the consumers or too high differential pressure and velocity. Since the DH from the CMs sometimes reach the buildings outside of the Hyllie area, which are not adapted to a lower supply temperature in the supply pipes, they must either become that, or the energy input from the prosumers must be regulated so that this situation does not occur.

Since the CMs can generate more heat in the summer, these applications are not economically viable at the present, due to the low DH prices in the summer. But as more DH consumers demand "green DH", the prices of this kind of DH could increase and make such applications profitable. The Hyllie climate contract and the fact that the buildings of the municipality of Malmö is to have 100% green DH in 2020 are aspects that could help create an increase of the green DH prices.

OUTLOOK

The present paper is just a first step in investigating the possibilities of utilising excess heat and/or cold from heat pumps and CMs in Hyllie. Since there are good geothermal conditions in the Hyllie, an investigation regarding the possibility to utilise the excess heat and cold from such installations would be very interesting. It would also be interesting to investigate the best supply temperature for the Hyllie area or other kinds of heat sources at prosumers, such as solar collectors or excess heat from supermarkets.

CONCLUSIONS

The new area Hyllie in Malmö, Sweden is targeting to have an energy supply consisting of 100% renewable or recycled energy by 2020. To raise the temperature of the excess heat from CMs and utilise that energy may help facilitate this aim. It is however of great importance how the electricity for the CMs is produced and how the system borders are drawn. How the replaced DH is produced is also essential. Lower supply temperatures from the CMs to the DH network give better COP and EER and less electricity need in the CMs. Lower supply temperatures is thus better for the cases with Nordic residual mix electricity and marginal electricity and higher supply temperatures are better for the case with renewable electricity. Lower supply temperatures however also cause more problems with too low supply temperatures to the consumers and too high differential pressures and velocities in the DH network.

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INTRODUCTION OF RES IN DH SYSTEM OF GREECE

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ABSTRACT

The district heating (DH) system of Greece, mainly supported from lignite fired stations, is facing lately significant challenges. Stricter emission limits, decreased efficiency due to old age and increased costs are major challenges of the lignite sector and are expected to result in the decommissioning of several lignite-fired units in the coming years. As a result, managers of DH networks are currently investigating alternative scenarios for the substitution of thermal power that it is expected to be lost, through the integration of Renewable Energy Sources (RES) into the system.

In this paper, the DH systems of Kozani and Ptolemaida are examined regarding possible introduction of RES. The first study examines district heating of Kozani and alternative future options for covering a part of city's thermal load. Different scenarios are examined taking into account the biomass and natural gas as alternative fuels. The second study refers to a biomass CHP plant (ORC technology, 1MWe, 5MWth) to be powered from a biomass mixture (80% wood chips and 20% straw, on thermal basis). During the winter the heat can support local district heating of Ptolemaida, whereas the power produced throughout the year can be sold to the power grid.

1. INTRODUCTION/STATE OF THE ART

DH systems provide heating for a wide range of customers, from residential building to agricultural sectors, including commercial, public and industrial customers. The share of renewable energy used in DH is constantly increasing, while the use of coal, oil and their derivatives decreases. Due to the need for rationalized energy consumptions, biomass use in industrial power plants and district heating & cooling is expected to roughly double, reaching 105 Mtoe in 2020, which represents about half of the gross inland consumption [1]. Projections for 2050 are even higher, as high temperature industrial process heat will highly rely on biomass and industries will need to produce energy in a more environmental friendly way. The above, combined with the use of cogeneration technologies make the DH as one of the most popular sources for heating. Furthermore, the obligation of reducing CO_2 emissions and increasing the share of renewable energy to meet European requirements is considered as one of the main driving forces for the development of the DH sector.

Several studies can be found in the literature, concerning feasibility and efficiency of DH systems based on biomass and natural gas. **Lazzarin et al** [2] analyzed the major DH natural gas based technologies (vapor and gas turbines, internal combustion engine, combined cycles). They compared the cost of heat and power produced in these plants to the cost of producing the same quantity of electrical energy by a reference Gas Turbine Combined Cycle (GTCC) and the cost of heat production by modern local heating technologies using natural gas as fuel (condensing boilers, electrical, gas engine and absorption heat pumps). The conclusion of this study was that district heating cannot always be considered as the most efficient system available for producing heat and power. When using natural gas as fuel, CHP systems are really the best only when the most efficient technologies (GTCC) are employed.

Stoppato [3] presented the results of the energetic and economic analysis of an ORC plant with nominal electric power of 1.25 MW which also produces 5.3 MW of heat. This plant is connected to the electric grid and to the local DH grid. The emissions have been evaluated and compared with those of the pre-existing situation: domestic boilers fed by natural gas or diesel oil. The analysis has shown that the present incentives lead to a not rational use of energy, since it is convenient to maximize electric production, with a total efficiency of about 15%, instead of cogenerating heat and electricity, with a total efficiency of about 80%. This is in agreement with the regulations, whose goal is only the production of electricity by renewable sources instead of fossil fuels.

Uris et al [4] presented a techno-economic feasibility assessment of a biomass cogeneration plant based on an ORC. From the results obtained in this paper it is possible to conclude that subcritical recuperative ORC systems are technically and economically feasible in Spain when selling electricity to the grid at market prices (without subsidies) and thermal energy to the consumer below market prices.

In another study, of **Erikssona et al** [5], a consequential life cycle assessment (LCA) was performed in order to compare district heating based on waste incineration with combustion of biomass or natural gas. The study comprises two options for energy recovery (combined heat and power (CHP) or heat only), two alternatives for external, marginal electricity generation (fossil lean or intense), and two options for the alternative waste management (landfill disposal or material recovery). The results indicate that combustion of biofuel in a CHP is environmentally favorable and robust with respect to the avoided type of electricity generation and waste management. A natural gas fired CHP is an alternative of interest if marginal electricity has a high fossil content. However, if the marginal electricity is mainly based on non-fossil sources, natural gas is in general worse than biofuels.

In this paper, two district heating networks of Greece based on fossil fuel (lignite) are examined regarding alternative options for covering a part of the nearby cities' thermal loads (Kozani and Ptolemaida). Different technologies and alternative fuels are assessed in order to choose the most cost efficient solution for these networks.

2. METHODOLOGY

2.1 Techno economic data for DH in Kozani

Three different scenarios for covering a total thermal demand of 70 MWth are analyzed:

a. **Scenario 1**: A natural gas boiler, producing useful thermal energy of 70 MWth.
b. **Scenario 2**: Two CHP biomass boilers (35 MWth each) with steam turbine unit producing a total of 70 MWth and 35 MWe. In this case the boilers are fed by a fuel mixture of 70% wood pellets and 30% straw (on a thermal basis).
c. **Scenario 3**: Two biomass boilers of 35 MWth each, producing useful thermal energy of 70 MWth in total.

The examined financing schemes are presented in **Table 1**. The construction time is assumed to be 2 years while subsidy's payment is made in two installments: 50% during the first year of the construction phase, and rest 50% during the second year.

Table 1: Financing schemes

Schemes	A	B
Own capital	20%	30%
Loan	**25%**	**15%**
Subsidy	55%	

The project life is assumed to be 25 years, while the residual value of the investment is not included in the analysis, as there will be no liquidation at the end of the analysis period. Main financial parameters are presented in **Table 2**, whereas fuels cost reduced to thermal energy are given in **Table 3**. Natural gas price accounts for 13.12 €/GJ while average prices for wood pellets and straw are 185 and 75 €/tn respectively.

Table 2: Financial parameters

Parameter	Value	Unit
Loan duration	15	years
Loan Interest rate	6.5	%
Depreciation rate for equipment	10	%
Depreciation rate for infrastructures	5	%
Tax rate	26	%
Discount rate	5	%

Table 3: Fuels cost

Fuel	Cost	Unit
Natural gas	47.23	€/MWh-th
Biomass (70% wood pellets + 30% straw)	31.34	€/MWh-th

Main income due to the operation of the new DH plant comes either from heat sale (scenarios 1 and 3) or from heat and electricity sale (scenario 2). Selling prices are given in **Table 4**.

Table 4: Energy market

Sources of income	Cost	Unit
Electricity selling price-FIT	150	€/MWh-th
Heat selling price	43.5	€/MWh-th

The selected three scenarios are assessed concerning crucial economic indices such as Net Present Value (NPV), Internal Rate of Return (IRR) and payback period. A sensitivity analysis is also conducted regarding the selling price of thermal energy to citizens and the cost of biomass fuel. According to the DH Company, the main criterion for the investment to be sustainable is the expected IRR values to be above 12%.

2.2 Techno economic data for DH in Ptolemaida

The scenario examined for Ptolemaida city is a Biomass Fired Boiler, for the Cogeneration of Heat near to 5 MWth and Power marginally lower than 1 MWel. The heat is supplied to the District Heating network of the city, with supply/return temperatures equal to 95/65 ^{0}C respectively and pressure equal to 25 bar. The magnitude of power output was chosen in order to achieve favorable Feed in Tariff (FIT) and easier licensing procedures. The most favorable technology for this order of magnitude small scale industrial application has proved to be the Organic Rankine Cycle (ORC). A Clausius–Rankine Cycle is adopted, using an organic working fluid instead of water–steam, while thermal oil is used as heat carrier between the Boiler and the heat&power production circuit. The heat is supplied to the DH network during the 200 days of winter, while electricity is sold to the power grid operator during the whole year. The availability of the plant is considered to be equal to 90%. The fuel is a biomass mixture of 80% wood chips and 20% straw (on a thermal basis). The properties of the 2 fuels are provided in **Table 5**.

Table 5: Fuels properties

			Wood chips	Straw
Proximate analysis	Ash	% w.t. (ar)	1.62	7.55
	Moisture		40.00	8.45
	Volatiles		49.20	65.55
	Fixed C		9.18	18.45
Net Calorific Value	NCV	kJ/kg (ar)	10,629	16,026
Ultimate analysis	C	% w.t. (daf)	53.13	47.76
	H		5.96	5.75
	N		0.31	0.46
	O		40.54	45.64
	S		0.04	0.12
	Cl		0.02	0.27

The biomass CHP plant is financially evaluated by economic indices, i.e. NPV, IRR and payback period, taking into account the income from electricity and heat, the fuel cost and various operating&maintenance costs. The detailed parameters used in the techno-economic analysis are presented in **Table 6.**

Table 6: Economic parameters

	Value	Unit
1. Fuel		
Wood chips price	80	€/tn
Straw price	60	€/tn
Mixture price reduced to NCV	6.77	€/GJ
2. Techno-economic		
Total Investment Cost	6,000	thousand €
Investment lifetime	20	years
Residual value	0	thousand €
Various annual operating costs:		
Personnel	160	thousand €
General O&M costs	1	% of CAPEX
Expendables	1	% of CAPEX
Insurance	0.5	% of CAPEX
Contigencies	2	% of other costs
3. Energy market		
Electricity selling price – FIT	230	€/MWh-el
Heat selling price	37.74	€/MWh-th
4. Financing		
Own Capital	40	%
Subsidy	0	%
Loan	60	%
Loan duration	10	years
Loan interest	8	%
Type of loan dose	constant	constant/ variable
Grace period	0	years
5. General financial information		
Inflation	2	%
Discount rate	8	%
Tax rate	30	%
VAT	not included	
Depreciation rate	10	%

It is to be noted that the table data were derived from official budgetary Technical and Financial quotations by several manufacturers, while the table assumptions were dictated by the DH Municipal Company of Ptolemaida.

3. RESULTS

3.1 DH network of Kozani

3.1.1 Economic evaluation

Based on the techno economic data presented in paragraph 2.1, the economic evaluation of the three scenarios was conducted. In **Table 7** total investment and operating costs are presented, while in **Table 8** results of financial analysis are given in terms of NPV, IRR and payback period for two loan rates (25% and 15%).

Table 7: Investment and operating costs

Scenario	Investment cost (€)	Operating cost (€)
1	16,141,840.00	15,661,698.26
2	186,965,350.00	39,101,238.40
3	26,598,000.00	10,350,202.95

In scenario 1 all financial indicators are negative, so this scenario cannot be considered sustainable. In scenario 2 with CHP biomass boiler, IRR and NPV values indicate a promising investment even though its high cost. Similar, in scenario 3, all indices are positive and make a viable investment. So, according to DH Company requirements, scenario 2 and 3 are considered profitable, presenting IRR values that exceed the threshold of 12%.

Table 8: Investment indices

Scenario	NPV (€)	IRR (%)	Payback period (years)
Loan 25% (A scheme)			
1	-47,098,036.84	-	>25
2	88,850,496.63	16.15	9
3	18,160,889.32	18.18	8
Loan 15% (B scheme)			
1	-46,591,520.86	-	>25
2	92,594,403.01	14.89	9
3	18,693,503.64	16.79	8

3.1.2 Sensitivity analysis

A sensitivity analysis was also conducted in order to have a complete picture of these investments. The sensitivity analysis examines two variables: the selling price of thermal energy and the cost of biomass fuel.

a. Selling price of produced thermal energy

Initially the cost of thermal energy produced by a domestic oil boiler with an efficiency of 92% is calculated in order to have an idea of the current cost benefit for citizens using the district heating system. The specific production cost per unit of thermal energy, increased by 3% due to boiler maintenance costs, amounts to 143.81 € / MWh-th, taking into account that average oil price in Greece is about 1.28 €/lt (May 2014).

According to the pricing policy of the Company a discount rate of at least 25% compared to the equivalent costs of heat production from oil is mandatory. The selling price of thermal energy today is 43.50 € / MWh-th, so the discount rate in relation to the specific cost of production from oil is 69.75%. The DH Company wishes to maintain its pricing policy, which takes into consideration the social nature of the project. Through this policy, it became possible the penetration of district heating during the first years of its operation and the maintaining of its client base throughout the duration of its operation.

For discount rates from 69.75% to 25%, a full financial analysis for the three scenarios of the study was made keeping fuel cost unchanged.

For Scenario 1, the sensitivity analysis indicated that the selling price of thermal energy should increase in order for the investment to be profitable. For financial scheme A, the selling price of thermal energy for which IRR takes the value of 12% is 58.06 €/MWh-th (see **Fig.1**). This means a price increase of 33.47% compared with the current price (43.50 €/MWh-th). Similarly, for financial scheme B, the selling price of thermal energy for which IRR takes the value of 12% is 58.13 €/MWh-th. This means a price increase of 33.63% compared with the current price (43.50 €/MWh-th).

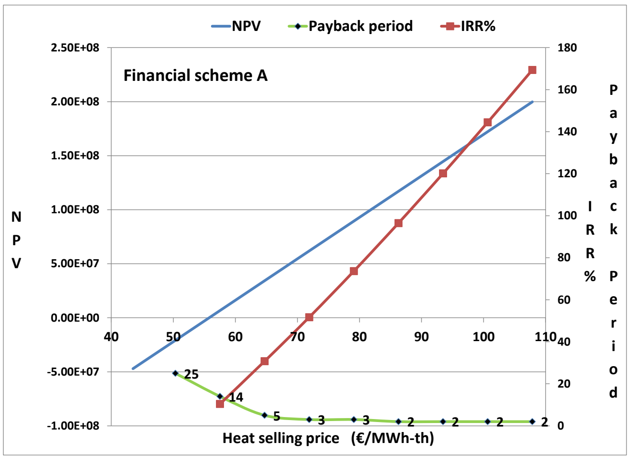

Fig. 1: Sensitivity analysis regarding heat selling price (scenario 1)

For scenario 2, it is noticed that the investment is profitable even for the current selling price of thermal energy (see **Table 8**). For both financial schemes, there is no need for price increase of thermal energy as long as IRR is above 12%.

For scenario 3, it is noticed that the investment is profitable even for the current selling price of thermal energy, with higher IRR and a bit lower payback period compared to scenario 2 (see **Fig. 2** & **Table 8**).

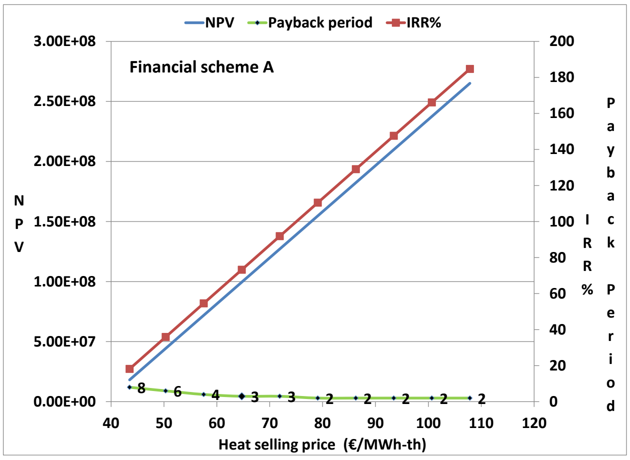

Fig. 2: Sensitivity analysis regarding heat selling price (scenario 3)

b. Cost of biomass fuel

In this sensitivity analysis, the variation range of biomass and natural gas cost was set at ±20% of the baseline value (31.34 & 47.23 €/MWh-th respectively), keeping stable the selling price of thermal energy at 43.50 €/MWh-th. **For Scenario 1**, the results of the analysis showed that in case of an increase or decrease of natural gas price, the investment remains unprofitable with negative NPV values. **For scenario 2**, the results of the analysis showed (**Table 9**) that in case of a potential increase in price of biomass up to 5% for financial schemes A and B the investment remains sustainable with IRR above 12%.

Table 9: Sensitivity analysis regarding cost of biomass (scenario 2)

	Financing scheme A			
	Cost of biomass (€/MWh-th)	**NPV (€)**	**Payback period (years)**	**IRR (%)**
20%	37.61	-2,096,682.60	>25	4.72
15%	36.04	20,676,375.04	18	7.68
10%	34.47	43,449,432.67	14	10.54
5%	32.91	66,077,438.99	11	13.34
0%	31.34	88,850,496.63	9	16.15
-5%	29.77	111,623,554.27	7	18.97
-10%	28.21	134,251,560.59	6	21.80
-15%	26.64	157,024,618.23	6	24.69
-20%	25.07	179,797,675.86	5	27.63
	Heat selling price equal to 43.50 €/MWh-th			

For Scenario 3, the results of the analysis showed that in case of an increase in price of biomass up to 5%, the investment is sustainable with IRR above 12% (see **Table 10**). In the opposite case of price reduction of biomass, the investment is getting of course even better.

Table 10: Sensitivity analysis regarding cost of biomass (scenario 3)

	Financing scheme A			
	Cost of biomass (€/MWh-th)	**NPV (€)**	**Payback period (years)**	**IRR (%)**
20%	37.61	-8,067,569.00	>25	-2.02
15%	36.04	-1,499,996.50	>25	3.82
10%	34.47	5,067,576.00	17	8.80
5%	32.91	11,593,316.82	10	13.49
0%	31.34	18,160,889.32	8	18.18
-5%	29.77	24,728,461.82	6	22.95
-10%	28.21	31,254,202.65	5	27.82
-15%	26.64	37,821,775.15	4	32.88
-20%	25.07	44,389,347.64	4	38.09
	Heat selling price equal to 43.50 €/MWh-th			

3.2 DH network of Ptolemaida

3.2.1 Technical layout – Optimal thermodynamic cycle

Based on the technical demands presented in paragraph 2.2 and on the technical specifications of the major components (boiler, turbogenerator set, heat exchangers for heat recovery) as provided by manufacturers' tenders, the optimal thermodynamic cycle configuration, in terms of (primarily) electrical and (secondarily) thermal efficiency, was elaborated and is presented in **Fig. 3**. The plant's layout was simulated with the process simulation software IPSEpro [6].

The basic equipment consists of the thermal oil Boiler, the power generation circuit (ORC) and the district heating section (i.e. the interface between the ORC and the DH network).

The thermal oil Boiler circuit uses Solutia Therminol 68 as heat transfer fluid from Boiler to ORC and is composed of a High Temperature thermal oil loop 260/315 ^{0}C and a Low Temperature thermal oil loop 155/260 ^{0}C. It also includes exhaust gas – thermal oil heat exchangers, a Biomass Combustor and an Air Preheater with exhaust gas (LUVO).

The Power generation circuit (ORC) uses Silicone Oil (MDM) as organic working fluid and comprises thermal oil – organic fluid heat exchangers, an organic fluid Turbine (with inlet/outlet operational parameters: 6 bar + 248 ^{0}C / 0.23 bar + 217 ^{0}C), an asynchronous Generator 999 kWel and a Recuperator.

The DH section (i.e. the interface between the ORC and the DH network) includes a water – cooled condenser exploiting turbine outflow for the DH demands in wintertime and an air – cooled condenser for the surplus heat in summertime or in wintertime partial load demand.

The main results of the plant's heat balance are summarized in **Table 11**.

Table 11: Overall heat balance results

		Value	**Unit**
Fuel	Biomass mixture consumption	2.1924	t/h
	Wood chips consumption	1.8806	t/h
	Straw consumption	0.3118	t/h
	Biomass mixture heat input	6.94	MWth
Power	Net power	0.999	MWel
	Net electric efficiency	14.39	%
DH	Useful thermal output	4.901	MWth
	Thermal efficiency	70.62	%
	DH water mass flow rate	38.98	Kg/sec

3.2.2 Economic Evaluation

Based on the techno economic data and assumptions of paragraph 2.2 and the technical results of paragraph 3.2.1, the overall investment indices are deduced and presented in **Table 12**, while **Fig. 4** depicts the evolution of the cumulative discounted cash flow over time.

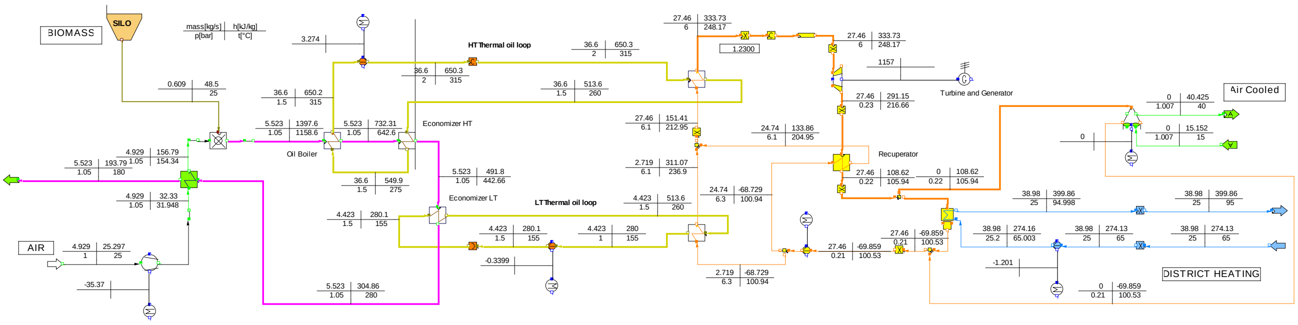

Fig. 3: Heat & Mass Balance Diagram

Table 12: Investment indices

NPV	639.28 thousand €
IRR	11.64 %
Payback Period	12.3 years

Fig. 4: Investment evolution over the years

Therefore this is a moderately profitable investment, eligible to JESSICA (Joint European Support for Sustainable Investment in City Areas, [7]) funding mechanism. The application that Ptolemaida DH Company submitted for entering JESSICA included the financing scheme of **Table 13**, which results in a quite profitable investment as shown in **Table 14**.

Table 13: Financing scheme with JESSICA

Own Capital	20	%
Subsidy	0	%
Bank Loan	10	%
JESSICA Loan	70	%
Bank Loan interest	8	%
Bank Loan duration	10	years
JESSICA Loan interest	3	%
JESSICA Loan duration	10	years

Table 14: Investment indices with JESSICA

NPV	1,407.79 thousand €
IRR	21,92 %
Payback Period	5.5 years

4. DISCUSSION

Recently in Greece, the Ministry of Environment, Energy & Climate Change (YPEKA) published (7/3/2014) a Bill entitled "Provisions on the rectification of the Special Account of article 40 of law 2773/1999 and other provisions" [8]. According to this, a review of FITs for electric power from operating RES and Cogeneration stations is foreseen. In the **Table 15** the new FIT values are presented.

Table 15: Latest review of FIT values for CHP stations

	Current FIT (€/MWh-el)	New FIT (€/MWh-el)	Variation (%)
CHP Biomass ≥ 5MW	150	135	-10,0
CHP biomass ≤ 1MW	230	198	-13.9

4.1 Impact on Kozani CHP plant

Based on these changes, scenario 2 must be reviewed, in order to see how the investment was affected by the change of the selling price of electricity. The old FIT was 150 €/MWh-el and according to the new deal is reduced by 10%.

The effect of this change is summarized in **Table 16**. It is noticed that the investment is no more profitable for DH Company, presenting an IRR lower than 12% and higher payback period in relation to the previous FIT.

Table 16: Effect of new FIT in scenario 2

FIT (€/MWh-el)	NPV (€)	IRR (%)	Payback period (years)
Loan 25% (A scheme)			
150	88,850,496.63	16.15	9
135	36,333,393.53	9.76	16
Loan 15% (B scheme)			
150	92,594,403.01	14.89	9
135	40,077,299.91	9.55	15

Moreover, the selling price of thermal energy for which the IRR is set to 12%, was determined. For financial scheme A, the selling price of thermal energy for which IRR takes the value of 12% is 48.25 €/MWh-th. This means a price increase of 10.92% compared with the current price (43.50 €/MWh-th). For financial scheme B, the selling price of thermal energy for which IRR takes the value of 12% is 49.68 €/MWh-th. This means a price increase of 14.21% compared with the current price (43.50 €/MWh-th).

4.2 Impact on Ptolemaida CHP plant

The impact of the new FIT (198 €/MWh-el instead of the so far applied one, i.e. 230 €/MWh-el) on the investment of Ptolemaida's CHP plant (with the financing scheme of **Table 13**) is shown in **Table 17**.

Table 17: Investment indices with New Deal's FIT

NPV	- 516,89 thousand €
IRR	1,87%
Payback Period	-

Thus, the investment is damaging under the current circumstances. In order for the investment to become profitable it is essential that a State subsidy is provided, e.g in the context of the forthcoming Partnership Agreement [9], although the subsidy will entail an even lower FIT (i.e. 180 €/MWh-el). By keeping constant the own capital and bank loan portions, the economic analysis was focused on the magnitude of the necessary subsidy and it was deduced that a subsidy of at least 40% is needed in order for the investment to become satisfactorily profitable. Such a financing scheme is presented in **Table 18** and the corresponding overall investment indices are shown in **Table 19.**

Table 18: Financing scheme with 40% subsidy and JESSICA

Own Capital	20	%
Subsidy	40	%
Bank Loan	10	%
JESSICA Loan	30	%
Bank Loan interest	8	%
Bank Loan duration	10	years
JESSICA Loan interest	3	%
JESSICA Loan duration	10	years

Table 19: Investment indices with 40% subsidy and JESSICA

NPV	206.15 thousand €
IRR	11.85%
Payback Period	10.6 years

5. CONCLUSIONS & OUTLOOK

Introduction of RES in DH system of Greece has much potential but each scenario must be carefully evaluated in terms of sustainability before final implementation. Regarding DH system of Kozani, the results of the economic evaluation indicated that all three scenarios being studied to cover the future thermal load can potentially become sustainable. Scenario 1 with natural gas boiler seems unattractive since an increase in heat selling price above 33% is required in order to become viable. Moreover, a reduction up to 20% of natural gas cost won't have any significant effect regarding sustainability of the project.

Scenario 2 with CHP biomass boiler, although it's a high cost investment, can be sustainable with an IRR above 12% even in the worst case that cost of biomass is increased by 5%. However, if the new, lower FIT is applied (135 €/MWh-el) then the investment becomes unattractive with IRR lower than 12% and high payback period (above 15 years). In this case, in order for the investment to become satisfactorily profitable, an increase of the heat selling price at least 10.92% (48.25 €/MWh-th) is required.

As far as the third scenario with biomass boiler (only for heat) is concerned, it is considered a good alternative for DH system of Kozani, because it's a low cost investment and remains sustainable even in the case that biomass price is increased up to 5%.

Finally, CHP plant for DH system in Ptolemaida seems a promising investment especially when using the JESSICA funding mechanism (IRR=21.92%, payback period of 5.5 years). Unfortunately, the impact on this investment is high under the current circumstances and the new FIT to be applied. In this case, in order for the investment to become satisfactorily profitable, a subsidy of at least 40% is required (IRR=11.85%, payback period of 10.6 years).

In conclusion, introduction of RES in DH system of Greece is a challenging task that DH operators have to manage in the future in order to increase the low carbon heat production. This task is getting even more difficult when country's economic conditions and motivation for development of RES are highly unstable.

ABBREVIATIONS

ar:	as received
CHP:	Combined Heat & Power
daf:	dry and ash free
DH:	District Heating
FIT:	Feed in Tariff
GTCC:	Gas Turbine Combined Cycle

IRR:	Internal Rate of Return
JESSICA:	Joint European Support for Sustainable Investment in City Areas
LCA:	Life Cycle Analysis
NPV:	Net Present Value
O&M:	Operations & Maintenance
ORC:	Organic Rankine Cycle
RES:	Renewable Energy Sources
VAT:	Value Added Tax

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DH Company of Kozani and Ptolemaida provided useful data regarding the operation of the networks and their future thermal needs.

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THE IMPACT OF GLOBAL WARMING ON DISTRICT HEATING DEMAND: THE CASE OF ST FÉLIX

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ABSTRACT

District heating networks (DHN) are one of the most attractive solutions for providing heating services to constantly expanding urban areas. However, climate change, driven by the increasing global warming effect, could have significant impact on heating demand, and consequently put the feasibility and profitability of new DHN systems into question. This paper deals with the effect of changed weather conditions (outdoor temperature and solar radiation) on heating demand, on a district level. Study was conducted on Saint Félix district located in Nantes, France. The district is consisted of 622 multi-family buildings and single-family houses, built in various periods over the last century (1915-1948, 1949-1974, 1975-1989, and after 1990). Heating demand was calculated for each building on an hourly basis, through the equivalent nodal network approach. The effects of building orientation and shape, attached walls, and shading from the surrounding greenery were taken into account. With the specific annual demand determined for the regarded period (2010-2050) for the complete district, heat demand-external temperature function slope variation (the Hekkenberg coefficient) can be observed. The results showed the decline in annual heating demand of approximately 3% per decade. The Hekkenberg coefficient values are between -2.90 to -2.85 and -2.93 to -2.87 (depending on the solar radiation scenario), decreasing with the outdoor temperature and solar radiation increase.

INTRODUCTION

About 6000 various DHN systems operate in Europe today, with more than 200000km of total length [1]. The capacity of installed systems varies throughout the Europe: in Scandinavian countries, they cover as much as 40%-60% [2] of the demand for heating and domestic hot water (DHW), while in the France, for example, the value is just 5% [3]. However, on the EU27 level, DHN has a share of only 13% of the current heat market [1]. Due to the numerous benefits of DHN systems (such as flexibility in heat sources utilization, improved environmental performance and energy management, better comfort conditions for consumers etc.), the expansion of existing and construction of new networks presents a tempting solution for reaching the goals for the future, set by policies proposed by the leading environmental and governmental organizations.

However, the effect of the imminent climate change could impact the building energy sector, reducing the heating demand and putting the feasibility and profitability of DHN projects under question. The impact of global warming on building energy consumption in the future was evaluated in numerous studies. Aebischer et al. [4], Frank [5] and Christenson et al. [6] modeled the effect of changed weather conditions on building heating and cooling demand in Switzerland. Wan et al. [7] used four representative climate types in China as a case study. Similar approach was used by Dolinar et al. [8] who studied the change in energy consumption for characteristic climates in Slovenia, and studies of Guan ([9], [10], and [11]) for Australia. In most of the studies, representative types of buildings were chosen (office building, residential house type etc.) based on the statistical survey for the considered location, and then the energy consumption was evaluated for different future climate scenarios to determine the rate of decrease/increase in heating/cooling demand. The exceptions were the works of Isaac [12] that considered energy consumption on a global level (based on the data from United Nations Habitat Global Urban Indicators Database), Xu et al. [13] and Olonscheck et al. [14] that conducted a study on the national level (for the state of California and Germany, respectively, based on the data from the national governmental bodies) and Nik et al. [15] for 153 buildings in Stockholm (also based on the data from governmental agencies). However, considering the variety of building types and size in urban areas, that are the main users of DHN services, calculations based on a representative building type could produce a misleading results for the network operators, as well as the downscaling of the demand calculated on a national/global level.

STATE OF THE ART

The electrical analogy approach for building energy demand calculations (resistance capacitance (RC) models) uses the analogy between the heat transfer and electrical current. This approach has been widely used in the literature due to the simplicity of calculations and the ability to describe the dynamic behavior of the buildings. Fraisse et al. [16] compared the results from several RC models with experimental and simulation results for the floor heating systems, and concluded that the accuracy of the models was satisfactory. Kampf and Robinson [17] developed the model with 5 resistors and 2 capacitors (5R2C) and compared the results with the data obtained through ESP-r simulation. The authors stated that this model produced reasonably accurate results for several types of walls. Furthermore, Peng and Wu [18] also used the analogy concept to develop their TEAM (ThermoElectricity Analogy Model) model. On the other hand, Široky et al. [19] considered the energy consumption calculated by the analogy method as an input for their predictive control model for building heating systems.

Hekkenberg et al. [20] suggested the use of regional dependence energy demand factor on cold stress (α or the Hekkenberg heating coefficient in further text) in building heating demand calculations. The coefficient was defined as the slope of energy demand-outdoor temperature function (see Figure 1). $\mathrm{T_{ht}}$ and $\mathrm{T_{cl}}$ stand for the heating and cooling threshold temperatures, while the β represents the regional dependence cooling demand on heat stress. The term of temperature independent demand relates to domestic hot water and industrial process heat demand. Authors suggested that these coefficients should incorporate various aspects and factors that influence the energy demand and the initial values for α and β were derived from the curves obtained by Valor et al [21]. It was stated that a value of $1\,\mathrm{u/℃}$ for α means that each ℃ below the temperature $\mathrm{T_{ht}}$ results in an increased heating demand by 1% of the average daily demand, and that value of $1\,\mathrm{u/℃}$ for β means that each ℃ above $\mathrm{T_{cl}}$ caused the increase in cooling demand for 1% of the average daily demand. Furthermore, sensitivity analysis was conducted to determine the influence of underestimation/overestimation of these factors on energy demand. The results of the sensitivity study showed that the underestimation/overestimation of the temperature dependence coefficients and/or threshold temperatures can cause underestimated/overestimated energy demand. It was highlighted that some parameters had different impact magnitude, depending on the regarded climate properties. The aim of this paper is to evaluate the possible impact of global warming (through the changed outdoor temperatures and solar radiation levels) on building heating demand on a district level, taking into account the variety in buildings type, age and size by using the Hekkenberg coefficient.

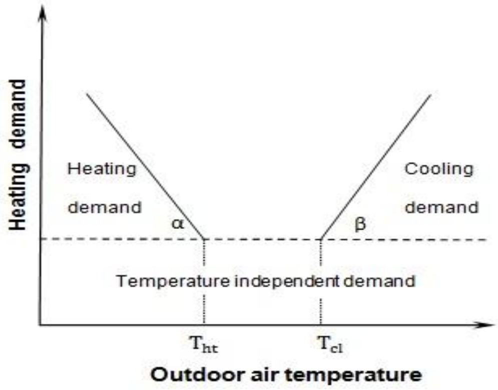

Fig 1. Heat demand-outdoor air temperature dependency patterns

METHODOLOGY

A two-step methodology is implemented in this study: approaches for the input data collection/organization and methods for energy demand calculations. The input data is consisted from district properties (number of buildings, size, orientation etc.) and weather data (hourly temperature and solar radiation values), while the energy demand evaluation is calculated through the RC equivalency model.

District database was obtained from a previous study [22]. Reference weather data (for the first period considered, i.e. reference case in further text) was received from the Meteo France (French national meteorological service), while for the future weather scenarios, IPCC predictions [23] were used. Following the results from the IPCC report, hourly temperature values were increased (shifted) for the recommended values for each future period considered.

The RC equivalency model used in this study relies on the 5R2C model developed by Kampf and Robinson [17]. The difference in our approach is that the capacity of the indoor air ($\mathrm{C_A} = 0$) is neglected due to the fact that thermal mass of the air is significantly lower than the thermal mass of the walls, thus having a minor impact on heat demand. Similar assumption was used in the thesis of Weitzmann [24]. The model itself is represented on Fig.2, while the physical representation of the model is shown on Fig.3.

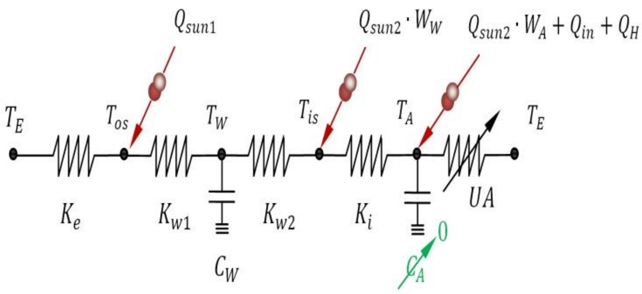

Fig. 2 The 5R2C model

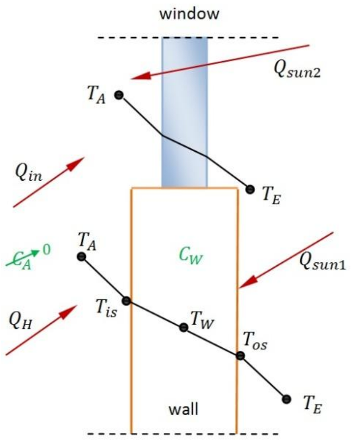

Fig. 3 Physical representation of the 5R2C model

The model represents a simplified electrical circuit where the temperature nodes (air and walls) receive heat from the solar energy (Q_{sun1} and $Q_{sun2}[W]$), internal sources ($Q_{in}[W]$) and the heating system ($Q_H[W]$). It takes into account convective and conductive heat exchange and the ability of multi-layered walls to store the heat. Solar radiation is divided in two parts: the amount that reaches the external surface of the walls (Q_{sun1}) and the amount that penetrates the room through the windows (Q_{sun2}). The amount that penetrates through the windows has two effects: it increases the indoor air temperature and the wall surface temperature (W_W and $W_A[\%]$ are the proportions of the solar radiation that affects the wall surface temperature and air temperature in the room, respectively). $K_e, K_{w1,} K_{w2,} K_{i,}$ $[W/K]$ represent the conductances between the outdoor air and external wall surface, the external wall surface and the inside of the wall, the inside of the wall and indoor wall surface and finally the internal surface of the wall and the inside air, respectively. T_E, T_W, T_A represent the outdoor air temperature, temperature inside the wall and indoor air temperature, while the T_{os} and T_{is} are the temperatures of the external and internal surfaces of the wall. The conductance to the environment through the windows and ventilation is defined as UA on the Fig.2, while the thermal capacity of the walls is represented through C_W.

For the evolution of the heat demand in future period, the slope of energy demand-outdoor temperature function (the Hekkenberg heating coefficient) is used. In our study, the accent is on the heating demand during the heating season, while the cooling needs are not taken into account. Temperature independent demand (domestic hot water and industrial processes demand) are neglected, considering that the main goal of this study was to evaluate the impact of changed weather conditions. The Hekkenberg heating coefficient is calculated for every building inside the district (based on the hourly demand values) and used to represent the change of heating demand in the future, caused by the global warming.

CASE STUDY

The district of St Félix is used as a case study, which is located in the northern part of the city of Nantes, France (Fig.4). The district is mainly residential and consisted of a single-family houses and multi-apartment buildings that were built during the various periods over the 20th century, which is divided into five different time intervals. Two industrial objects are excluded, since the accent of this study was on the residential sector.

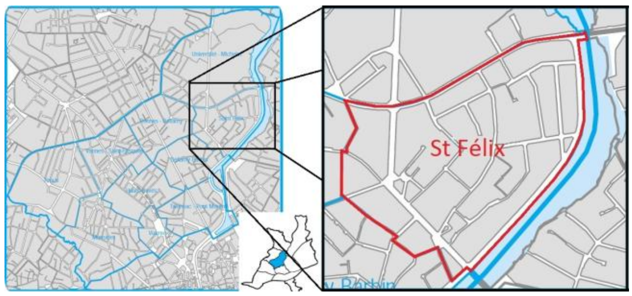

Fig. 4 The position of St Félix (data source: INSEE [25])

The age of each building was concluded based on the materials, envelope properties and architectural type used, as proposed in the work of Graulière [26] and reports from APUR [27]:

1) *Age group 1 (before 1915):* local materials (stone, terracotta etc.), thick and heavy walls, low envelope efficiency, high thermal inertia;

2) *Age group 2 (1915-1948):* stones and bricks, inefficient envelope, limited thermal bridges due to the high compactness ratio;

3) *Age group 3 (1949-1974):* post-war architecture, thin walls, high glazing surface, untreated thermal bridges;

4) *Age group 4 (1975-1989):* systematic insulation, applied standards from the first thermal regulations after the oil crisis;

5) *Age group 5 (after 1990):* applied building standards from the second series of thermal regulations;

Considering the typology of the buildings, four types are considered as a representative, in accordance with the distinction done in the INSEE [25] data base:

1) *Multi-apartment building, attached:* buildings with more than two floors, attached to other buildings;

Table 1: Buildings of St Félix district

	<1915	1915-1948	1949-1974	1975-1989	>1990	Total
Multi-apartment building, attached	16	17	26	24	22	*105*
Single-family house, attached	86	147	134	52	14	*433*
Multi-apartment building, detached	0	1	4	5	6	*16*
Single-family house, detached	18	20	14	9	7	*68*
Total	*120*	*185*	*178*	*90*	*49*	**622**

Source: Darakdjian [22]

2) *Single-family house, attached:* buildings with two or less floors, attached to other buildings;
3) *Multi-apartment building, detached:* buildings with more than two floors, with isolated position;
4) *Single-family house, detached*: buildings with two or less floors, attached to other buildings;

This division for the St Félix district is represented in Table 1. It is clear that the attached single-family houses prevailed in all age groups, while the detached multi-apartment buildings were inferior in all age groups. Most of the buildings were built in period 1915-1948 (30%) and during the post-war period (29%), while the number of buildings built after 1990 has the smallest portion (8%). The parameters used in this study depending on the building age are shown in Table 2. The height of the buildings was used combined with the assumption that height per floor is 2.5m (which is a common assumption in civil engineering). After calculations, buildings with more than 2 floors are sorted as a multi-apartment buildings and buildings with 2 or less floors as a single-family house, as mentioned previously. Glazing ratio (the percentage of the glazing on each side of the building) is used for calculations of the solar gains and heat losses. The values were concluded from the statistical survey for each age group and both multi-apartment and single-family houses with the average of 10 measurements for random facades (the distribution of the windows on external walls was considered equal, except for the attached buildings). The results of this statistical survey are shown in Table 3. It is clear that the glazing ratio was increasing throughout the 20th century, doubling for single-family houses and almost quadrupling for multi-apartment buildings. The attachment of the walls is not crucial only for the creation of building typology, but also for the heat demand calculations. Assuming that the indoor set point temperature (20^{0}C) is the same for all buildings, it is considered that there is no heat transfer through the attached walls due to the indoor air temperatures equilibrium. The perimeter of the attached walls was determined through the OrbisGIS software. However, the difference in height of the attached buildings is not taken into account. This assumption is justified with the fact that there is a small discontinuity in the attached buildings height in the regarded district. The effect of the orientation is also taken into account [22], considering that not all walls are oriented to the south and thus exposed to the maximal solar radiation. Six different values were suggested by APUR [27] for the confrontation coefficient, based on the facade orientation. However, these values are valid only for the facades, and not the whole building. In this study, for various numbers of attachments, different coefficient values are assigned for the whole building:

1) If there is no attached walls, the value of the coefficient is equal to average value given by APUR (0.58);
2) If there is one attached wall, several cases are possible:
    - If the attached wall is along the east/west axis, $\mathrm{C_{or}} = 0.58$;
    - If the attached wall is oriented south, but it is cancelled by the surrounding building, $\mathrm{C_{or}} = 0.48$;
    - If the attached wall is oriented north, $\mathrm{C_{or}} = 0.68$;
    - If the shared walls have angles of about 45^{0}: for the south obstructions $\mathrm{C_{or}} = 0.53$ and $\mathrm{C_{or}} = 0.63$ for north;
3) For the cases of buildings with 3 or more attached walls (that represent approximately 3.5% of the regarded district buildings), no universal law could be determined and the coefficients were calculated manually.

Considering that shadowing of the surrounding buildings and greenery can significantly impact the heat consumption in buildings, this effect is also considered [22]. The shadowing was determined in OrbisGIS, using static model without the inclusion of the sun path. The assigned factors that reduce the amount of solar radiation that reaches the building walls due to the shadowing are represented in Table 4.

Table 2: Parameters used for heat demand calculations depending on building age

Building period	U_{roof}	U_{floor}	U_{wall}	U_{window}	V_{air}	W_W	W_A	$Q_{in,s}$
Before 1915	0.4	4.8	2.3	4.5	2	0.9	0.1	5
1915-1948	0.3	5.6	2.9	4.5	1.6	0.9	0.1	5
1949-1974	0.3	1.7	2.7	4.5	1.3	0.9	0.1	5
1975-1989	0.3	0.6	1	3.1	1	0.9	0.1	5
After 1990	0.2	0.4	0.5	1.9	0.5	0.9	0.1	5

$U_i[W/m^2/K]$ represents the heat transfer coefficient, V_{air} [vol/h] is the ventilation rate, $Q_{in,s}[W/m^2]$ is the specific internal gain; Source: APUR [27], Monteil [30];

Finally, the future weather data scenarios were created for the next 40 years, using the measured meteorological data obtained from Meteo France for Nantes and predictions from the IPCC Synthesis Report [23]. Since the prediction of 0.2^{0}C annual temperature increase for the next two decades was considered valid in the synthesis report for several scenarios, this value is adopted for our case study. Furthermore, considering that the precision of the weather predictions was stated as accurate for only next two decades, the same temperature increase was assumed for the other two decades until the year 2050. The data obtained from the national meteorological agency was measured in 2004, but considering that the time step in this study was 10 years, the values for the reference year (2010) were considered the same. Four representative years were then used (2020, 2030, 2040 and 2050) and each hourly value of outdoor air temperature was increased for 0.2^{0}C. Due to the fact that the projection of possible change of solar radiation hourly values (for both direct and diffuse, long-wave and short-wave radiation) is highly variable and even rough projection could be difficult [28], the sensitivity of solar radiation values was considered in the range of 80-120% of the reference value (as suggested in [29]).

Table 3: Glazing ratio obtained by statistical survey for regarded types and age of the buildings

Building period	Single-family house GR	Multi-apartment building GR
Before 1915	16.4%	11.2%
1915-1948	16.2%	13.4%
1949-1974	26%	28%
1975-1989	25.4%	45.2%
After 1990	32.2%	43.6%

Table 4: Shadowing coefficient values depending on the number of obstructions

Number of obstructions	Associated coefficient
0	1
1	0.9
2	0.8
3	0.7
4	0.6
5	0.5

RESULTS AND DISCUSSION

The results for the evolution of the district heating demand for St Félix are represented in Table 5 and Fig.5. It is clear that the demand decreases with the shift of outdoor air temperature, as expected. The values vary depending on the solar radiation scenario, but the general trend is the average decrease of 2.78% per decade and 10.62% in 2050 compared to 2010. The variation of 80-120% of hourly solar radiation values caused the difference in the demand results of average 3.8%. With the specific heating demand $[W/m^2]$ calculated for the whole period, Hekkenberg heating coefficient was calculated for all scenarios (Fig.6). The values are increasing with the decrease of the demand, from -2.90 to -2.85 $W/m^2/K$ for the lowest solar radiation scenario (80% compared to the reference case (2010 value) and from -2.93 to -2.87 $W/m^2/K$ for the highest solar radiation scenario (120% of the reference value). The value of the coefficient depends not only on the weather conditions, but also on the building properties, which is illustrated on Fig.7. Buildings that were built in later periods have higher level of insulation and quality of the materials, thus reducing the heat losses to the environment, and consequently reducing the heat demand and increasing the value of the coefficient.

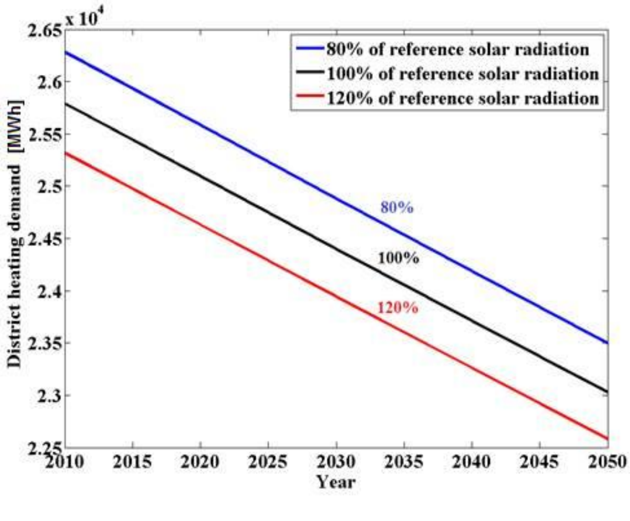

Fig. 5 District heating demand for the whole district, 2010-2050

Table 5: Decrease in the district heating demand for the period 2010-2050

Amount of solar radiation [%]	**Year**					**Decrease rate per decade[%]**	**Decrease for period 2010-2050[%]**
	2010(ref.)	*2020*	*2030*	*2040*	*2050*		
	District heating demand $[\cdot 10^4 \mathrm{MWh}]$						
80	2.63	2.56	2.49	2.42	2.35		
90	2.60	2.53	2.46	2.39	2.33		
100	2.58	2.51	2.44	2.37	2.30	2.78	10.62
110	2.56	2.49	2.42	2.35	2.29		
120	2.53	2.46	2.39	2.33	2.26		

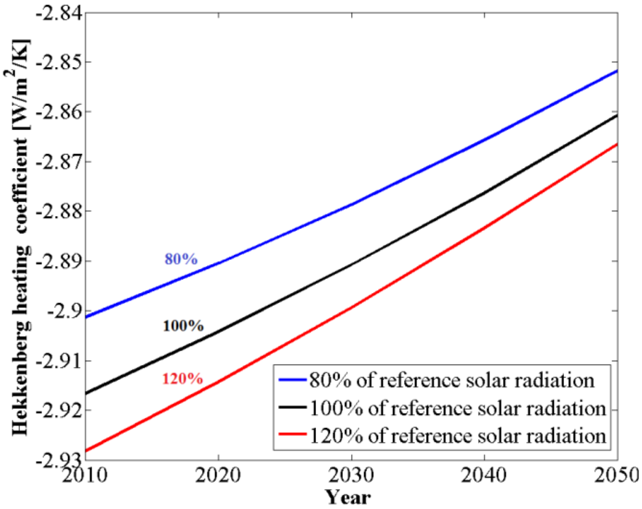

Fig. 6 Hekkenberg heating coefficient for period 2010-2050

Consequently, the highest values of the coefficient are for the building period after 1990. The average value of the coefficient for all building types and periods is $-2.91\ \mathrm{W/m^2/K}$.

Considering that the temperature shift is constant (0.2°C per decade), the expected behavior of Hekkenberg heating coefficient change should be linear. However, the behavior proved to be non-linear (see Fig. 6), which can be explained with the Fig.8 and Fig.9. One building is randomly chosen (in this case building 70), and specific heating demand is calculated for the whole heating season for the reference and temperature offset scenario (which is set to be 1°C offset, for better resolution), see Fig.8. Obtained values of the slope were -5.33 and -5.25$\mathrm{W/m^2/K}$ (for the nominal and shifted temperature values). It should be noted that the model was created so that the negative heating demand values (periods when the indoor air temperature is above the set point temperature) are not taken into account, due to the assumption that in those cases, heating is turned off. As a consequence of removing these values, the values inside the black lined square on Fig. 8 have more significant influence on the slope of the function, thus changing the value of the slope coefficient.

Furthermore, by definition, the Hekkenberg heating coefficient is the first order coefficient of a linear regression between hourly values of the specific heating demand and the outdoor air temperature, obtained by a least square method. The specific heat demand-outside air temperature function $\mathrm{HD_f(T_E)}$ is given by:

$$\mathrm{HD_f(T_E)} = \alpha \mathrm{T_E(h)} + \theta \quad (1)$$

where θ is the intercept of the function and h is the regarded hour with heating requirements during the season (as mentioned previously, in this case the heating season is from the 1st of October until the 10th of May, 5328h). As a result of shifted temperature values for the future weather conditions, the number of heating hours $\mathrm{N_h}$ is decreased. Furthermore, the hour dataset that is consisted of these values and used for the heating demand calculations is not the same. The datasets for the cases without and with the temperature shift respectively are denoted $\mathrm{D_{ref}}$ and $\mathrm{D_{shift}}$, see equations (2) and (3):

$$\mathrm{D_{ref}} \in \{\mathrm{h} | \mathrm{HD_{RC}}(T_{E,ref}) > 0\} \quad (2)$$

$$\mathrm{D_{shift}} \in \{\mathrm{h} | \mathrm{HD_{RC}}(T_{E,shift}) > 0\} \quad (3)$$

where $\mathrm{T_{E,ref}}$ and $\mathrm{T_{E,shift}}$ are the reference and shifted outdoor air temperatures (respectively) and $\mathrm{HD_{RC}}$ is the specific heat demand calculated through the previously presented RC model. Obviously, $\mathrm{D_{ref}}$ is included in $\mathrm{D_{shift}}$.

Since the hourly heating demand is a result of free heating (solar radiation), thermal inertia of the walls and heat losses to the environment, there is no physical reason that during the hours that after the outdoor temperature shift do not require heating, the amount of received free heating is the same:

$$\frac{1}{\mathrm{N_{h,ref}}} \sum_{\mathrm{h}=1}^{\mathrm{N_{h,ref}}} \mathrm{I_{s,h \in Dref}} \neq \frac{1}{\mathrm{N_{h,shift}}} \sum_{\mathrm{h}=1}^{\mathrm{N_{h,shift}}} \mathrm{I_{s,h \in Dshift}} \quad (5)$$

where $I_{s,h}$ is the value of the solar radiation for a regarded h hour, N_{ref} is the number of hours in the reference scenario and N_{shift} is the number of hours in the shifted temperature scenario. This physical evidence explains the Hekkenberg heating coefficient behavior with introduced outdoor temperature changes.

For even better understanding of this behavior (non linear), change in outdoor air, indoor air and wall temperatures during the whole heating season (5328h) are observed (Fig.9). Comparing the values for the outside air temperature/wall temperature, the effect of heat inertia can be noted, especially for the hours when the wall temperature is higher than the indoor air temperature. Thus, it can be concluded that the reason for the coefficient non-linearity is the thermal inertia in the periods when the indoor air temperature is higher than the comfort temperature. Consequently, the heat demand for the next hour is reduced, or the heat losses are even completely covered, thus decreasing the number of heating hours during the season.

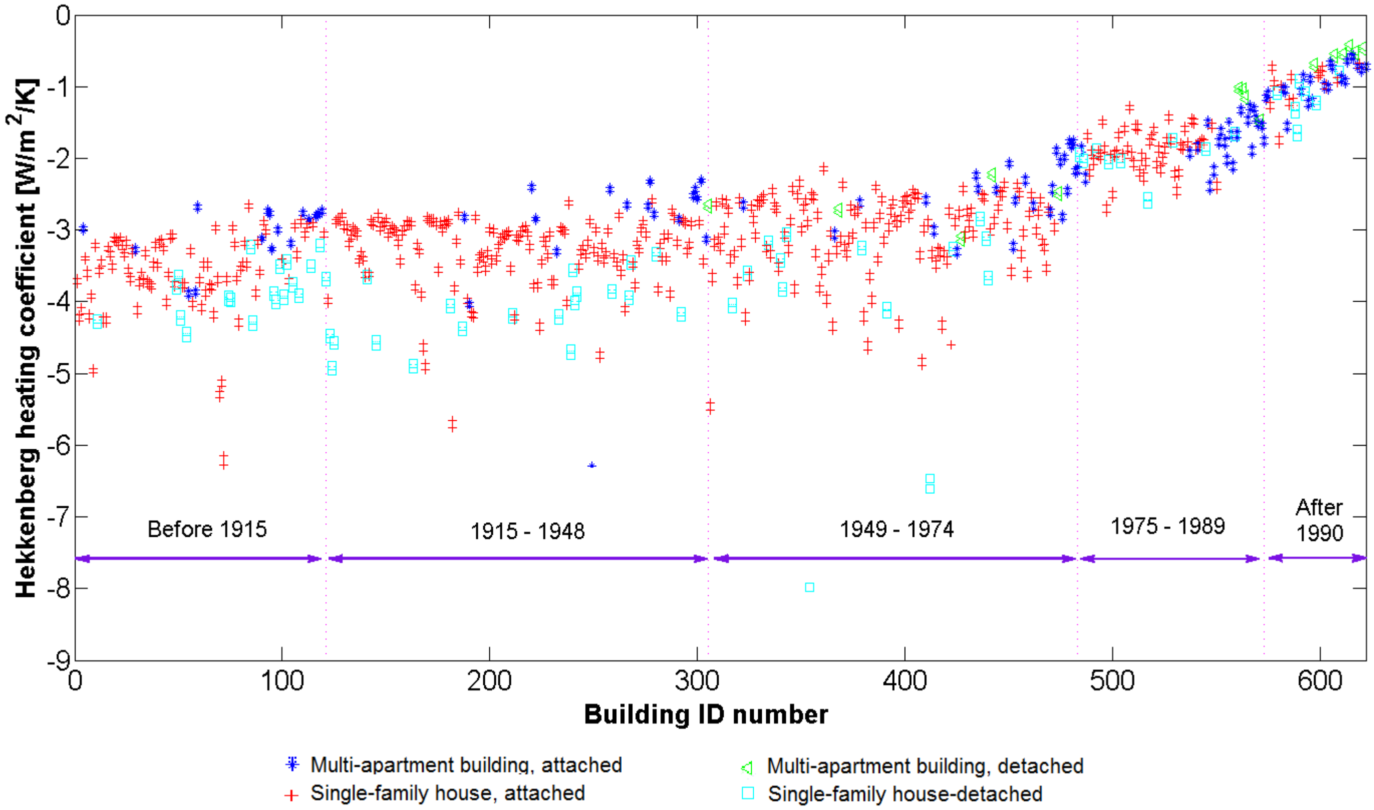

Fig. 7 Hekkenberg heating coefficient values, depending on the building age and type 3

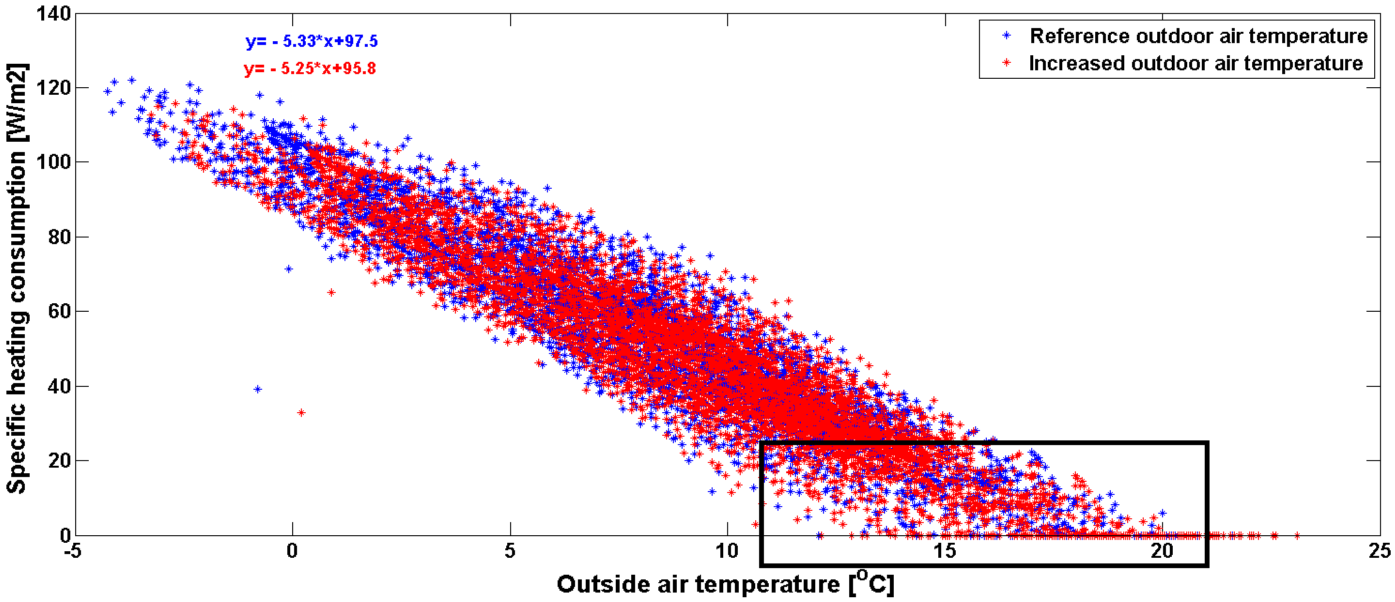

Fig. 8 Specific heat demand for the building no.70

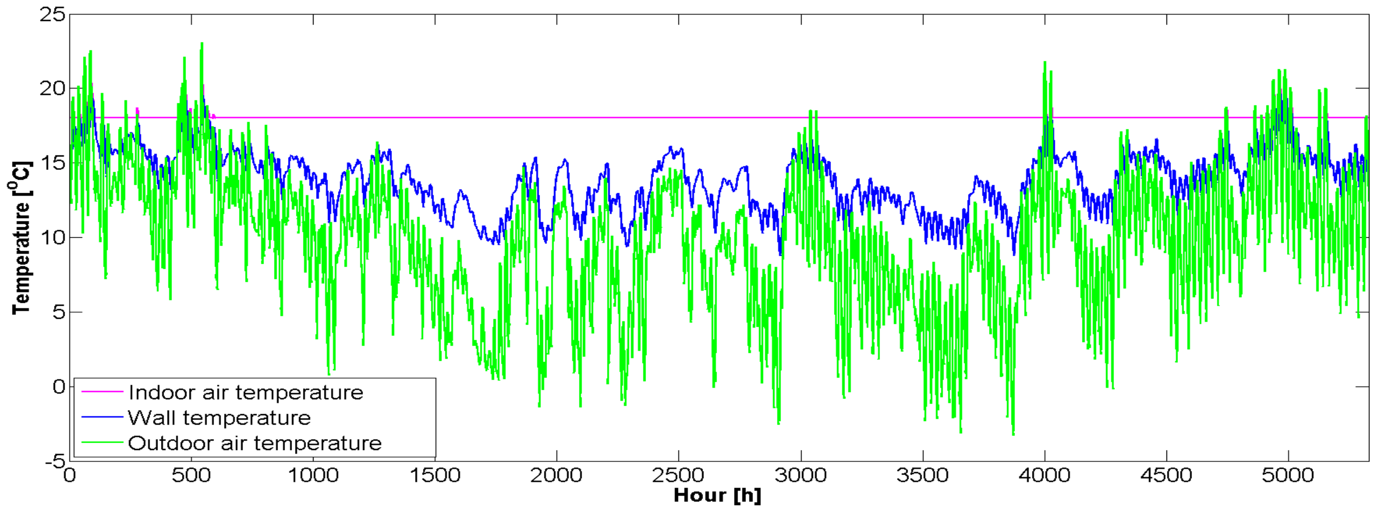

Fig. 9 Change in outdoor air, indoor air and wall temperature during the heating season, building no.70

CONCLUSION

The main goal of this study was to evaluate the impact magnitude of the changed weather parameters on heat demand on a district level, considering the period up to year 2050 and by using the 5R2C model and the Hekkenberg heating coefficient. For a case study, the district of St Félix in the city of Nantes was used, consisted of 622 single-family and multi-apartment buildings. The results show the average decrease in heating demand (for 0.2^{0}C temperature increase per decade weather scenario) of 2.78% per decade, and 10.62% average decrease in year 2050 compared to 2010 reference value. Due to the hourly solar radiation values predictions uncertainty, sensitivity analysis was conducted in range of 80-120% compared to a reference value, and it is concluded that this variation can change the heating demand up to 3.8%.

The values for the Hekkenberg heating coefficient increases with the decrease of the heat demand, from -2.90 to -2.85 $\mathrm{W/m^2/K}$ and -2.93 to -2.87 $\mathrm{W/m^2/K}$ for the lowest and highest solar radiation scenarios, respectively. Furthermore, it is clear that the values of the coefficient do not depend only on the weather conditions, but also on the building age (and consequently properties). Buildings built in the last considered period (after 1990) have the highest coefficient values, which correspond to the lowest demand. Additionally, the behavior of the coefficient is non-linear, even considering the constant temperature offset. The cause of this behavior is found in the thermal inertia effect, due to the release of accumulated heat in the walls.

This study presents one of the possible approaches to tackle the district heating demand change in the future, using the 5R2C thermoelectricity model for the building energy demand calculations and the Hekkenberg heating coefficient for the representation and the analysis of the results. Considering the approach presented on Fig.1, temperature independent demand (domestic hot water, industrial process heat) could also be regarded in the study, along with the inclusion of the heat island effect and the retrofitting of the buildings.

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DISTRICT ENERGY SYSTEMS DEVELOPMENT: THE SPANISH CASE

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ABSTRACT

Against what happened in America, the distributed energy did not reach Europe until the twentieth century (Dresden 1900). From that date, the development of these systems was exponential in Western and Northern European countries, to the point that more than 5000 district heating systems are in operation today, within the European Union.

However, Spain does not appear in the DHC (District Heating & Cooling) statistics until 2004 (one century later), with the construction of the Barcelona Forum&22@ district energy system. Today, there have been identified over 139 systems with a heating output of over 850 MW.

The objective of this research is to figure out why the development of these systems was delayed more than a century in Spain. In order to answer it, the examples constructed and in project will be studied and analyzed (including those developed in the XX century, which are still in operation today) comparing and contrasting them with the European systems in operation to try to give some answers to the delay.

Finally, this research is intend to promote this kind of infrastructures in future Spanish urban developments and consider district energy systems as a part of the urban infrastructures, along with roads, water supply or power distribution as in other European countries.

INTRODUCTION / PURPOSE

District Energy systems are defined as urban infrastructures that fulfill many city energy demands by an often-citywide heat distribution network, which receives heat from one or many large heat-generation facilities [1].

This kind of systems has been developed throughout history differently across continents and countries. The major reasons are the different circumstances and conditions of the aspects such as energy policies, with different regulations and legal requirements; energy prices and economic conditions for investment and finally the different weather conditions of countries.

These facilities are not recent solutions, as the oldest district heating system still in operation is located in Chaudes-Aigues, France in operation as early as the 14th century [2].

Birdsill Holly, an inventor and hydraulic engineer, is often credited with being the first to use district heating on a successful commercial basis. As a result of an experiment in 1876 involving a loop of steam pipes buried in his garden, Holly developed a steam supply system in October 1877 [3]. Several district heating systems were started in North American cities in the 1880s [4]. The fuel source was steam coal. In New York, the Manhattan steam system went into operation in 1882. It exists today as the steam division of Consolidated Edison, and provides steam for heating, hot water and air conditioning to approximately 1.800 customers (2000) [5].

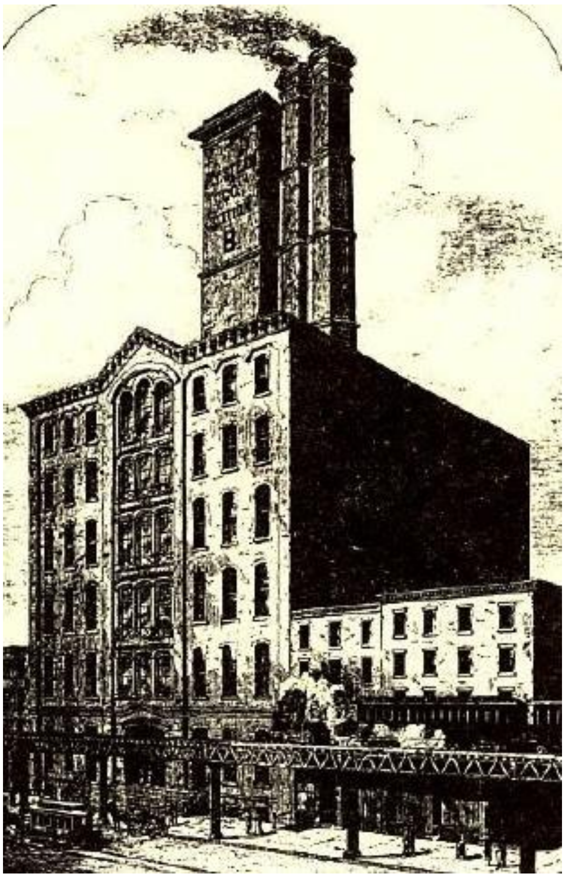

Fig. 1 Picture of the first New York steam plant, in Greenwich Street, constructed in 1881.

Against what happened in America, the distributed heating does not reach Europe until the twentieth century, not because it is seen as something negative but because necessary investments to create a complete system of generation in existing cities. The earliest district heating system was built in Dresden in 1900, although it was not a commercial project [1]. Fernheizwerk Hamburg Gmbh initiated a commercial project for the city of Hamburg in 1921, which was followed by systems in Kiel in 1922, Leipzig in 1925, and Berlin in 1927. Outside Germany, district heating systems were started in Copenhagen in 1925, Paris and Reykjavik in 1930, Utrecht in 1927, Zürich in 1933, and Stockholm and Helsinki in 1953.

All these early projects are the basis of the development of existing district heating systems in the countries around Europe. The initiatives for development these systems were taken at a municipal level and the systems grew subordinated to market conditions through competition with other heat production systems. In the 1970s, district heating became part of the national energy policy in many of these countries, driven by global energy crises of 1973 and 1979 [6].

Currently, the European countries with the further development of this type of systems to supply thermal energy demands are the Nordic countries, Russia, the countries of Eastern Europe or Germany.

However, Spain failed to establish these facilities as general solutions, and all this, despite the fact that there are several and very interesting examples developed in Spain during the XX century [7].

The purpose of this paper is to resolve the question of why the development of District Energy systems were delayed more than a century in Spain, contrary to what happened to other European countries.

STATE OF THE ART

Spain is a country with poor tradition of District Heating systems since heating demand is not a main issue for most of the climatic areas and the Cooling technology has not been available at large scale until the last decades.

Therefore, there are no preceding studies in this area, since the issue has not raised much interest until the turn of the XX century. Since the liberalization of the electric market in the eighties allowing the introduction of cogeneration systems, the DH technology has started to be considered as a possibility in Spain. The introduction of this kind of technology in the residential area, together with the possibility of including refrigeration and thus implementing a District Heating and Cooling (DHC) system, has made it possible to foresee a positive evolution for this kind of facilities [8].

Spain and district heating are two words that for years have not hung very well together. This perception has begun to change because the Spanish government has realized that the country gradually is deviating too much from its Kyoto obligations and because the energy intensity is approx. 20% higher than the EU-15 and almost twice the level of Denmark. Regarding meeting the EU objective for 2020, Spain is lagging significantly behind. Therefore, the Spanish government '*has taken the bull by its horns'* and over the last 5-6 years they have launched several initiatives and national plans to reduce energy consumption at all levels in society, and the political focus on energy efficiency and renewable energies is getting stronger [9].

The technical code of the Spanish buildings (CTE) [10] contains very little information about DHC systems and there is a lot of ignorance about what this technology is, what can do, and what benefits DHC technologies can give to the consumers and to the environment.

Nowadays, DHC shows great potential to be at the forefront in the transformation of the European energy sector towards a sustainable future [11].

Since the measure of the implementation of the legislation about bonus for the electricity sale of cogeneration systems the number of DH/DHC systems had increase, also the plans to do it. In 2007 the number of DH/DHC systems was 13 [8], today, there have been identified over 139 systems with a heating output of over 850 MW [12]. So this sector is actually emerging in this country.

There aren't still any national targets related to DHC systems, but energy agencies and urban planners are being gradually interested in this kind of systems. With this and the national policy for energy efficiency and saving emissions, the future is the increase of these systems in new urban areas.

METHODOLOGY

In order to answer the question of why the development of these facilities was delayed more than a century in Spain, will be studied in depth, the few examples (unfortunately) built in Spain, assessing both the diversity of solutions as the problems that have arisen over its lifetime.

The selected DHC examples will be analyzed in the urban and technology context in which them have been developed; they will be analyzed in issues relating to urban development, urban infrastructure and engineering. The series of examples selected are outstanding in terms architectural design, implementation at urban scale, resources used to produce heat, use of leading technologies and number of user connected. Then, the conclusion will be drawn for applying these findings in future urban developments.

Among the systems that have been studied in this research the following stand out:

- **University City of Madrid.** One of the first solutions of this type of infrastructure carried out in Spain and which is still in operation. It was designed in 1931 by the architect Manuel Sánchez Arcas in collaboration with the engineer Eduardo Torroja and advised by the Brown Bovery Company. Besides the production plant, the thermal conditioning project of the University City, included 12 substations and the distribution network in form of galleries easily accessible throughout the route. The design took advantage of the knowledge acquired studying the models visited by the designers in several trips around the world, specially the Power House at Harvard and the Heating Plant in Berkeley. The thermal power plant supplied heat to all buildings raised in the Campus until the fifties (12.000 m2). Currently is still working changing the fuel source from coal, to natural gas, having used in the meantime diesel oil [13] [14].

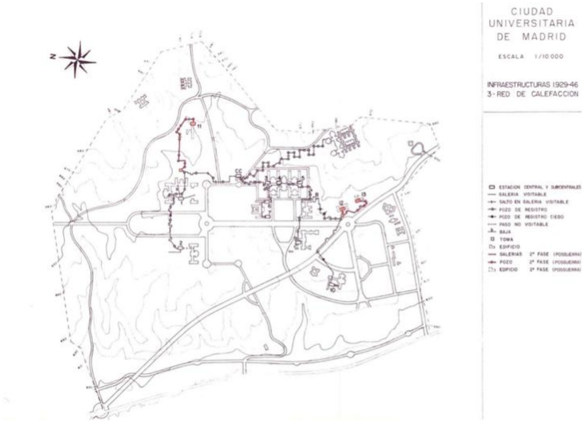

Fig. 2 Drawing of the layout of the District Heating system of the University City of Madrid designed in 1931.

- **Eduardo Torroja Construction Science Institute.** The architects Echegaray and Barbero in collaboration with the engineer Torroja designed this system, in 1948, in Madrid. A single thermal power plant with hot water boilers has been placed externally to the buildings. This system includes a single refrigeration plant and the distribution network which is laid in the basement as union between the different buildings that compose the Institute Complex. The implementation on this installation is due to the valuable idea and experience of the director of the Institute and the intention for the building for research, which converts the building itself in a field of study [15].
- **Pamplona District Heating System Preliminary Design.** The following example is an ambitious proposal that the industrial engineer Joaquín Castiella drew in 1961 to provide heating for three different areas to be developed in Pamplona, that never came to fruition despite having the political authorities support and providing a profitable economic study to the supplier of the service. It consisted in a central facility of heat production, probably fed with nuclear energy, from where the heat is carried by the vehicle chosen, steam, or superheated water, through a network of pipes to buildings provided with a suitable heat exchanger.

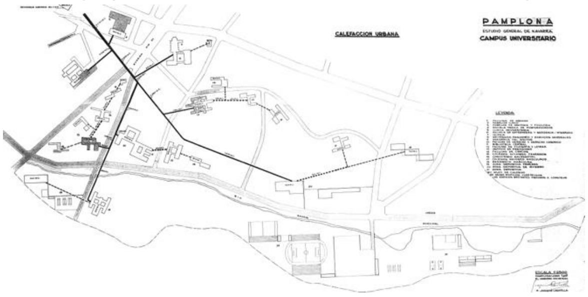

Fig. 3 Drawing of the layout of Pamplona District Heating preliminary design drawn by Joaquín Castiella in 1961 [16] [17] [18].

- **Campus of the Public University of Navarra.** Another example of a district heating system is the Thermal power plant of the Public University of Navarra (UPNA) designed in 1989 by the architect Francisco Javier Sáenz de Oíza in Pamplona. In this university campus, the heat is produced in a central power plant located in the northwest corner and carried in form of superheated water through a network formed by prefabricated concrete galleries, registrable and visitable along the itinerary forming a closed distribution loop with forward and return pipes. From this network the secondary circuit of each building will be supplied using a plate heat exchanger. With the design of this Campus, Sáenz de Oíza finally succeeded in his homeland, after an extraordinary career in which he received numerous awards, including the Prince of Asturias Award, and he perfectly reflected his concern about the American technique designing the campus in image and likeness of the American ones [19].

Fig. 4 Picture of the prefabricated concrete gallery of the District Energy system of the Public University of Navarra.

- **Forum and 22@ DHC system.** Despite the urban importance of the examples mentioned above, it was not be until the turn of the century when the first Spanish district energy reference for European experts comes, the construction of the Forum in 2004 in Barcelona. An innovative district cooling and heating plant with heat supply to a total area of 488.000 m2 in accordance with them most up-to-date environmental and economic policies. It constitutes a pioneer initiative which will support the principles of Forum 2004, since it will supply energy to the Forum Building, the Convention Centre, a University Campus, hotels with economically favourable air-conditioning and heating conditions and the needs of 800 dwellings in the 22@ neighbourhood. Cofely Spain SAU, Aguas de Barcelona, TERSA, ICAEN and IDAE made this infrastructure possible through the foundation of Districlima S.A. [20] [21] [22].

Fig. 5 Layout of the Forum and 22@ DCH system.

- **ExpoZaragoza 2008.** Taking advantage of the opportunity of the International Exhibition ExpoZaragoza 2008 and the consequent urban development of Ranillas meander, the people in charge of the event decided to provide the new planned neighbourhood with a District Heating and Cooling infrastructure. The production plant can supply heat, hot water and air conditioning to all buildings that have been built with a total of 180,000 m2. It is located in a unique building of modern architecture designed by the architect Iñaki Alday. The energy distribution network is performed by buried pipes forming closed loops with a length of 5 kilometres between the plant and substations located in each building [23].

Fig. 6 External view of the thermal power plant of the ExpoZaragoza DHC system.

Another examples recently built that endorse the splendour of these infrastructures during the current century are the biomass district heating system in Cuéllar, Segovia or the Justice town in Madrid which one of the buildings designed is a thermal power plant, that have had a great media coverage and have made such infrastructures become popular among the Spanish population such as environmentally friendly facilities.

The main actors of the DHC systems mentioned above have been contacted in order to inquire about the technologies, dimensions and experiences gathered on every installation. These actors include regional energy agencies, town halls, ESCO`s, neighbourhood association, facility operators, users, or any other entity in charge of an installation of such characteristics.

RESULTS

Once all the examples discussed above and a few more have been studied and analysed in depth, comparing and contrasting them with similar European ones, the following answers can be emphasized as responses to the delay of this type of infrastructures in a country like Spain:

- **Lack of technical knowledge.** The academic training that Spanish architects and town planners have received in the Spanish Schools of Architecture in the twentieth century has not considered the teaching of urban infrastructures, whose influence is remarkable when designing new urban developments. Only technicians with their own motivations regarding this topic, acquired this knowledge through trips abroad, study of scientific publications or collaboration with foreign companies, specialized in this subject.
- **Lack of expertise of urban planners, architects and engineers to design these systems.** The Spanish town planning during the twentieth century has followed the key principle of economy against the sustainable development, so this kind of facilities were not valued by large economic outlays raised when establish new residential and tertiary areas. The lack of references of these facilities built, cause that in the Schools of Architecture (in charge of the training of competent technicians to carry these systems out) the students are not taught about this type of infrastructures, so, if it is not taught, nor it is investigated, generating therefore, a negative closed circle for this discipline.
- **Lack of interest and support from private companies (ESEs, ESCOs…**). In a country like Spain, where there is no tradition of such solutions, in which the interest of energy lobbies have been developed in other ways and where the warm weather in much of the territory does not

allow returns on investments as elsewhere, it is especially significant that private companies can import their DHC technologies assuming their own risk.

- **Financial problems.** These are projects that require long term investments, so besides the active approach of the city administrators, the participation of ESCOs is essential, since they can promote such infrastructures because they provide the necessary capital for the development of these projects in which the performance must be guaranteed and the price of the energy supplied should be beneficial for the consumers.
- **Political reasons.** They are needed in the government officials and politicians who dare to manage the development of such complex infrastructure whose development requires the involvement of more than one term, due to the long period of time required from the initial conception of these infrastructures until the commissioning.
- **Climate aspects.** The location of the country in the southern Europe, in the so called Mediterranean area, makes it seem that the needs of energy demand may not be as high as in other northern European countries. According to the European heating index [24] the heat demand for space heating not vary significantly in Europe. The normalised space heat demand in Stockholm should only be 20% greater than the heat demand in Brussels. Therefore Madrid is expected to have a 20% smaller heat demand than Germany for example.

DISCUSSION

The small number of urban projects with district heating system in Spain makes that the use of this technology is relegated to large urban development (university campus, hospitals complexes, international exhibition centres…), as reflected in the examples mentioned before, in which such important issues as the planning of urban infrastructures or the sustainable growth of the city are essentials when designing new urban developments.

Especially significant is the Forum and 22@ District Heating systems, by far, the largest within the country and almost unique. The execution of this project cannot be well understood without explaining the factors and actors that led to it. First of all, there was a vast territory that should benefit from a through urban transformation to be carried out by the local administration. This transformation, unavoidable for the competitiveness of the city over the coming decades, was undertaken on the occasion of a specific event: the celebration of the Forum of Cultures 2004.

What today is known as 22@ technological district in Barcelona, where much of Districlima´s DHC runs now, was years ago one of the most important industrial centres in the country. From 1950 to 1970 due to a big crisis, dozens of factories had to shut their doors, and the area began to deteriorate. In this situation, with thousands of square meters in clear deterioration, the Barcelona City Council laid out a plan of urban and social long-term transformation to revitalize the area and attract to it the new ‘factories’ of the XXI century.

As a part of the strategy to attract this kind of business, first class infrastructures such as DHC systems were needed. But this political will needed the experience and solvency of a leader energy group, in this case, DFG-Suez Group, which through its Spanish subsidiary COFELY España SAU, invests, operates and manages the project since 2004 through Districlima SA; of which it is the major shareholder, concessionaire company for the 22@ and the Besos area.

In addition to this interest and advocacy from a private company, it should be remarked the support received from local institutions, through the companies 22@ Barcelona (Company belonging to the City Council of Barcelona) and Besos Consortium (Barcelona City Council and Sant Adria de Besos Council) who, both as systems regulators and promoters of urban and economic development of their areas, provide the definite boost for the successful implementation and development of the network from an innovative and environmentally committed city point of view.

OUTLOOK

The example of the thermal power station of the University City of Madrid, built some time ago, when the experts did not have enough knowledge to carried these facilities out in Spain and copied from other experiences made abroad should make us reflect on the need of this type of infrastructures with proven effectiveness after 80 years of operation. This example should make us think about the need for teaching these kinds of infrastructures for future developments.

Therefore, it is necessary that the technicians (town planners, architects, engineers) who are in charge of the development of cities have the adequate knowledge to design this type of infrastructures since that lack of knowledge cannot be a reason for the absence of these facilities. In the same manner, there are necessary civil servants and politicians with technical knowledge to manage the development of these complex infrastructures.

Besides, say that, the current Spanish technicians responsible for carrying out urban development are architects, so it is essential that the Schools of Architecture (responsible for training them), include the teaching of this type of infrastructure to the development of urban approaches more rational and friendlier to the environment.

Finally, it is essential the participation and investment of private companies in charge of carrying out the large disbursements that this type of infrastructures require, in addition to being carriers of scientific knowledge gained through their experience.

CONCLUSIONS

With the turn of the century, (XXI century, century of information) energy agencies and urban planners are becoming gradually interested in this kind of systems.

Despite the delay of over a century, compared to other European countries, it seems that this trend will be maintained and an exponential growth for this type of infrastructure is expected. By the year 2020, Spain is expected to multiply DHC systems by 200%.

The Barcelona project is a clear example of the of how the binding of the different parties involved (energy agencies, town halls, private companies, neighbourhood associations, consumers…) is the driving force to develop this kind of urban infrastructures, with proven effectiveness in countries with more than one hundred years of experience using them.

This example shows that, despite being an infrastructure that requires a very long-term planning and large initial outlays, once commissioning is welcomed by the population thanks to its benefits.

Consequently, all the methodology outlined in the previous section is only intended to promote such infrastructures in future Spanish urban developments. This desire is presented as a competitive solution not only for the power plant operator but also for the consumers, and hence for the city, encouraging the implementation of such systems with many advantages and contributing to the energy efficiency of the urban areas. Therefore, this paper has as ultimate goal the consideration of district energy systems as a part of urban infrastructures, along with water supply or electricity distribution.

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SESSION 15

Key elements in District Heating and Cooling systems

IMPROVED MAINTENANCE STRATEGIES FOR DISTRICT HEATING PIPE-LINES

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ABSTRACT

The main objective of this work was to establish facts and tools, which could help us to obtain and predict present and future technical status of pre-insulated bonded district heating pipes in operation. In order to simulate ageing of polyurethane (PUR) insulation an accelerated thermal ageing method was used. Accelerated ageing was performed by applying three different elevated temperatures to the service pipes. The effect of the diffusion of oxygen through the casing was examined by ageing district heating pipes with two different thicknesses of the casing pipes.

The evaluation of the technical status of the pipes after artificial or natural ageing was done by measuring the shear strength (adhesion) between the PUR foam and the steel service pipe. The tangential shear strength test method was mainly used for evaluation of the status of the pipes. The SP plug test method, which is a cheaper and more practical method in the field, was also used, and the results were compared with those from the tangential shear strength test method.

In the framework for improved maintenance strategies, the failure mechanism was considered as loss of adhesion between polyurethane and the service pipe. The deterioration of the adhesion was assumed to be a thermo-oxidative process governed by an Arrhenius relationship. A model of how the development of faults related to adhesion and costs of heat losses in a district heating distribution network was sketched.

INTRODUCTION

The aim of this work is to give tools and knowledge for better maintenance planning of district heating net-works of pre-insulated bonded pipes with polyurethane insulation. The deterioration mechanism studied is coupled to the adhesion between the polyurethane and the service pipe. Knowledge about the deterioration speed is to be gained from accelerated laboratory aged pipes and pipes that have been in field operation. Tools for obtaining technical status of pipes in field operation and in the laboratory are to be developed. The technical status and the deterioration speed will provide ability to forecast future technical status and also remaining technical life of the pipes, when an end-of-life criterion is defined.

Modernisation of the pipelines is a top priority in order to enhance the efficiency of the distribution systems according to the technology platform DHC+ [1]. In Sweden, approximately 16 000 km of pipeline are installed, with an average construction cost of 500 €/m, see Reference [2]. In order for the current replacement rate of 50 km per year to be feasible, an expected technical life of 320 years would be required, while in reality, pre-insulated bonded pipes of current standard may last for 30 – 70 years. These pipes are built up of a steel service pipe, insulating polyurethane (PUR) foam and a protecting casing pipe of polyethylene (PE).

STATE OF THE ART

Status assessment has become a top priority issue during the last years. German field studies have shown that ageing of the polyurethane (PUR) foam does not follow the time/temperature relation on which the EN 253 product standard is based, see References [3], [4] & [5] and the papers by Meigen & Schuricht [6] and Schuricht [7]. This discrepancy is supposed to be oxidative degradation of the foam. The significance of this phenomenon with respect to long term strength and thermal insulation capacity remains to be clarified.

In review of the previous work, it is concluded that it is crucial to map out the complex relationships and understand, which degradation process is predominant and under what conditions. The PUR foam thermal and mechanical properties and their deterioration could be affected by changes of solid polymer matrix and gaseous phase derived from blowing agent. There is still a lack of knowledge on how components of district heating distribution systems alter and deteriorate with time. This makes it difficult to forecast future economy and needs of maintenance and renewal.

The polyurethane foam in pre-insulated pipes can age in different ways as summarized in a literature survey reported by Sällström *et al*. [8].

Thermal ageing: At high temperatures the polymer is deteriorated, i.e., the polymer structure changes when bonds break. The foam becomes brittle and mechanical properties get worse.

Oxidative ageing: Oxygen diffuses into the foam through the casing and reacts with the polyurethane oxidatively. The foam becomes brown and mechanical properties get worse.

Ageing due to cell gas diffusion: The air diffuse into the foam through the casing and carbon dioxide and blowing agent diffuse out of the foam. The thermal conductivity of the foam increases. The solid phase of foam is intact.

Ageing due to deterioration of polymer structure: At high temperatures (above 150°C) the polymerisation reaction can go in the opposite direction and the polyurethane will be divided into polyol and isocyanate, see the paper by Schuricht & Leuteritz [9].

In Reference [3] and also in the paper by Meigen & Schuricht [6] results of axial strength of 110 field samples are reported. The axial strength is measured at 23 °C in the laboratory. The samples of naturally aged district heating pipes were taken from flow and return pipes. The axial shear strength was measured to vary from 0.01 to 0.46 MPa. The activation energy 150 kJ/K mole was used for calculating an equivalent service time at the service temperature 120 °C. Comparisons of results with the requirement 0.12 MPa from standard EN 253 and requirement from AGFW of 0.03 MPa were made.

Schuricht [7] discusses the development of the deterioration of the shear strength. After an initial deterioration rate, the deterioration curve flattens out, which is explained as post curing of the polyurethane foam. After further ageing, the deterioration rate increases again. Samples undergoing accelerated ageing at high temperatures above 180 °C show this behaviour. The importance of the oxidation was also pointed out. In the paper by Schuricht [7] and in Reference [4] the temperature dependence of ageing is evaluated from 78 samples of both flow and return pipes by studying the difference of axial shear strength of flow and return pipe. Deterioration gradients and methods calculating for equivalent time at 120 °C by relations similar to Arrhenius are discussed. Equipment for determining axial shear strength in the field was presented.

In Reference [5] studies of ageing of polyurethane foam in bottles without and with access to oxygen were reported. The deterioration of the shear strength was investigated. The experiments are carried out in the temperature range from 120 to 180 °C. The activation energy without access to oxygen, i.e., the thermal reaction, was determined to be 98 kJ/mole and the corresponding value with access to oxygen, i.e., the thermo-oxidative reaction, was 190 kJ/mole. Cell gas diffusion and thermal conductivity are also investigated in the report. The deterioration of the axial shear strength is studied for pipes stored at ambient temperature 90 °C and pipes in a test bench with 150 °C inside the service pipe with ambient temperature about 23 °C. In the latter case the temperature of the casing will be about 30 °C. The pipes with 150 °C inside the service pipe show a rapid deterioration, but then the curve flattens out after 5000 h and in some cases the pipes even improve (heals). The last results given are for the ageing during 22 000 h. There is no rapid deterioration that follows after the flattening out. The deterioration of the pipes stored at 90 °C was less, but they showed a similar behaviour. The continuously produced pipes showed no deterioration for 90 °C. The presents of an aluminium foil or a double thickness of the polyethylene casing gave no essential improvement, see Reference [9].

Olsson *et al*. [10] studied diffusion through the polyethylene casing of district heating pipes. The permeability of carbon dioxide, nitrogen and oxygen was measured. Two experimental methods were used. Further studied of diffusion through the polyethylene casing and also in the polyurethane foam were presented in the paper by Olsson *et al*. [11]. Diffusion of cyclopentane was studied and activation energies for the diffusion of different gases were given. Larsen *et al*. [12] concluded that the permeability of carbon dioxide, nitrogen and oxygen is essentially higher for the new bimodal polyethylene than the previously used unimodal polyethylene.

METHODS

In this work, the focus is technical status of pre-insulated district heating pipes and to provide a better understanding as basic information for forecasting future technical status. The failure mode studied here is simplified and limited to the loss of adhesion between the polyurethane insulation and the steel service pipe. The shear strength of the pre-insulated district heating pipes is a measure of adhesion. There are different measurement methods available that can be used in the laboratory and in the field. Two methods are described in the standard EN 253: the axial shear strength test and the tangential shear strength test. The third method considered is called the SP plug test method, and it has been developed in a previous project.

The axial shear strength is measured by use of a tensile testing machine. Usually three cylindrical pipe samples of length L are cut from the pipe. The axial force is applied on the service pipe and the sample rests around the casing pipe.

The tangential shear strength test is carried out on samples of the casing pipe and polyurethane still attached to the service pipe. Radial cuts through the casing pipe and the polyurethane towards the service pipe are made. In the laboratory the advantages are that many samples can be extracted from one pipe and that the samples can be tested intermittently during artificial ageing without dismounting the pipe.

SP plug test method was developed in a previous SP project, see the paper by Sällström *et al*. [13]. A hole saw is used for creating a cylindrical plug attached to the service pipe. Aluminium pipes are glued to the pipe, see Figure 1. A rig with a bearing is used for applying a torque manually, which is measured by static torque transducer, see Figure 2. The maximum torque M_p is measured and registered.

The plug shear strength τ_p is obtained as

$$\tau_p = 16\ M_p / \pi\ d^3 \qquad (1)$$

where

M_p = measured maximum torque
d = diameter of plug

In the axial shear strength test method and in the tangential shear strength test method the shear stress will be constant at the projected fracture surface, but in the SP plug test method the shear stress varies linearly at projected fracture surface. In the previous study by Sällström *et al*. [13] a first step towards developing a simple and cheap method for technical status assessments of existing pipes in operation without shutting the pipes down was taken. The advantages are less digging, less damage pipe (which can be repaired easily), simple mobile tools can be used for taking samples and performing measurements as compared to field versions of the axial or tangential shear strength test methods. All the presented methods have been used in the project, but the tangential shear strength test method has been most commonly used.

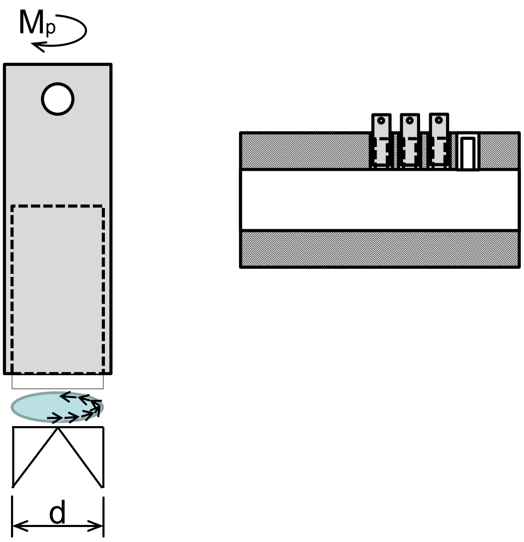

Figure 1: Sketch of SP plug test method for measuring shear strength

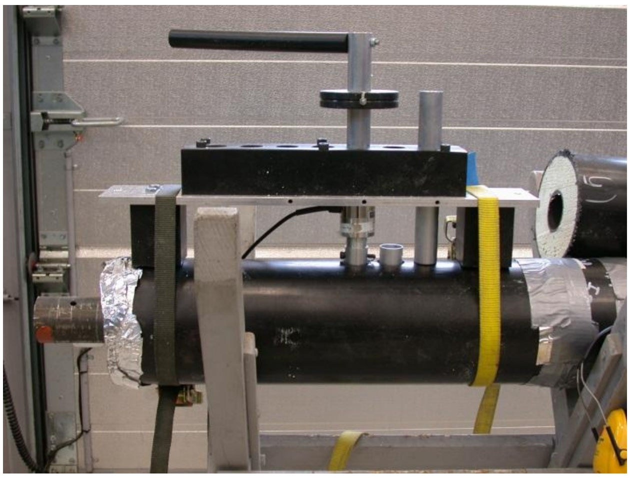

Figure 2: Picture of setup of SP plug test method

Figure 3: Artificial ageing set up

MANUFACTURING OF PIPES

Eighteen pipes DN50/160 of length 6 m were manufactured by Logstor with two different thicknesses of casing for this project. Seven pipes had a 3 mm PE casing and 11 pipes had a 0.13 mm PE foil. The traditional production method was used, but a mould was used for the pipes with thin casing.

ARTIFICIALLY AGED PIPES

The artificially (accelerated) ageing considered was limited to thermo-oxidative process in the polyurethane at the service pipe, i.e., the deterioration of the adhesion between the polyurethane foam and the service pipe. Both HDPE (High Density Polyethylene) casing and PUR insulating foam were exposed to higher temperature than their normal temperatures in operation. A heated chamber was built for creating an elevated ambient temperature. A set up of the new manufactured pipes from LOGSTOR was arranged. The pipes were artificially aged in the heat chamber in order to understand the ageing process, and apply that knowledge on pipes in operation. During the artificial ageing the service pipe were kept at different temperature levels. The reason for using three levels was the intension to calculate the activation energy in the Arrhenius relation. The purpose of the elevated ambient temperature was to increase the diffusion of oxygen through the casing, and hereby the available oxygen for the deterioration of the adhesion at the service pipes. At the same time there will be an accelerated ageing of the polyethylene casing.

The thinner casing pipe (0.13 mm) was chosen for investigating the roll of the oxygen diffusion through the casing by using different barriers against oxygen diffusion. The thin casing means an increase of diffusion rate by 23 times. The pipes were sealed by gluing aluminium sheets at the ends for prohibiting diffusion there. After testing of adhesion the holes in the casing pipes were sealed with aluminium tape.

The pipes were placed horizontally in the chamber with controlled and monitored ambient temperature at 70 °C, see Figure 3. The ambient temperature level 70 °C was chosen, since the laboratory equipment could not sustain higher temperatures. In the paper by Olsson et al. (2002) diffusion of gases in the PUR foam and through the PE casing is studied. The activation energy E_a for diffusion of oxygen through polyethylene is determined to 35 kJ/mole. The Arrhenius relation gives an increase of the diffusion rate by 13 times when the temperature is elevated to 70 °C as compared to the temperature in service 10 °C.

RESULTS AND DISCUSSION

Both accelerated laboratory aged pipes and pipes from field operation have been measured by use of the tangential shear strength test method and the SP plug test method. After each decided accelerated ageing time at least three samples were tested and the results were recorded. In both methods, the results of the shear strength did show similar tendency. For some samples, the shear strength has also been measured with the axial shear strength test method.

The results of measured shear strength of pipes aged during various times and temperatures are presented in Figure 4 and Figure 5. The tangential and plug test methods were used for pipes with 3 mm PE casing. Each point in diagram is the mean value of at least three measured values.

Comparisons of the shear strength results from the accelerated aged pipes using the tangential shear strength and the SP plug test methods indicate generally higher values for the results from the SP plug method. However, a similar pattern from both methods for various temperatures has been obtained.

The deterioration of the pipes with internal temperature at 140 °C and 150 °C was more severe than anticipated. The results of measured shear strength of pipes aged during various times and temperatures are presented in Figure 6 and Figure 7. The tangential and plug test methods were used for pipes with 0.13 mm PE casing. Each point in diagram is the mean value of at least three measured values.

The thin casing pipes behaved unexpected at high ageing temperatures and the pipes with thin casing aged at 140 °C and 150 °C were replaced after 18 weeks. Gaps between the service pipes and the PUR foam were observed after ageing of the pipes with the thin casing. The size of the gaps seems to increase by increasing temperature.

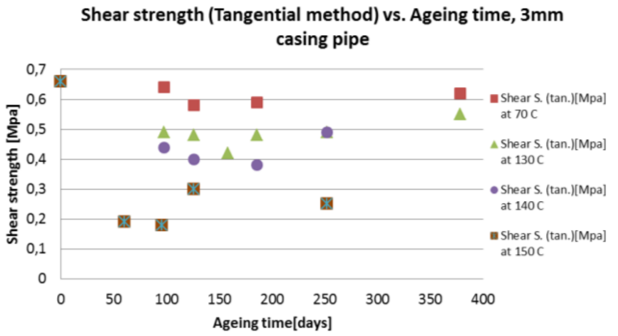

Figure 4: Tangential shear strength as function of ageing time for pipes with 3 mm PE casing. Ageing temperatures are 70, 130, 140 and 150 °C in service pipe and ambient temperature is 70 °C

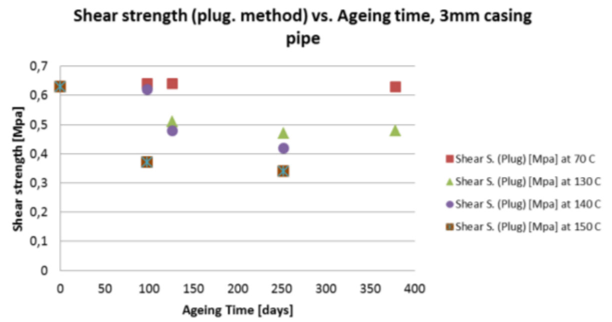

Figure 5: Shear strength (plug method) as function of ageing time. Ageing temperatures are 70, 130, 140 and 150 °C in service pipe, while ambient temperature is 70 °C.

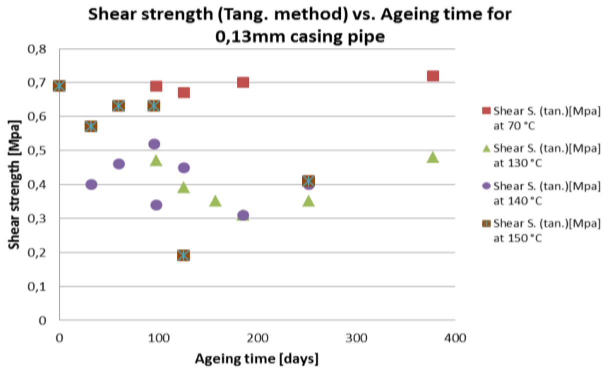

Figure 6: Tangential shear strength as function of ageing time for pipes with 0.13 mm PE casing. Ageing temperatures are 70, 130, 140 and 150 °C in service pipe and ambient temperature is 70 °C.

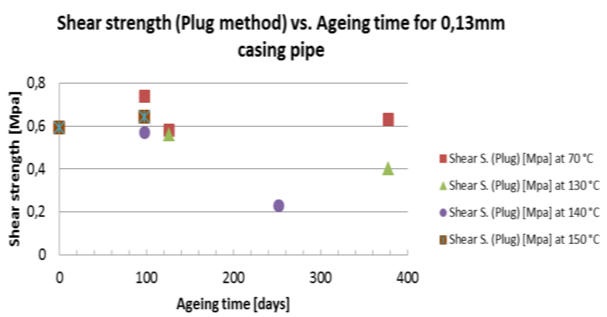

Figure 7: Shear strength (plug method) as function of ageing time for pipes with 0.13 mm PE casing. Ageing temperatures are 70, 130, 140 and 150 °C in service pipe and ambient temperature is 70 °C.

Both for the pipes with thin and normal casing large gaps have been formed. For the thin casing the gap is larger. In Figure 8 an attempt to find a tendency curve for the obtained results from accelerated ageing pipes is made. The purpose is to clarify the behaviour of deterioration of shear strength. The slope of the tendency curves for 130 °C, 140 °C and 150 °C ageing temperatures show that the shear strength decreases fast during the first period of time less than hundred days and then it flattens out. After about 200 days the tendency lines show another slope with slightly increasing shear strength. Similar observations are also discussed by Schuricht (2005) for pipes aged at high temperatures in the laboratory, but after long time the ageing plateau was followed by a faster deterioration of strength.

A possible explanation of the initial deterioration could be the increase of the cell pressure and volume due to increased temperature in the cells adjacent to the service pipe according to

$$PV = nRT \qquad (2)$$

Here, the variables are pressure *P*, volume *V*, amount of gas *n*, the ideal gas constant *R* and temperature *T*. In this situation, there will be large stresses and strains in cell walls attached to the service pipe. There will also be stresses, due to that the thermal expansion for PUR is higher than for steel. The adhesion between PUR foam and service pipe will successively decrease when cell walls break. This could explain why the decrease in the shear strength is more pronounced at higher temperatures and also why the strength flattens out with time, when a new stable configuration is reached. This hypothesis is also strengthened by the observation of the formation of gaps between the service pipes and the PUR foam for the thin casing pipes aged at 140 °C and 150 °C.

Figure 9 shows a comparison of the results for the shear strength vs. ageing time for the pipes with 3 mm and 0.13 mm casing aged at 130 °C in service pipe, which is not so far from operation temperature of a supply pipe. The results show, that the decreasing of the shear strength flattens out after a while and does not change upon prolong exposure. The difference between the results of the shear strength for thin and normal casing was not significant.

The purpose of ageing of the thin casing pipes was to speed up the diffusion of oxygen and demonstrate the thermo-oxidative reaction of PUR. Both the raising of the ambient temperature from 10 to 70 °C and the decreasing of the thickness of the casing from 3 mm to 0.13 mm will contribute to increased diffusion of oxygen.

If diffusion of oxygen through the casing and the following thermo-oxidative degradation of PUR were the main reasons for the decrease of the shear strength, then it should be a significantly faster thermo-oxidation of the pipes with the thin casing compare to the normal casing. If the PUR degradation is dominated by a thermo-oxidative reaction, the degradation process should continue until the degradation is complete with zero shear strength.

However, our results from the accelerated ageing show that the changes of the shear strength do not depend on the thermo-oxidation of PUR, since the processes of the two casings have not significantly different slopes and they do not continue to zero. The processes seem to have a physical character instead. There is a need for further studies of the insulation material and the morphology of it in the pipe system, and the various processes linked to the different slopes of the shear strength deterioration.

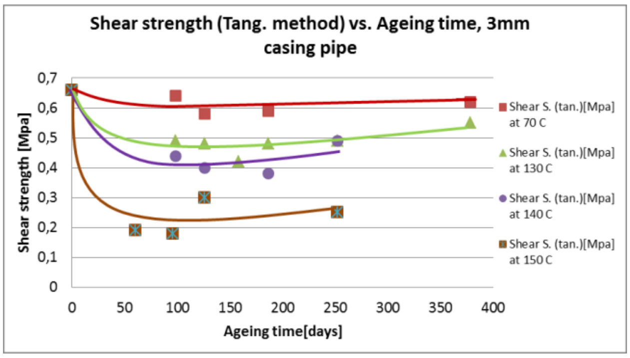

Figure 8: Tangential shear strength vs ageing time for pipes with 3 mm PE casing.

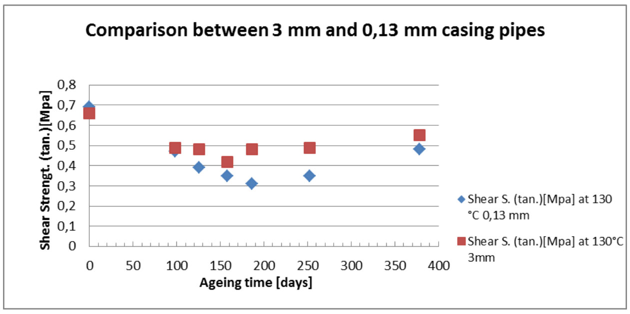

Figure 9: Comparison of tangential shear strength as function of ageing time for pipes with 3 mm and 0.13 mm PE casing at 130 °C.

Figure 10: Supply pipe from Goyang network in Korea after 18 years in operation

CASE STUDY OF PIPES IN OPERATION

In order to try to understand the natural ageing process for DH pipes and correlated that to the laboratory study with accelerated ageing of pipes, a case study has been performed. Old pipes from operation for the case study were selected from two different DH networks and delivered to SP: the district of Goyang in Korea and Trondheim in Norway owned by KDHC and Statkraft, respectively. The pipes had been installed at different points in time and aged between one and 38 years.

A pipe sample is shown in Figure 10. Some of these pipes were measured by using both the tangential shear strength test method and the SP plug test method. The pipes with other casing diameters were only tested with the SP plug test method. The axial shear strength was also used for a few pipes.

The tested from operation pipes were differed from the pipes manufactured for our laboratory ageing in many aspects. The pipes from Goyang in Korea had the blowing agent CFC 11 and the casing HDPE pipes were 3.5 mm thick.

The shear strength of supply and return pipes in operation are presented in Figure 11 and Figure 12. The oldest pipe (38 years) and the youngest pipe (one year) from Norway have been exposed to the same temperatures for the supply and the return pipes, respectively. When looking at the shear strength results measured by SP plug test method on the supply pipes in operation, irrespectively of the type of polyurethane and blowing agent used, a slow degradation rate is shown during 38 year of service for the Norwegian pipes, see Figure 11. A slow degradation is also indicated by the axial shear strength results.

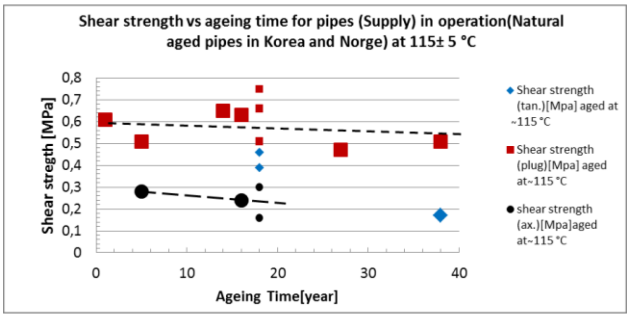

Figure 11: Shear strength as function of ageing time for supply pipes aged naturally in operation from Norway and Korea. Results signed by squares come from plug tests of pipes. Diamonds indicate results from tangential strength tests. Circles indicate results from axial shear strength tests. Small and large marks indicate results of pipes from Korea and Norway, respectively.

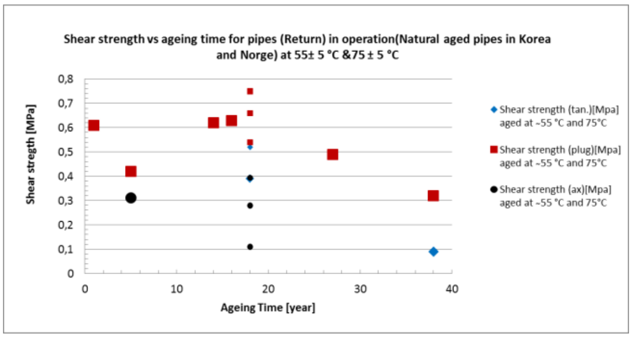

Figure 12: Shear strength as function of ageing time for return pipes aged naturally in operation from Norway and Korea. Results signed by squares come from plug tests of pipes. Diamonds indicate results from tangential strength tests. Circles indicate results from axial shear strength tests. Small and large marks indicate results of pipes from Korea and Norway, respectively.

MODEL FOR IMPROVED MAINTENANCE STRATEGIES

Maintenance cannot be considered as a separate action that can be optimised within any company. In the short run the profit of the company can be optimized by neglecting the maintenance, but after some years problems with malfunction systems will eventually occur. There will be costs for repairs and also for loss of sales. There can also be fines related to lack of delivery. The other extreme would be maximize the status of the asset at any costs, and try to keep it as new. Instead, the life cycle of the asset has to be considered. The asset has to be acquired, utilized, maintained and eventually disposed. During the life cycle of the asset the costs, the risks and the performance of the asset shall be optimized. Here, the asset is the heat district distribution system and we focus on companies managing these systems. However, in this project not all type of maintenance activities related to the distribution system is considered. Here, we focus on the adhesion between the polyurethane and the service pipe.

Hence, the failure mechanism is considered as loss of adhesion between polyurethane and the service pipe. Let us assume that we start out with a stress free district heating distribution system. When the temperature within the district heating system increases, the steel service pipe will expand. When there is adhesion between the polyurethane and service pipe and also at the casing pipe, the soil will induce friction forces along the casing. In the zones near bends where the pipes move, the axial force is built up to the fix force where axial strain becomes zero. The soil and the adhesion limit the displacements due to temperature changes in the district heating system. This also means that bending stresses at bends and T-pieces will also be limited. When adhesion is lost, fatigue of the steel service pipe at bends and T-pieces occurs due to the variation of distribution temperature. In the standard EN 253 it is stated that the adhesion or axial shear strength should be more than 0.12 MPa. This limit can be used for judge the status of the district heating pipe. A lower value can also be chosen, but the risk of failures can then increase above an acceptable level.

Besides the failure mechanism and the acceptable limit a status assessment method is needed. Field measurements methods, like the SP plug method can be used as a tool to measure the adhesion value. If no up to date measurements are available, estimations can be obtained from, e.g., previous measurements and deterioration functions.

The deterioration of the adhesion is in this chapter assumed to be a thermo-oxidative process governed by an Arrhenius relationship. The hypothesis of a physical deterioration mechanism is not yet proven and therefore not used here. The reaction rate k_1 at the temperature T_1 [K] depends on the activation energy E_a as

$$k_1 = A_0 \exp\left[-\frac{E_a}{RT_1}\right] \quad (3)$$

The ideal gas constant is denoted R. The deterioration function can be used for estimating actual status of the adhesion today from previous measurements and also give prognoses of future status, based on the choice of operating temperature.

In order plan the maintenance or the renewal pertaining to the loss of adhesion. The status of the flow and return pipes have to be known after a certain service time ta. For constant reaction rate, the status of the flow and return can be written as

$$s_f = s_0 - k_f t_a \qquad s_r = s_0 - k_r t_a \quad (4a, b)$$

The initial adhesion s_0 is assumed to be the same for the flow and return pipes. For the flow and return pipes, the reaction rates are

$$k_f = A_0 \exp\left[-\frac{E_a}{RT_f}\right] \qquad k_r = A_0 \exp\left[-\frac{E_a}{RT_r}\right] \quad (5a, b)$$

The operating temperature in the flow pipes is denoted T_f and the return temperature T_r. The initial status is obtained as

$$s_0 = \left[\frac{k_f}{k_r} s_r - s_f\right] / \left[\frac{k_f}{k_r} - 1\right] \quad (6)$$

By use of equations (4a, b), (5a, b) and (6) the status of the particular pair of pipes can be predicted for a future point of time t_b. During a certain degradation period studied, the operating temperature can vary with the season which can be taken into account by applying a method of lumping the time for a set of temperature spans. Say that three temperature levels are used, which give three degradations rates. A sum for this can be introduced in Equations (4a, b) with products of degradation rates times the pertaining operation times.

To be able to predict future maintenance related to adhesion, the maintenance pertaining to failure of adhesion has to be known at a certain time. For the time the maintenance is known the strength can be estimated from previous measurements. A simpler scenario would be to have measurements of strength and required maintenance for the same point in time. In the model it is assumed that the maintenance will increase in proportion to the decrease of the adhesion.

For the temperature losses a simple approach is used. Initially the thermal conductivity is assumed to be 26 mW/m K and it increases linearly over 30 year to a level that is 30% higher. The losses for a pair of single pre-insulated district heating pipes are calculated according to EN 13941. A sketch of the model for improved maintenance is shown in Figure 13.

The input data needed, the assumptions made and the forecasted data are illustrated in Figure 14. In order to show how development of faults related to adhesion and costs of losses in a district heating distribution network, a simplified model of the network in Goyang in Korea is used. Input data calculation estimates are given in Table 1. The activation energy is assumed to be 100 kJ/mol instead of the value 150 kJ/mol used in standard EN 253. Costs of heat and repair of pipes are assumed.

Table 1: Input data for calculations

Parameter	**Value**	**Unit**
E_a	100	kJ/mol
R	8.314	J/K mol
Limit shear strength	0.12	MPa
Cost of heat	40	Euro/MWh
Average cost/fault	10 000	Euro
Conductivity of PUR	0.0259	W/mK
Final value 30 yrs	0.0337	W/mK

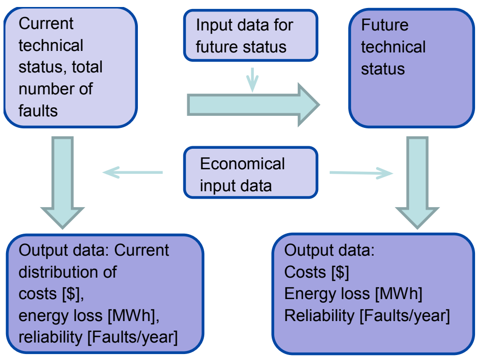

Figure 13: Sketch of model for improved maintenance.

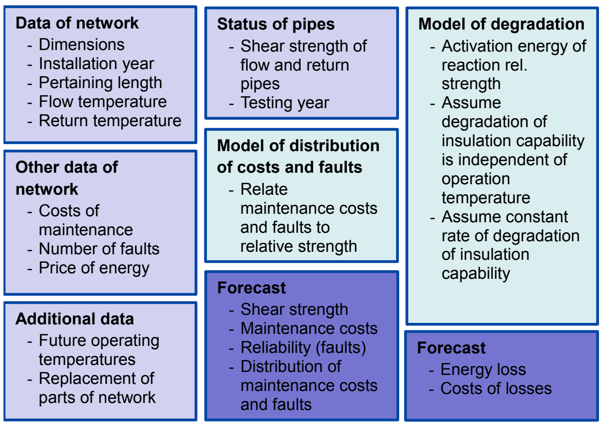

Figure 14: Input and output data of model for improved maintenance.

Table 2: Basic data of example district heating network

Pipe section id	Dimension	Type	Installa-tion year	Length [km]	Average supply tempera-ture [°C]	Average return tempera-ture [°C]	Tempera-ture diff for losses [°C]	Heat loss new pipe [W/m]	Heat loss old pipe [W/m]
A1	DN700/800	Single	1994	85 000	103	56	79.5	166.2	197.4
A2	DN700/800	Single	1999	18 000	103	56	79.5	166.2	197.4
A3	DN700/800	Single	2004	24 000	103	56	79.5	166.2	197.4
A4	DN700/800	Single	2009	35 000	103	56	79.5	166.2	197.4
B1	DN300/450	Single	1994	163 000	100	56	78	64.5	80.1
B2	DN300/450	Single	1999	34 000	100	56	78	64.5	80.1
B3	DN300/450	Single	2004	46 000	100	56	78	64.5	80.1
B4	DN300/450	Single	2009	67 000	100	56	78	64.5	80.1
C1	DN50/125	Single	1994	82 000	97	56	76.5	29.3	37
C2	DN50/125	Single	1999	17 000	97	56	76.5	29.3	37
C3	DN50/125	Single	2004	23 000	97	56	76.5	29.3	37
C4	DN50/125	Single	2009	34 000	97	56	76.5	29.3	37
Sum				628 000					

Table 3: Input data for example of district heating network in first five columns. Other columns contain calculated results for time of testing.

Pipe section id	Year of testing	Flow pipe: Shear strength [MPa]	Return pipe: Shear strength [MPa]	Actual number of faults per year and km	Relative reaction rate flow & return	Esimated initial strength [MPa]	Degrada-tion rate [MPa/ year]	Number of faults per year [-]	Costs of faults [Euro/ year]	Losses [W/m]	Value of losses per year [EURO/yr]
A1	2010	0.36	0.5	0.000030	96.53	0.50	0.009	2.6	25 500	183	2 237 962
A2	2010	0.4	0.5	0.000020	96.53	0.50	0.009	0.4	3 600	178	460 443
A3	2010	0.44	0.5	0.000010	96.53	0.50	0.010	0.2	2 400	172	595 953
A4	2010	0.49	0.5	0.000005	96.53	0.50	0.010	0.2	1 750	167	842 890
B1	2010	0.36	0.5	0.000030	74.63	0.50	0.009	4.9	48 900	73	1 709 231
B2	2010	0.4	0.5	0.000020	74.63	0.50	0.009	0.7	6 800	70	343 797
B3	2010	0.44	0.5	0.000010	74.63	0.50	0.010	0.5	4 600	68	447 915
B4	2010	0.49	0.5	0.000005	74.63	0.50	0.010	0.3	3 350	65	627 313
C1	2010	0.36	0.5	0.000030	57.46	0.50	0.009	2.5	24 600	33	394 466
C2	2010	0.4	0.5	0.000020	57.46	0.50	0.009	0.3	3 400	32	78 638
C3	2010	0.44	0.5	0.000010	57.46	0.50	0.010	0.2	2 300	31	102 142
C4	2010	0.49	0.5	0.000005	57.46	0.50	0.010	0.2	1 700	30	144 709
Sum								12.9	128000		7 985 458

Table 4: Input data for example of district heating network in first three columns. Other columns contain calculated forecasted results.

Pipe section id	Status for year	Assumed future tempera-ture	Relative reaction rate	Forecasted strength flow pipe [MPa]	Forcasted life until	Forecasted number of faults per year and km	Forecasted number of faults per year	Forecasted costs of faults [Euro/ year]	Forecasted losses [W/m]	Forecasted value of losses per year [EURO/yr]
A1	2030	108	1.522	0.091	2028	0.000119	10.1	100 966	204	2 500 658
A2	2030	108	1.522	0.120	2030	0.000066	1.2	11 956	204	529 551
A3	2030	108	1.522	0.132	2031	0.000033	0.8	7 971	200	691 188
A4	2030	108	1.522	0.182	2034	0.000013	0.5	4 699	195	980 859
B1	2030	105	1.532	0.088	2028	0.000122	19.9	199 437	83	1 947 254
B2	2030	105	1.532	0.118	2030	0.000068	2.3	23 113	83	406 176
B3	2030	105	1.532	0.129	2031	0.000034	1.6	15 635	81	535 262
B4	2030	105	1.532	0.179	2034	0.000014	0.9	9 147	78	753 640
C1	2030	102	1.543	0.085	2027	0.000127	10.4	103 855	38	452 841
C2	2030	102	1.543	0.115	2030	0.000070	1.2	11 871	38	93 882
C3	2030	102	1.543	0.126	2030	0.000035	0.8	8 030	37	123 492
C4	2030	102	1.543	0.176	2034	0.000014	0.5	4 732	36	176 041
Sum							50.1	501 415		9 190 843

The network has been built and expanded since 1992, and statistics are available until 2011. The nominal diameters of the pipes are in the interval from DN20 to DN850. The mean operation temperature from the power plant is 103°C in the flow pipe and the mean return temperature is 56°C. The standard deviation of both the flow and return temperature is about 5°C. The complete length of the network is 627 km. For simplicity only three pipe sizes have been used and the expansion is assumed to have taken place at four distinct years, i.e., 1994, 1999, 2004 and 2009. The pipes have been lumped to the chosen pipe sizes and building years. Basic data are shown in Table 2. A temperature decrease of 6°C is assumed. The heat losses are calculated for a district heating pipes with a cover of 0.6 m and a soil temperature of 8°C.

In Table 3 feigned test data of adhesion (shear strength) are used. Repairs related to pipes are yearly between 9-22 in the district of Goyang. The failure mechanisms of these repairs are not known. In the example studied the number of yearly faults related to adhesion is assumed in Table 3. The relative reaction rate between flow and return is calculated. For the highest operation temperature the deterioration rate is 97 times as high for the flow pipe as compared to the return pipe. The initial strength is calculated to be the same as in the return pipe at the time of the test. The yearly deterioration rate is calculated. With the assumptions made, the number of faults or maintenance actions related to adhesion becomes 13 and the cost for these are assumed to be EUR 130 000. The losses in the network is calculated to be 200 GWh and the value is estimated to be EUR 8 000 000. The losses for this simplified network are much larger than the losses in the real network in Goyang.

In Table 4 the status of the network is forecasted year 2030. The temperature levels are assumed to be increased 5 °C on the flow pipe. This means that the reaction rate will increase by more than 50%. The forecasted shear strength is calculated based on the shear strength 2010, which is assumed to be measured, and the deterioration rate for the new temperature, which is assumed to be applied from 2010 until 2030. Here, the requirement for the shear strength is set to 0.12 MPa, which also is the criterion for end of life. The year, when end of life is reached, is also calculated. The forecasted yearly maintenance per km is calculated as the maintenance 2010 times the strength 2010 over the forecasted strength 2030. In this example, the number of faults or maintenance actions related to adhesion becomes 50 and the pertaining cost is EUR 501 000. The heat losses are estimated to increase to 230 GWh and the costs for that are estimated to EUR 9 200 000.

CONCLUSIONS

The results of the measured shear strength of the artificially aged pipes after various ageing times and temperatures indicate a similar tendency of deterioration for both the tangential shear strength and the SP plug test methods. The thin casing behaved unexpected at 140 ºC and 150 ºC by after testing showing big gaps between the insulating PUR foam and the service pipe. These gaps mean bad adhesion and there was no sense to measure the shear strength.

The results show that the shear strength deterioration of the pipes follows different slopes. The shear strength decreases rapidly in the beginning, then it obtains a stable level (the curve flattens out), and after that it slightly increases towards the end of our experimental time. The difference between the results of the shear strength for thin and normal casing was not significant.

Neither the raising of the ambient temperature from 10 to 70 °C nor the decreasing of the thickness of the casing from 3 mm to 0.13 mm could contribute to speed up the diffusion of oxygen and demonstrate the thermo-oxidative reaction of PUR. Our results show, that the changes of the shear strength of the pipes in the test set-up used do not depend on the thermo-oxidation of PUR, since the processes of the two different casing have not significantly different slopes and they do not continue to zero. The processes seem to have a physical character instead. The results have not shown any corroborating evidence for Arrhenius relationship in support of the calculation of the activation energy.

Results of the shear strength tests from supply pipes aged during one to 38 years show a slow deterioration rate. It is anticipated that the stable level is reached. The original values of the shear strength of these pipes are not available. Regardless of variation of type of pipes and the original values of the shear strength, the results show a similar behaviour (a slow deterioration rate) as the artificial aged pipes.

The project has provided a framework for forecasting future technical status, maintenance needs and costs and energy losses based on known technical status, today's maintenance needs and estimated future operating temperatures. The maintenance activities of the distribution system are based on the technical status. The theoretical calculations and information from Korea and Norway DH-pipe networks have been used for demonstrating the model.

In the framework, the failure mechanism is considered as loss of adhesion between polyurethane and the service pipe. The deterioration of the adhesion is assumed to be a thermo-oxidative process governed by an Arrhenius relationship. Our hypothesis of a physical deterioration mechanism is not yet proven and therefore is not used here. In order to show how the development of faults related to adhesion and costs of heat losses in a district heating distribution network, a simplified model of the network in Goyang in Korea was used.

The model has been used to forecast of the status of the network in the year 2030. The temperature levels were assumed to be increased 5 °C on the flow pipe. This means that the reaction rate will increase by more than 50%. In the scenario discussed, the forecasted shear strength was calculated based on the shear strength 2010, which was assumed to be measured, and the deterioration rate for the new temperature, which was assumed to be applied from 2010 until 2030. Here, the requirement for the shear strength was set to 0.12 MPa, which also is the criterion for end of life. The year, when end of life is reached, was also calculated. The forecasted yearly maintenance per km was calculated as the maintenance 2010 times the strength 2010 over the forecasted strength 2030. In the example treated, the number of faults or maintenance actions related to adhesion is increased by a factor of 3.9. The heat losses are estimated to increase by 15%.

OUTLOOK

Comparison of the stable level of the shear strength measured by SP plug test for the artificially aged pipes and the naturally aged pipes shows that the value from the naturally aged pipe fit very well into the set of values from the accelerated laboratory ageing. It is clear that the stable level value of the shear strength decreases almost linearly with increasing temperature, but it is not directly dependent on the ageing time within our investigated time limit. These results represent a strong indication that the ageing process is of a physical nature and not a result of an oxidation process. There is a need for further studies of the insulation PUR material and the morphology of it in the pipe system, and the various processes linked to the different slopes of the shear strength deterioration.

ACKNOWLEDGEMENT

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THERMAL INFLUENCE ON AXIAL PULLOUT RESISTANCE OF BURIED DISTRICT HEATING PIPES

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ABSTRACT

District heating (DH) pipes are subject to recurring changes in temperature of the transported medium, usually water, due to operational needs. As these pipes are typically buried in the ground, the expansion and contraction in the pipelines caused by these thermal changes inevitably invoke soil-pipe interaction. Different complex mechanisms are involved in such interaction situations.

This research project focuses on the potential changes in axial soil resistance with radial expansion of buried DH pipes. An existing soil chamber was adapted to test full-size water-filled district heating pipes. Different heating histories are applied to the water mass inside the pipe before the pipe is axially pulled at a constant rate, while load and displacement during the pulling process are recorded. Data collected from strain gauges mounted on the pipe at the soil interface contribute to understanding of the mechanisms involved.

A significant influence of temperature increase of the transported medium on the axial pullout resistance of buried DH pipes is demonstrated. The findings illustrate the need for considering thermal influence in designing DH pipeline networks. Further testing is recommended to expand the experimental database that can be used to benchmark analytical predictions and lead to more efficient designs of buried DH pipe systems.

INTRODUCTION/PURPOSE

District heating pipes are subject to cyclic changes in temperature of the transported medium, usually water, due to different temperatures throughout their life cycle. The DH pipes are installed at ambient temperature, but exposed to much higher temperatures from the transported medium during operation, thus leading to thermal pipe expansion. Cyclic thermal loading of DH pipes is inevitable due to different operational needs requiring different temperatures in the transported water mass. Pipes will expand and contract both radially and axially under such thermal variations. As DH pipes are typically buried in the ground, this could cause significant soil-pipe interactions that have to be accounted for in design.

Weidlich and Achmus (2008) [1] carried out an experimental and numerical investigation on the reduction of friction in axially displaced DH pipes. As a part of the research work, they investigated changes in axial resistance due to cyclic axial displacement. Weidlich and Wijewickreme (2012) [2] presented an outline of various influences to be considered, including loads due to relative lateral displacements and thermal expansion. It is fair to state that previous work on the topic of soil-pipe interaction of DH pipes is scarce. Clearly, data from controlled experimental work on pipelines subject to axial movement, particularly conducted at full-scale level, is needed to advance the knowledge of the response of buried DH pipe systems subject to ground movement.

With this background, the current research focuses on the development of axial soil resistance during cyclic thermal loading generated from the transported medium. The work presented herein can be considered as a presentation of early results from this exploratory work to understand the mechanisms involved in soil-pipe interactions during heating and cooling cycles. It is expected that, in the long run, this work would contribute to the cost-effective design of DH pipe networks.

STATE OF THE ART

Over the years, numerous studies have been performed on steel pipes to characterize the behavior when the pipes are subjected to ground movement. These involve laboratory tests spanning from centrifuge tests to full-scale model tests, field testing and monitoring, numerical and analytical modeling, thus,

Figure 1: An overview of the ASPIRe soil chamber

Figure 2: Heating equipment:
Top left: microprocessor-controlled electrical heaters
Right: propane heater
Bottom left: pipe with removable end cap, hoses for in/outflowing water and cable for thermal sensor

resulting in the development of simplified models and approaches to assess the performance of buried pipelines in a reasonable manner. There have been studies to understand the performance of polyethylene (PE) pipes subject to very high static soil pressures (e.g. Brachman et al. 2000 [3]) and soil loading from ground movements relative to piping (e.g. Wijewickreme and Weerasekara 2014 [4]). As previously mentioned, reported experimental research on the response of buried DH pipe systems subject to ground movement is very limited although there may be findings from investigations performed (by private entities) for specific uses that are either not published and documented, or cannot be generalized to other conditions. Due to this lack of alternative approaches, soil-pipe interaction models developed for steel pipes (ASCE 1984 [5], ALA 2001 [6], PRCI 2004 [7]) are often considered for analyzing PE pipe configurations as well.

A common approach to estimate axial resistance of pipes is included in several guidelines, including ASCE (1984) [5]:

$$T = \frac{\pi \cdot D \cdot H \cdot \gamma \cdot (1+K_0) \cdot tan\delta}{2} \qquad (1)$$

where D = pipe diameter, H = height of soil over pipe centre line, γ = soil bulk density, K_0 = lateral earth pressure coefficient at rest and δ = interface friction angle between the soil and the pipe. δ can be obtained from small scale interface tests. Different approaches for K_0 exist, some of which potentially underestimate the normal stress around the pipe due to soil dilation, as reported in Wijewickreme et al. (2009) [8]. Therefore, it is possible that changes to the K_0 value around DH pipes could also manifest due to different thermal loading histories in the transported content.

Figure 3: Pipe being aligned before adding soil layers

METHODS/METHODOLOGY

A number of axial pullout tests of buried DH pipes were conducted in this study. A large soil chamber developed as a key component of the Advanced Soil Pipe Interaction (ASPIRe™) facility by Wijewickreme et al. (2009) [8] at the University of British Columbia, Vancouver, B.C., Canada, was used with some modifications for the present testing. The chamber has dimensions of 3.8 m x 2.5 m x 2.5 m comprising a steel-frame construction with timber planks and plywood sheets. A flexible divider wall was introduced to limit the chamber width to 1.1 m for the current testing. An overview of the test chamber can be found in Figure 1. The chamber is equipped with two 418 kN actuators, controlled by a system manufactured by MTS, Minnesota, USA.

DH pipes with an outer diameter of 520 mm, manufactured by Logstor, Denmark, were tested. The core pipe is made of steel, while the outer layer is made of high-density polyethylene (HDPE). Polyurethane foam provides insulation between the outer layer and core pipe. The pipe ends were closed with one welded steel end cap and one removable aluminium end cap to provide a watertight space in the pipe. A heating system consisting of a pump, two microprocessor-controlled electrical heaters and a propane heater with a power of 20 kW was installed to control the water temperature. An overview of the heating equipment is included in Figure 2. A standard temperature increase of ΔT = 50°C was used for all tests to examine the differences between different heating histories, like heating-pulling vs. heating-cooling-pulling. During tests, the pipe ends were covered in fiberglass insulation to minimize heat loss. The pipe specimen was purposely selected to be longer than the soil chamber, so that it extended through both ends of the chamber. This ensured a constant length of the soil-pipe interface during pullout and avoided soil disturbance at the back of the chamber.

Fraser River sand, which has been chosen for many previous studies at The University of British Columbia,

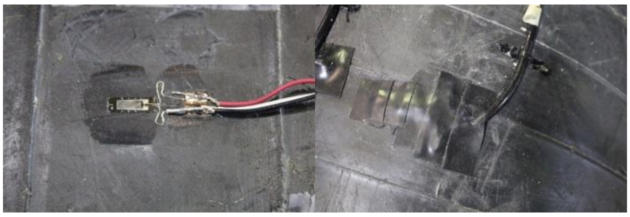

Figure 4: Strain gauges glued to HDPE surface before and after application of protective layers

was used as the soil backfill material around the pipe for the testing conducted in this study. The sand has an average grain size D_{50} of 0.3 mm and a coefficient of uniformity C_u of 1.5. Minimum particle size is 0.0074 mm. Minimum and maximum void ratios are 0.62 and 0.94. Moist sand was used in this study, with average water contents of 2.9 to 4.6 %.

For each test, the pipe was buried at a depth such that the H/D ratio is 1.5, where: H = the soil depth to the springline of the pipe; and D = pipe outer diameter (D). All results presented herein originate from tests on DH pipes with D = 520 mm and an H = 780 mm. As such, this resulted in a depth of 520 mm from the soil surface to the crown of the pipe. The photograph in Figure 3 shows the pipe being aligned before adding the surrounding backfill soil. Soil backfill was added in lifts with each having a thickness of 200 to 300 mm. Each lift was compacted to a medium-dense packing of roughly 1600 kg/m³ using a static roller or a tamper plate. For each test, density was determined by measuring the soil weight in multiple buried bowls of known volume. The pipe was then filled with water, before different heating histories were applied to the water mass.

During heating and cooling phases, the temperature at different locations of the test system was monitored using a total of seven thermal sensors: (a) three at the soil-pipe interface; (b) one buried in the soil mass 150 mm away from the interface; (c) two to log water temperature; and (d) one to measure ambient air temperature. For one test, strain gauges were mounted on the pipe surface, using a procedure specifically developed for PE pipes (e.g., used by Groves and Wijewickreme [9] for natural gas pipes) to ensure proper bonding and waterproofing while limiting local stiffness increase. Gauges were installed on two diameters, one in the middle of the soil chamber, one for reference just outside the chamber. At each diameter, a pair of gauges (for axial and radial direction) was located at the crown and on both sides of the pipe. A gauge before and after protective layers were installed can be seen in Figure 4.

In a given test, after the selected heating history was applied, the pipe was pulled at a constant rate of 0.25 mm/s to measure the change in axial resistance to relative movement. Two tests were performed without heating to provide a baseline for comparison. A load cell was mounted on each actuator to record load, while a string potentiometer was connected to the pipe to record displacement during pullout.

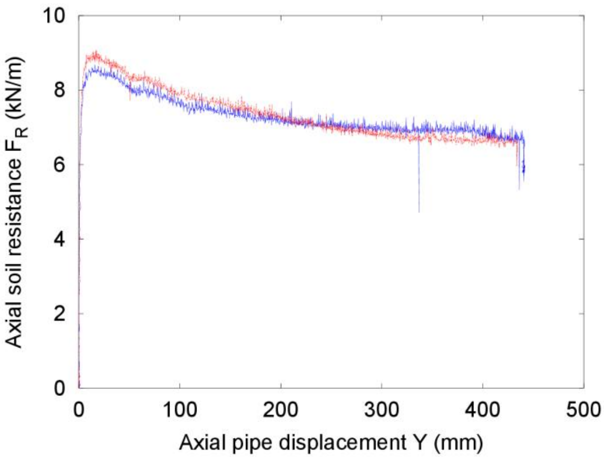

Figure 5: Results of two baseline tests without heating of the water mass. D = 520 mm, H/D = 1.5.

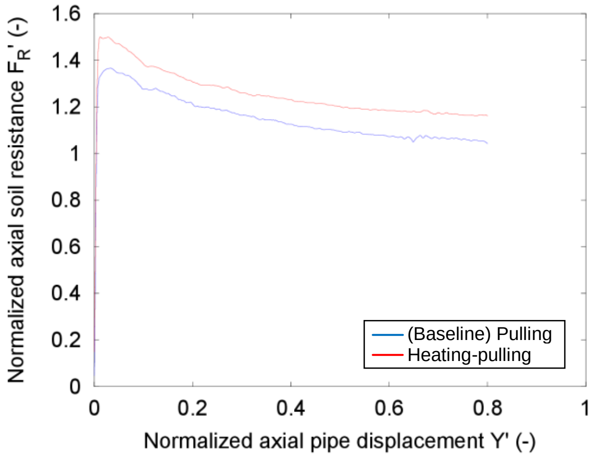

Figure 6: Comparison of average from baseline tests to average from tests with hot water mass inside the pipe during pullout. D = 520 mm, H/D = 1.5.

RESULTS

The first part of this section shows the results of baseline tests and tests with a simple heating history are presented. The second part presents results of a test including strain gauge data.

Results of pipe pullout tests are usually presented in a dimensionless format to simplify comparison with other tests. Normalized axial soil resistance F_R' is defined in equation (1) below:

$$F_R{}' = \frac{F}{\gamma \cdot H \cdot D \cdot L} \quad (2)$$

where F = measured axial pullout resistance and L = length of pipe. Normalized axial pipe displacement Y' is defined in equation (2) below:

$$Y' = \frac{Y}{D} \quad (3)$$

where Y = pipe displacement.

Figure 5 shows results of two identical baseline tests, where the pipe was pulled without applying any heating

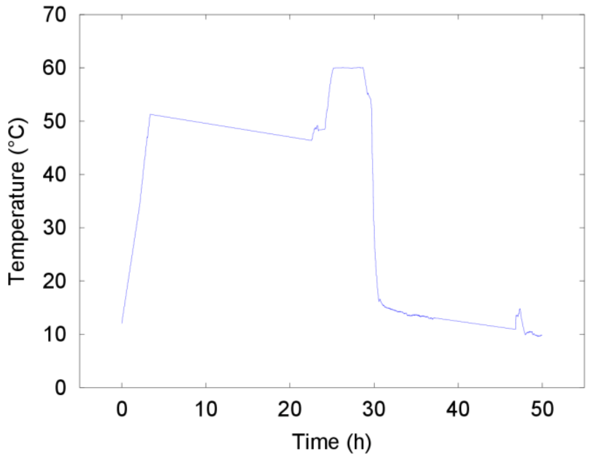

Figure 7: Temperature history of the water mass

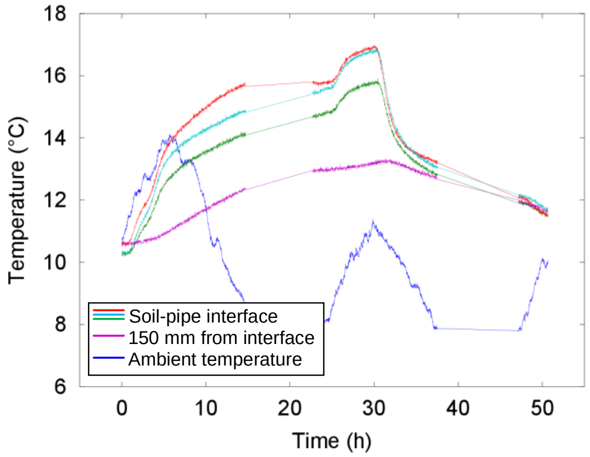

Figure 8: Temperature history at the soil-pipe interface, at 150 mm from the interface and ambient

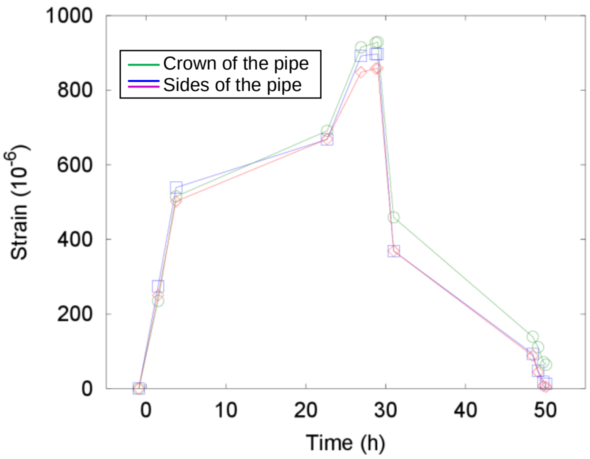

Figure 9: Radial strain at the HDPE layer on the crown and on the sides of the buried pipe

history. To ensure that the initial stress conditions match other tests, the pipe was still filled with water at ambient temperature. As may be noted, this comparison proves a reasonable repeatability, indicating that the chosen experimental equipment and procedure is suitable for this research.

A comparison of heated and non-heated tests is included in Figure 6. For this figure, the two tests with the same heating history were averaged for each curve. It is of interest to note that both the curves have a distinctive peak value, as previously observed by Wijewickreme et al. (2009) [8] on tests for steel pipes. Peak axial resistance load is reached at small displacements of Y'=0.015, while the resistance levels out when Y' moves beyond 0.7. Peak and large-displacement loads are noticeably higher for the heated tests compared to the baseline tests. The difference is significantly larger than those between tests with identical heating history presented in Figure 5.

The following is a presentation of results from a test where strain gauges are attached to the HDPE surface of the pipe. This pullout test was conducted on a pipe subjected to one heating-cooling cycle. The temperature history for the water mass is shown in Figure 7. It is to be noted that the initial time condition (t = 0 hour) in the graphical presentations corresponds the start of heating of the water inside the pipe. Due to operational constraints, the water temperature was only brought up by 40°C on the first day, and then increased to the target temperature on the next day at around t = 25 hours. The temperature was then kept constant until no more significant change in temperature was measured at the soil-pipe interface. Once this heating phase was completed, cooling was started by introducing cold water to the pipe until the lower target was reached.

Figure 8 presents the temperature history: (i) at three locations on the soil-pipe interface (red, cyan, green); (ii) 150 mm away from the interface in the soil mass (purple); and (iii) the ambient air temperature over the entire period (blue). At two occasions around t = 15 hours 15 and 38 hours, the temperature logging stopped accidentally, and had to be restarted manually the next morning.

The pipe and soil specimen were installed at an ambient temperature of roughly 10°C. After reaching the target increase of ΔT = 50°C, the temperature at the soil-pipe interface saw an increase of 6°C to 7°C. Inside the soil mass at a distance of 150 mm, this increase over the same time history was still around 3°C.

Readings of the strain gauges are presented in Figure 9. Roughly 60% of the maximum strains are reached at the end of the first heating phase at t = 4 hours. Strain reaches its peak in harmony with the peak temperature level that was reached around t = 25 hours.

DISCUSSION

The experimental results, as shown in Figure 6, indicate a significant influence of the change in temperature of the water mass on the pullout resistance. It appears that the large-strain axial soil resistance increased by about 15% if the water mass was heated by ΔT = 50°C before pullout, when compared with the resistance observed in the baseline test under otherwise same conditions. This suggests that changes in circumference of the pipe due to thermal expansion may have caused the normal stress around the pipe to increase; since frictional force is a function of normal stress, this would lead to an increased overall pullout resistance.

Strain at the soil-pipe interface could be monitored throughout one test during this research project. Figure 9 shows the changes in strain during the different stages of the test. Average peak radial strain is 860 microstrain (10^{-6}) after the constant phase at the upper temperature. This translates to an increase in circumference of 1.4 mm.

Expansion of the HDPE layer on the outside of the pipe can be explained through two mechanisms. First of all, strains due to thermal expansion of the temperature increase at the HDPE layer. Secondly, strains from the steel pipe at the core of the pipe could affect the outer layers. Since steel has a very high thermal conductivity, it can thus be assumed that the temperature of the steel core pipe material will increase almost in harmony with the temperature of the water mass.

After the first, fast heating phase of this test, as seen in Figure 9 between hour 0 and 4, strains measured at the HDPE layer on the soil-pipe interface had already reached roughly 60% of the maximum strain. However, the average temperature at the soil-pipe interface, has only increased by some 30% of the maximum temperature increase in the same time period. It took another 4 hours for the temperature at the interface to reach 60% of the maximum temperature increase.

It is possible that this “additional” strain is due to expansion of the steel pipe at the core that affects the outer HDPE layer through the polyurethane foam.

OUTLOOK

The above observations are only based on results from a limited number of sensors installed on one pipe, as this is an early exploratory project. It is expected that further investigations could contribute to higher confidence and bring more insights into the mechanisms involved in soil-pipe interaction of district heating pipes under cyclic thermal loading.

Firstly, additional tests under controlled conditions in a soil chamber can confirm the results of the present work and expand the test database to include the effect of different parameters such as pipe diameter, temperature increase, number of cycles or duration of cycles. Secondly, production systems buried in the ground could be instrumented to gather data that would otherwise not be possible to obtain from laboratory testing due to limitations in time and space. If field testing is undertaken, strains and movements in pipe networks with complex geometries could be monitored during several full seasonal temperature cycles.

CONCLUSIONS

The work presented in this paper illustrates the significance of full-scale testing with regard to understanding the soil-pipe interaction in DH pipe systems under cyclic thermal loading. The results could be used to explain and predict axial loads experienced by buried DH pipes, and in turn, contribute to designing cost-effective and durable district heating pipe networks.

It has to be noted that the work presented herein represents early results from an ongoing investigation. More detailed and quantitative findings from further experimental work combined with analytical and numerical evaluations are required to understand this complex soil-pipe interaction problem.

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CLASSIFICATION AND TEMPORAL ANALYSIS OF DISTRICT HEATING LEAKAGES IN THERMAL IMAGES

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ABSTRACT

District heating pipes are known to degenerate with time and in some cities the pipes have been used for several decades. Due to bad insulation or cracks, energy or media leakages might appear. This paper presents a complete system for large-scale monitoring of district heating networks, including methods for detection, classification and temporal characterization of (potential) leakages. The system analyses thermal infrared images acquired by an aircraft-mounted camera, detecting the areas for which the pixel intensity is higher than normal. Unfortunately, the system also finds many false detections, i.e., warm areas that are not caused by media or energy leakages. Thus, in order to reduce the number of false detections we describe a machine learning method to classify the detections. The results, based on data from three district heating networks show that we can remove more than half of the false detections. Moreover, we also propose a method to characterize leakages over time, that is, repeating the image acquisition one or a few years later and indicate areas that suffer from an increased energy loss.

INTRODUCTION

Distribution of heat to homes and industries through district heating networks is today one of the most common heating sources in Swedish and Nordic cities. However, the pipes degenerate with time [3] and due to bad insulation or cracks, energy or media leakages might appear. Bad insulation can, for example, be caused by cracks in the outer protective shell, allowing water to enter the insulation layer thus significantly reducing the insulation effect. In addition to being expensive for the network owner, the loss of media or energy also has negative impact on the environment [4]. Therefore, it is of great interest to the owner to have efficient and reliable methods for leakage detection, especially when considering the fact that the pipes generally are placed underground, it is very expensive to dig in the wrong place. Moreover, major leakages of 50 m^3 media or more per day may also cause the ground to collapse due to erosion, whereby large amounts of media at boiling temperature are exposed.

This paper presents methods for detection, classification and temporal characterization of such leakages. We have used a commercially available system for large-scale airborne thermal image acquisition, acquiring data from several Nordic cities.

For *detection* of potential leakages, we use the method previously published by Friman et al. [1]. The method is used to analyse the acquired imagery, finding and indicating the areas for which the pixel intensity (temperature) is higher than normal. Apart from the sought-for media and energy leakages, there are several types of objects and phenomena that give rise to such detections. Examples are areas that, for some reason, are warmer than their surroundings, for example, chimneys, cars and heat leakages from buildings. In a large city, there might be several thousands of false detections.

Thus, we want to reduce these false detections as much as possible while maintaining the number of true detections at a fixed level (we use 99%). In order to achieve this goal, we follow a two-step *classification* procedure, as proposed in [2]:

1. Extract building locations from publically available geographic information, and remove all detections located on buildings.
2. Extract image features and use a machine learning method to classify detections as true (media/energy) or false detections.

Next, we propose a novel method for temporal characterization and visualization of the energy loss of the network. Long-term degradation of a pipe might not be detected as a single leakage, but by analysing larger areas and compare the radiated energy from two flights separated by one or a few years, such effects can be detected. The area covering the district heating network is divided into square cells and the comparison of energy loss is done for each cell individually.

Related work

Over the years, various methods for monitoring of district heating networks have been developed. For example, methods based on change in impedance or frequency response for a thread installed inside the insulation of the pipe. Another common method is to use liquid level switches. They measure the flow of media in the inlet and outlet and if the flow differs, the operator knows that there is a leakage somewhere along that section of the pipe. The major problem with the above described methods is that it may not be easy to localize the leakage based on the provided information. They detect the presence but not the exact location.

Methods for large-scale monitoring of district heating systems by aerial thermography (that is, using an aircraft equipped by a thermal camera), have been investigated by Ljungberg et al. in the 80's [3],[6],[7] and Axelsson [8]. The results are somewhat antiquated due to the drastic development of thermal cameras during the last two decades. Also, ground-based thermography has been investigated using hand-held cameras [9]. Compared to aerial thermography, this has several drawbacks, such as restricted access to many areas of interest and less scalability.

The first system with automatic image analysis was presented by Friman et al. [1]. The system uses anomaly detection in order to detect abnormally warm areas along the pipes. However, the problem is the large number of false detections. To reduce the number of false detections, buildings are segmented in order to avoid detections due to, e.g., chimneys when the pipes pass under buildings.

Berg and Ahlberg [2], used the detection from [1], proposed a new building segmentation method and reduced the number of false detections even more through classification.

Regarding temporal characterization of remote sensing data, the equivalent within the field is change detection. Change detection is a common usage of remote sensing data which has been extensively studied. Applications include various kinds of environmental monitoring (e.g., land use and land cover (LULC) change, deforestation and crop monitoring; see [10] for a review of such applications), urban change [11], and military target detection [12],[13]. The employed methods usually assume multispectral, sometimes even hyperspectral data, or SAR data [11]. Methods vary greatly, depending of the type of change to be detected, and they can be pixel-based [12]-[14] or object-based [15].

Contribution

The contribution of this paper is a system incorporating recent and novel advances in thermal monitoring of district heating networks:

1. The detection method invented by Friman et al. [1] and modified by Berg and Ahlberg [2].
2. The machine learning/classification method proposed in [2].
3. A previously unpublished method for temporal characterization and visualization of district heating network energy loss.

STATE OF THE ART

The state of the art of detecting district heating leakages by airborne thermography is represented by the method by Friman et al. [1] mentioned above, and we use that as a foundation of our work.

Regarding image-based classification of district heating leakages, the only attempt we are aware of is our previous work [2]. The state of the art of object classification in thermal imagery in is presumably represented by pedestrian detection in the automotive industry and target recognition in the defence industry, neither very eager to publish their latest methods. Object classification in general has, however, made significant progress the last decade, with a plethora of new image feature descriptors [18] as well as classification methods such as boosting methods [20] and random forests [21].

Regarding change detection, the state of the art is very application-dependent. While, for example, Theiler [14] compares different pixel-based methods and Blaschke [15] describes the state of the art of object based methods, neither solves our problem. Pixel-based methods find the pixels that have changed since the previous data acquisition in order to point out small targets or, e.g., a land cover attribute change. Object-based methods aim at pointing out that objects have been added to (or removed from) the scene. In our case, we are interested in pointing out an attribute change of one or more objects within a certain area, and the state of the art methods are, therefore, not directly applicable.

METHODS

The methods used in this work can be divided into four different categories. *Data acquisition*, *detection* of leakages in acquired data, reduction of false detections by *classification* and finally *temporal analysis* of energy loss. Each category is further described below.

Data acquisition

The thermal infrared images are captured from an aircraft in the night or at dawn to avoid the effect of sun heated objects and cars etc. blocking the view of the street. At this time of day, the ground and buildings will have adopted a homogeneous background temperature and people are not as actively using different kind of vehicles as they are during the day. Furthermore, there should preferably not be any foliage or snow blocking the thermal radiation from reaching the sensor. This provides two windows for data acquisition, one during spring and one during autumn.

During the acquisition, the position, velocity and angles of the aircraft are stored in order to facilitate georeferencing. Weather stations are also placed in the area for camera calibration.

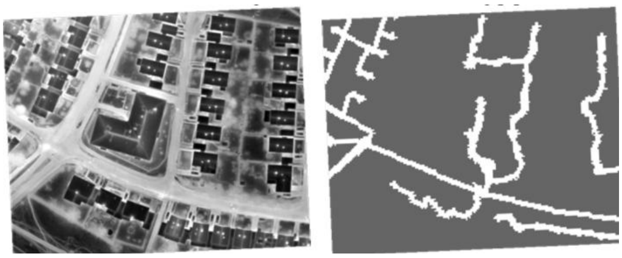

Fig. 1 Thermal image (left) together with its corresponding heat pipe mask (right). White areas within the mask represent the corridor around the network in which the detector will search for pixels with unnaturally high intensity values.

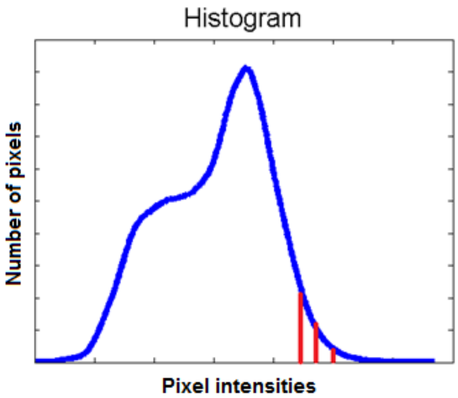

Fig. 2 Histogram of all pixel intensities within the heat pipe mask from one flight. The red, vertical lines illustrate how the histogram is thresholded in order to create several layers of detections.

The data used in this paper was acquired by a cooled mid-wave FLIR SC7000 Titanium with a resolution of 640x512 pixels and a field of view of 11°. At an altitude of 800 m, this yields a pixel footprint of 25x25cm.

The number of flights required in order to cover the whole area depends on the size of the area. For a medium-sized Swedish city, about three flights are needed.

Detection

Geographical information on where the heat pipes are buried is provided by the network owner. An assumption that can be made about the leakages is that they will only appear close to a pipe. Therefore, a binary mask is created to be used for detection of unnaturally warm areas. A binary mask corresponding to an image is an image with the same size as the original image and containing binary values (0 and 1) only. The 1's represent the interesting area within the original image, and the 0's represent the uninteresting parts of the image. In this case, the mask represents a corridor around the pipe network with width 2.5 meters. Within this corridor, the detector searches for unnaturally warm areas. In Fig. 1, a captured thermal image together with its heat pipe mask can be seen. Then, statistics of the radiated energy is calculated in the form of a histogram of all pixel intensity values within each heat pipe mask and flight, an example is given in Fig. 2. Since conditions may differ from one flight to another, the captured images from each flight are treated separately.

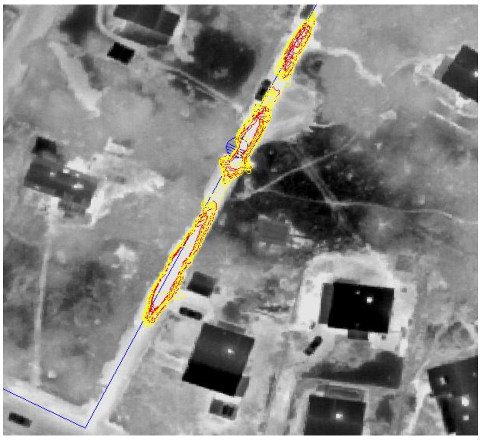

Fig. 3 Example of visualization of two layers of detections (red and yellow lines). The blue line is the district heating network.

The objective is to find areas within the mask that contain pixels with unnaturally high intensity values. This is achieved by finding the thresholds that generate the upper percentiles (0.95, 0.97, 0.99, 0.995, 0.999, and 0.9995) of the histogram. That is, we find the areas that correspond to the 5%, 3% and so on "warmest" pixels within the heat pipe mask and flight. Each percentile gives rise to a layer of detections, so that in total there are six different layers. It is worth noting that a detection is an extended object that has a shape and an intensity distribution, it is not only a point object.

When the detections are visualized to the operator, he or she can choose different colours for different layers. In Fig. 3, an example of the visualization is provided. The blue line is the district heating network and the red and yellow lines correspond to two different layers of detections where the yellow in this case is the more permissive one. Additionally, the detections are ranked based on the amount of radiated energy providing the operator with a ranking list of all detections.

Classification

Classification is the task of deciding to which of a set of predefined categories a new observation belongs. In this case, two categories, or classes, were used: True detections (both media and energy leakages) and false detections. The idea is to use classification to reduce the number of false detections presented to the operator.

Classification using building masks

The method for leakage detection described above finds a lot of areas that are unnaturally warm but not true leakages. There are plenty of such objects and phenomena present in a city. For example, ventilation

Fig. 4 An example of a building mask (right) created from a raster map (left). The white areas in the mask correspond to buildings in the map.

outlets, warm car engines, ground heating (to melt snow and ice) and energy leakages from buildings. Sometimes, the heat pipes pass beneath buildings, causing warm chimneys, ventilation outlets and atriums to appear as detections.

In order to minimize the number of false detections caused by objects on top of buildings, a building mask is created from raster map images made available by OpenStreetMap[1]. In these maps, buildings have a certain colour, a fact that can be used for thresholding based on colour and creating a binary mask. An example is given in Fig. 4.

The OpenStreetMap images are stored in GeoTIFF format which means that there is world coordinate information associated to each pixel. This fact facilitates image registration, i.e., the task of connecting pixels in the building masks to pixels in the thermal images.

Classification using a classifier

Classification using building masks removes some of the false detections, but far from all. Detections due to other things than buildings are still there. In order to reduce the amount even further, we have evaluated whether or not a classifier, specifically a supervised classifier, can be used for that purpose. We give an overview of the method here, and the details are published in [2].

A supervised classifier is trained by providing it labelled examples to learn from. The training can either be done offline (done once) or online (done continuously). In this work, only offline methods were considered. Part of the success of a supervised classifier is its ability to generalize, that is, draw general conclusions based on only a few observations.

The objects, detections in this case, which are to be categorized into different classes have to be described to the classifier somehow. Therefore, a feature vector is created for each detection. A *feature* is defined as "the specification of an attribute and its value" [16]. For example, a feature for a sample of the object human could be its height, shoe size or hair colour. A *feature vector* is simply a vector containing multiple features.

Table 1 Image features used for classification.

Feature	**Description**
Median intensity	Median intensity within the detection.
Standard deviation	Standard deviation of the intensity within the detection.
Coverage	Ratio of the detection area inside the heat pipe mask.
Elongatedness	$\frac{area}{4d^2}$, where d is the number of erosions [19] needed to make the detection disappear.
Concentricity	Measurement of how central the maximum intensity is within the detection.
Connected components	Number of other detections that lie within a certain radius from the detection.
Border average	Mean intensity within an area around the detection.
Distance to building	Distance from maximum intensity value to the wall of the closest building.

If N is the total number of features and the features are scalars, then the features form an N-dimensional feature space in which all feature vectors lie. The objective of the classifier is to, by observing labelled examples, find a decision boundary in this space. The decision boundary should then be used to correctly classify previously unseen observations. If the decision boundary is too complex, the classifier will not be able to generalize properly.

The "goodness" of 19 different scalar features were evaluated using the Mahalanobis distance [17] and a final set of 8 image features, provided in Table 1, was used for classifier evaluation. Several types of classifiers were evaluated as well, however, classifier evaluation is not covered here; only the best performing classifier used in the proposed system will be further described. See [2] for details.

The classifier used in the proposed system is the Random forest [21] classifier. Basically, it consists of a forest of decision trees. A decision tree is a hierarchal, decision structure composed of nodes and leaves. At each node, a binary test is made which leads either to another node or to a leaf, see example in Fig. 5. When reaching a leaf, the object is assigned the class label of that leaf. Which test to use in each node is decided when the tree is trained.

[1] http://www.openstreetmap.org

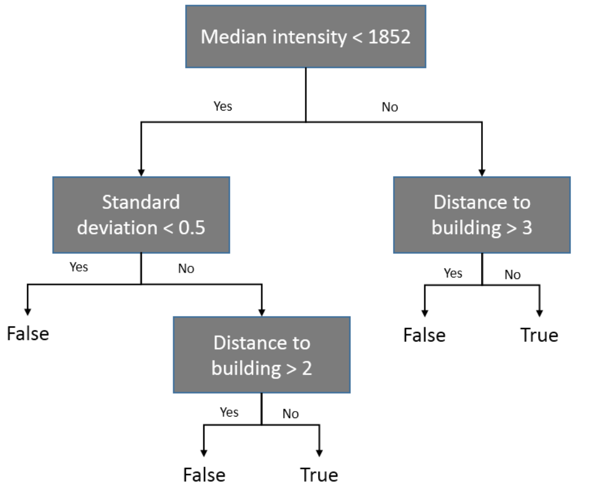

Fig. 5 Example of a decision tree. At each node, a binary test is made (the tests in this tree are examples) and at each leaf, the object is classified as true or false.

A Random forest classifier consists of multiple, random decision trees. Each tree votes on to which class the object belongs. The class assigned to the object is the class with the most votes. We use 120 trees with an average depth of 10 and splitting at nodes based on one randomly selected feature.

Temporal analysis

If the acquisition of thermal imagery covering a city is repeated one or a few years later, it is possible to compare the status of the network at the first acquisition with the status at the second acquisition. An automatic comparison method and a visualization technique have been developed for this purpose.

First, a grid consisting of cells, size 50×50 m, is created for the covered area, see Fig. 6. The grid has M rows and N columns (depending on the size of the area). For each acquisition a and cell (m,n), a total radiated power, $P^a_{m,n}$, is calculated ($a = 1,2$; $m = 1,2,\dots,M$ and $n = 1,2,\dots,N$).

Since we know the temperature at the ground, we can compute the radiated power for each detection. For this purpose, Stefan-Boltzmann's law

$$\frac{dQ}{dt} = \varepsilon\sigma(T^4 - T_0^4)A \qquad (1)$$

is used. $\sigma = 5.67 \cdot 10^{-8}\,\mathrm{W\,m^{-2}K^{-4}}$ is the Stefan-Boltzmann constant, A is the area, and ε is the emissivity of the object which in this case mainly consists of ground in different forms. Soil, grass and asphalt typically have an emissivity around 0.92. T is the mean temperature of all pixels within the detection. T_0 represents the background temperature and is estimated as the mean temperature of all pixels within the current heat pipe mask and flight.

The total radiated power (TRP) of cell (m,n) and acquisition a, $P^a_{m,n}$, is calculated as in Eq. (2). For each

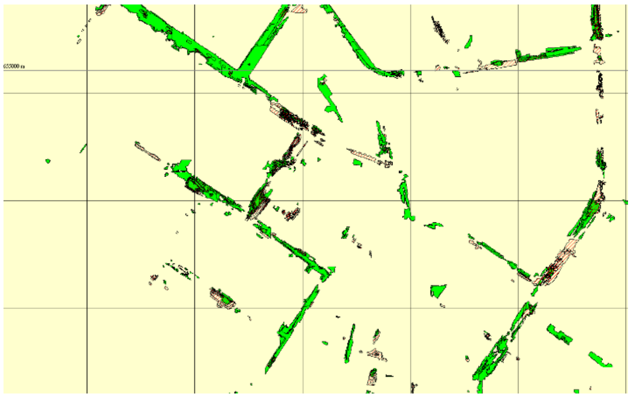

Fig. 6 A part of the grid covering the area. The detections from the old acquisition campaign are marked with red, dashed lines and the new detections are green and filled.

layer, the sum of the radiated power of all detections that have their centroids in cell (m,n) is computed. The TRP of a cell is then defined as the mean of this sum over layers, i.e.,

$$P^a_{m,n} = \frac{\sum_l \sum_k \varepsilon\sigma(T_k^4 - T_0^4)A_k}{L}. \qquad (2)$$

$k \in S_{m,n,l,a}$ where $S_{m,n,l,a}$ is the set of detections in acquisition a and layer l that have their centroids inside the boundaries of cell (m,n). Finally, $l = 1,2,\dots,L$ is the layer and, as mentioned above, the total number of layers in this case is $L = 6$.

The difference of radiated power, $\Delta_{m,n}$, for each cell represents the change in radiated power from the previous acquisition until the current one. It is calculated as the difference of TRP's for the two acquisitions $\Delta_{m,n} = P^1_{m,n} - P^2_{m,n}$.

When the comparison results are visualized to the operator, each cell is colored according to its calculated TRP difference, $\Delta_{m,n}$, and the grid is overlaid on top of a mosaic of the thermal images, see Fig. 7. Red indicates an increase in radiated power and green indicates a decrease. Transparency is used to visualize the degree of change. The cells with the largest increase/decrease are assigned zero transparency and the cells with lowest full transparency. The transparency scale is then linearly distributed for all cells with TRP differences in between. If there is no change at all, i.e. $\Delta_{m,n} = 0$, the cell will be colorless.

Evaluation methodology

As mentioned in the description of supervised classifiers above, the methods need labelled examples, or ground truth samples, for training. That is, information on which detections that have proven to be true and false respectively. The system, as described in [1], has been used in over 20 different Nordic district heating networks in recent years, and three of these were chosen for sample collection. These networks were chosen based on their ability to provide ground

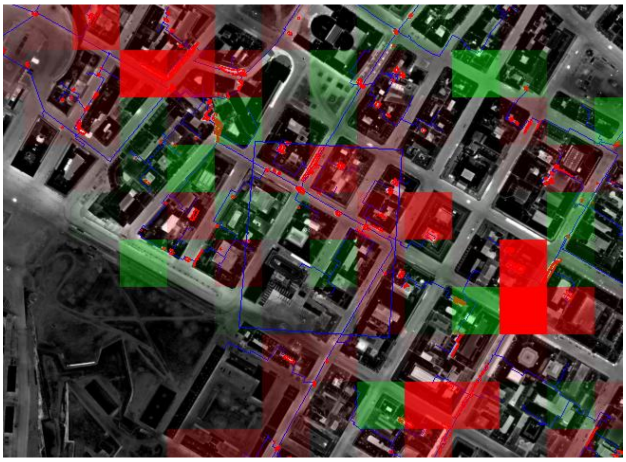

Fig. 7 Visualization of changes in radiated power. A red square indicates that the area suffers from an increased energy loss while a green square means that the energy loss within the area has decreased.

Table 2 Number of ground truth samples for each layer and class.

Layer no.	**1**	**2**	**3**	**4**	**5**	**6**
Threshold	0.05%	0.1%	0.5%	1%	3%	5%
True	34	39	71	89	99	80
False	71	75	148	237	294	348

truth samples. The distribution of samples can be seen in Table 2. In order to evaluate the generalization ability of the classifier, a method called 10-fold cross validation [20] was used. The samples are split into 10 different folds. Then, the classifier is trained 10 times, each time using 9 different folds and validated using the 10th. In order to achieve reliable evaluation results, the validation data has to be previously unseen by the classifier.

The confusion matrix [16], Fig. 8, is a common way to describe the different kinds of errors that appear when performing classification. We want to minimize the false positive rate while maintaining a true positive rate of 99%. The limit of 99% comes from the fact that the cost of misclassifying a true detection is much higher than misclassifying a false one.

RESULTS

Classification

19% of the false alarms could be removed solely with the use of building masks. In Fig. 9, an example of a false detection that has been removed with the help of the building based segmentation is provided. The false positive rate of the Random forest classifier combined with the building segmentation based classification is 42% when samples from all layers were combined into one dataset. That is, 58% of the false detections can be removed while maintaining a true positive rate of

		Predicted	
		True detection	**False detection**
Actual	**True detection**	True positives (true detections correctly classified)	False negatives (True detections that were incorrectly classified as false)
	False detection	False positives (false detections that were incorrectly classified as true)	True negatives (False detections correctly classified)

Fig. 8 A confusion matrix, a common way to visualize the performance of a supervised classification method.

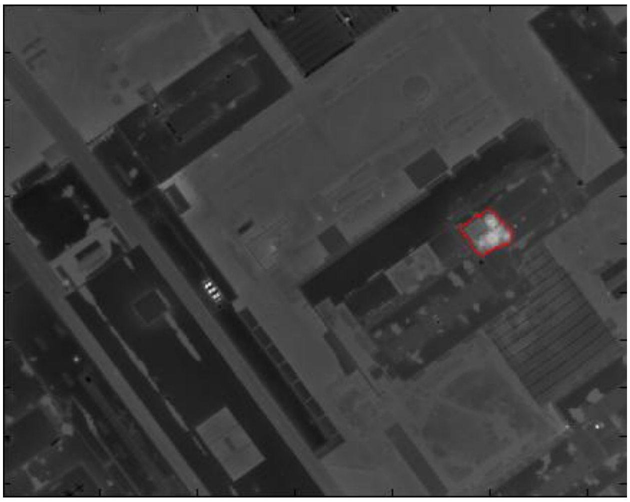

Fig. 9 Example of a false detection (marked with red boundaries) that has been removed with the help of a building mask.

		Predicted	
		True detection	**False detection**
Actual	**True detection**	True positives: 408	False negatives: 4
	False detection	False positives: 493	True negatives: 680

Fig. 10 The confusion matrix containing the final results.

99%. The confusion matrix from Fig. 8 has in Fig. 10 been filled out as an illustration of the final results. In a typical medium-sized Swedish city, there are typically around 3000 detections in the 0.995 percentile layer. Among these 3000, only about 10 are true media leakages. Thus, being able to reduce the number of false detections with 58% greatly reduces the workload for the operator.

Temporal analysis

The temporal analysis had, at the time of writing, been used in the described form in one city. Unfortunately,

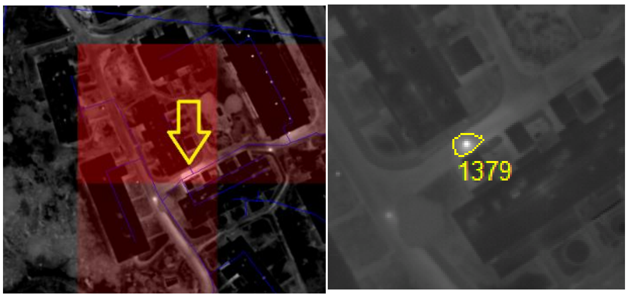

Fig. 11 A cell (left) that has been marked as suffering from an increased energy loss that proved to contain a true media leakage (right). The yellow arrow indicates the position of the leakage within the cell and the yellow number is the ID of the detection.

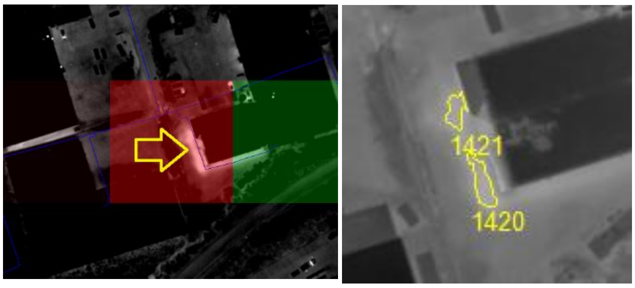

Fig. 12 Another example of a cell (left) that has been marked as suffering from an increased energy loss that proved to contain a true media leakage (right). The yellow arrow indicates the position of the leakage within the cell and the yellow number is the ID of the detection.

that city was not one of the three for which ground truth samples for classifier evaluation had been collected. However, some confirmed leakages have been provided by the network owner allowing us to draw some conclusions about the result. In Fig. 11 and Fig. 12, examples are shown of how the visualization of the comparison clearly indicates cells containing confirmed media leakages as suffering from an increased energy loss.

One particularly interesting example where the comparison acts as a complement to detection ranking based on radiated power is presented in Fig. 13. Here, a major media leakage of 70 m^3/day gave rise to some headaches for the network owner who had searched unsuccessfully for the leakage for several years. The district heating pipe laid on top of a bed of gravel and beneath the said pipe was a larger stormwater pipe along which all media from the district heating pipe ran. Due to this choice of path by the media, the temperature difference that could be measured at ground level was only 3°C, placing the detection far down the detection ranking list. Nevertheless, the change in radiated power since the last acquisition was noticeable and in the visualization the cell containing the detection was marked in red.

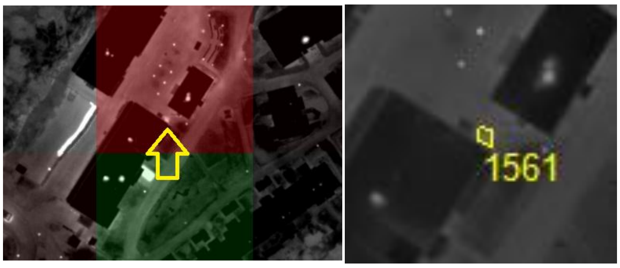

Fig. 13 Example of major leakage made visible by the comparison acting as a complement to detection ranking based on radiated power.

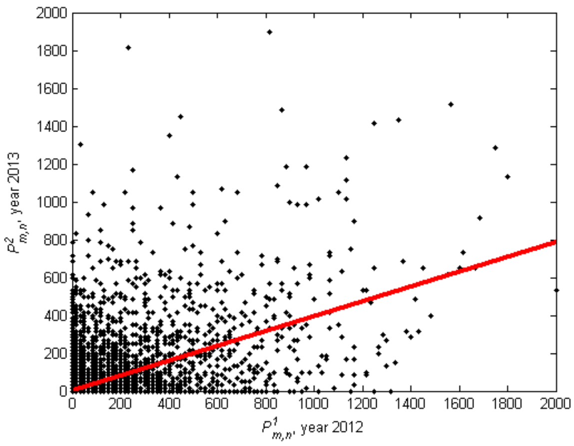

Fig. 14 Scatter plot of the TRP's for each cell (black dots). The red line is a line that has been fitted to the points. It indicates whether or not the overall energy loss of the network has decreased or increased.

In order to make an assessment of the overall status of the network at the current versus the previous acquisition, a scatter plot as the one in Fig. 14, can be used. Each scatter point corresponds to one cell and each cell has two TRP's, $P^1_{m,n}$ and $P^2_{m,n}$, here the x- and y-axis respectively. A red line has been fitted to the points through a least squares fit. If the energy loss has not changed, the angle α between the line and the x-axis is 45°. A smaller α, as in Fig. 14, indicates that in general, there has been a decrease in energy loss. In fact, this conclusion coincided with the network owner's feeling about the network's status.

DISCUSSION

Classification

With the use of the building segmentation based classification, 19% of the false detections could be removed. There could, however, be a bias present among the ground truth samples since false detections on top of buildings are easier to find than other kind of false detections and thus a larger percentage of such false detections might have been labelled. If so, the false detection reduction rate, in reality, is lower than 19%. However, this has not been further investigated. Also, the number of detections on top of buildings varies between different cities depending on how much pipes that actually pass beneath buildings.

Furthermore, in the maps generated by OpenStreetMap it has been observed that there sometimes are missing buildings. The opposite error, buildings present in the map but not in reality, has not been observed. Missing buildings is a kind of error that in this case is quite forgiving, since it only leads to false positives, i.e., false detections incorrectly classified as true ones. The opposite, "false" buildings, could result in true detections being classified as false ones (false negatives), which is an unwanted scenario since the cost for false negatives is much higher than for false positives.

Temporal analysis

Regarding temporal analysis, it should be emphasized that the presented method for temporal analysis is an approximation. It provides a measurement of the radiated power at ground level, but how the heat transfers from the pipe through the soil remains unexplored. It is, however, clear that the properties of the pipe, material, depth, insulation etc., and the soil composition affects how much radiated power that reaches the ground surface.

The presented visualization technique with red and green squares gives the operator a quick overview of the status of the network. He or she can soon pinpoint the most critical areas.

OUTLOOK

We will continue the work on improving false detection reduction, temporal analysis and quantization of energy loss with the goal of providing the operator with an even more accurate tool for large-scale monitoring of district heating networks.

CONCLUSIONS

In this paper, a complete system for large-scale monitoring of district heating networks has been presented. Methods for media/energy leakage detection in thermal images and reduction of false detections through classification have been described and a method for temporal analysis of energy losses has been proposed.

The system allows the operator to get a quick overview of the status of the complete network and can be used as a complementing tool for maintenance planning.

The proposed temporal analysis improves usability of the system and the visualization allows the operator to get a quick overview of what areas that should be studied more carefully.

ACKNOWLEDGEMENT

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EVALUATION OF VACUUM INSULATION PANELS USED IN HYBRID INSULATION DISTRICT HEATING PIPES

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ABSTRACT

It is of interest to lower the energy losses from district heating pipes both for economic and environmental reasons. This paper evaluates a hybrid insulation solution where Vacuum Insulation Panels (VIP) are put around the supply pipe in a district heating pipe and the rest of the casing pipe is filled with polyurethane foam (PUR).

The apparatus for the "guarded hot pipe" method was used to estimate the thermal properties of single pipes, which have been used as input in finite element models for simulation of twin pipes in field. The simulations indicate a total reduction in the energy loss between 18% and 32% compared to pipes of the same size with pure PUR insulation. Furthermore, the losses from the supply pipe decrease by up to 56%.

To achieve the low energy losses, the vacuum in the panels has to be preserved over the life span of the VIP. In field measurements, a hybrid pipe prototype was connected to the district heating grid in Varberg (southwest Sweden). After almost two years, the pipe is still working without any detectable deterioration of the insulation performance. The panels have also been tested at high temperatures in laboratory with promising results.

INTRODUCTION/PURPOSE

In 2012, 57% of the energy consumption in Swedish buildings was distributed by district heating [1].Some of the energy, fed into a district heating network is lost due to heat transfer from the heated water to the surrounding. For a sparser district heating grid or a grid with lower energy outtake, the energy losses in the distribution will be a proportionally larger part of the input energy.

As a part of the research program "Värmegles", environmental impact of district heating in sparse Swedish neighbourhoods were evaluated [2]. One of the conclusions was that it is very important for the environmental performance of sparse district heating networks with a district heating system with small heat losses.

The purpose of this work is to evaluate the possibilities to reduce the thermal losses from district heating pipes by the use of vacuum insulation panels. The presented work focus on a hybrid pipe concept where vacuum insulation panels are used together with polyurethane foam, as shown in Fig. 1. The concept is based on a conventional pipe type where polyurethane foam fills the cavity between a steel service pipe and a polyethylene casing pipe.

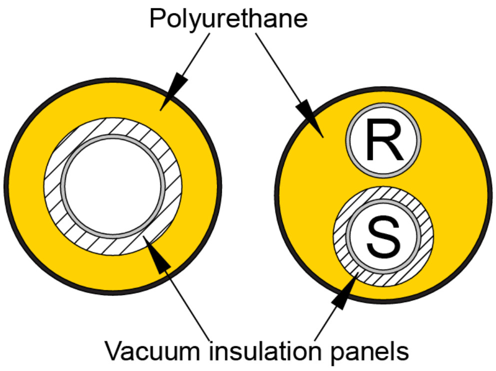

Fig. 1 Description of the hybrid insulation pipe concept. S stands for supply pipe and R stands for return pipel.

STATE OF THE ART

The work with hybrid insulated district heating pipes started investigating a variation of concepts for high thermal performance district heating pipes [3]–[5]. The project finished with the hybrid insulation concept where a vacuum insulation panel was used as high performance insulation close to the hot pipe. A prototype was created and installed in field for measurements and an initial estimation of the payback time was 12 years [4].

The work continued in a new project focusing on hybrid insulation concept with vacuum insulation panels showing the progression of laboratory measurements and field measurements [6]. This paper reports this continuation and an up to date presentation of the latest results for the laboratory measurements, the numerical simulations and the field measurements.

The fundamental idea of the concept, shown in Fig. 1, is that, in a cylindrical geometry, the effect of the insulation is closely related to how close it is to the centre of the cylinder. This means that a high performance insulation close to the centre can have a large impact on the heat flow out from the pipe. The thermal conductivity of polyurethane foam, presented by district heating pipe producers range from 23 mW/(m·K) to 27 mW/(m·K) dependent on the production method [7]–[9]. These values can be compared to measurements on vacuum insulation panels where the thermal conductivity in the centre of the panel range in between 2.5 mW/(m·K) for glass fibre and 7 mW/(m·K) for polyurethane foam for pressures below 0.1 mbar[10]. Commonly for long life span applications, nano-porous materials like fumed silica is used since the thermal conductivity of the material is reduced already at higher pressures. Measurements have shown a centre of panel conductivity below 5 mW/(m·K) already at pressures below 10 mbar and still below 8 at pressures around 100 mbar [10].

To obtain the vacuum in the vacuum insulation panels, the core material is enveloped by a diffusion barrier. The diffusion barrier is commonly a metalized polymer laminate. Thin layers of aluminium are alternating layers of some organic polymer. This leads to a high thermal conductance along the surface and through the edges of the panels. Consequently, this creates an optimization conflict since more aluminium in the diffusion barrier prolong the life span of the panel but at the same time it increases the thermal transport in the edges of the panel [10].

The use of vacuum insulation for high temperature applications has also been suggested for the use in heat storage where the ratio between the insulation volume and the thermal storage volume can be of importance, especially for small storage tanks where the surface to volume ratio is large [11]. No tests on the long time performance was presented.

METHODS/METHODOLOGY

The work can be separated into three main parts; laboratory measurements of thermal performance, numerical simulations of heat transfer and field measurements on prototype pipes connected to an active district heating network.

Laboratory measurements

In the laboratory, an apparent thermal conductivity of the hybrid pipes has been measured with the methodology from EN 253 using a "guarded hot pipe" apparatus [12]. The standard method gives the conductivity for a homogenous insulation material in the pipes. To obtain the apparent thermal conductivity of the vacuum panel, the insulating effect of the polyurethane have been back calculated from the performance of the whole pipe according to Eq (1) based on the equation for a 1 dimensional axi-symmetrical heat flow [13].

$$\lambda_{app.VIP} = \frac{Q \cdot \lambda_{PUR} \cdot \ln(r_2/r_1)}{\lambda_{PUR} \cdot 2\pi \cdot (T_3 - T_1) - Q \cdot \ln(r_3/r_2)} \qquad (1)$$

where Q is the power input to the pipe in the "guarded hot pipe" apparatus (W/m). λ_{appVIP} and λ_{PUR} are the apparent thermal conductivity of the vacuum insulation panels and the thermal conductivity of polyurethane foam obtained from measurements on a reference pipe produced with the same foam at the same time as the test pipe (W/(m·K)). The terms r_1, r_2 and r_3 are the outer radius of the steel pipe, the outer radius of the vacuum insulation panel and the outer radius of the polyurethane foam insulation (m). The terms T1 and T3 are the temperatures at the inner and outer surfaces of the test pipe (°C). The terms are also described in the pipe section in Fig. 2.

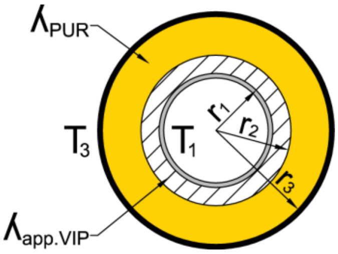

Fig. 2 Description of input for calculation of apparent thermal conductivity.

The resulting total conductivity for the hybrid pipe, from the "guarded hot pipe" measurements, can also be seen as indication of the energy loss. The results can be compared to polyurethane but the thermal conductivity is only representative for hybrid pipes with the same dimensions and material proportions.

The high temperature performance of the vacuum panels has been tested by heating some panels in an oven and continuously measuring their internal pressure with a measurement device supplied by the panel producer. The panels have been held in an oven at a constant temperature of 70°C for almost a year.

The results from "guarded hot pipe" can be seen in Fig. 8 and the results from the high temperature performance measurements can be seen in Fig. 16 in the results chapter.

Numerical simulations in Comsol

Numerical simulations on thermal performance were made in the finite element software Comsol 4.3b [14]. The pipes were modelled in 2 dimensions assuming the flows along the pipe to be small because of symmetry. Two cases were modelled; a model of a single hybrid pipe in a laboratory setting comparable to "guarded hot pipe" measurements and a model of a twin pipe in field.

The results from the simulations of the single pipe in the laboratory were used to estimate the properties of the vacuum insulation panels in more detail. The vacuum insulation panels introduce an extra complexity to the pipe section geometry through the high thermal conduction in the diffusion tight envelope of the panels, shown as a dashed line in Fig. 3. To separate the heat conduction through the envelope from the heat conduction in the core of the vacuum insulation panels, a simulation model was created with the boundary conditions shown to the right image of Fig. 3 described in Table 1.

The thermal conduction through the envelope was simulated by using the results from the “guarded hot pipe” measurements of the hybrid pipes. The thermal conductivity of the core of the vacuum insulation panel was obtained from the panel producer and the thermal conductivity of the polyurethane foam was taken from measurements on reference pipes. The properties of the envelope were adjusted until the heat losses in the simulations corresponded to the heat losses from the “guarded hot pipe” measurements.

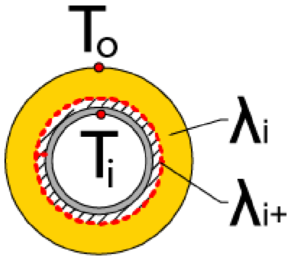

Fig. 3 The image describes the material input and boundary conditions for the finite element model of single pipes in the laboratory. The thick dashed line show the thermal bridge in the diffusion tight envelope surrounding the vacuum insulation panels.

Table 1 Description of materials and boundary conditions for simulations of single pipes in laboratory.

	Description	Set value
λ_i	Thermal conductivity of polyurethane.	from reference
λ_{i+}	Thermal conductivity in VIP core.	4.5 W/(m·K)[1]
T_i	Temperature on the inner surface of the steel pipe.	~ 80°C
T_o	Temperature on the outer surface of the casing pipe.	21°C

[1]From the producer of the vacuum insulation panel.

The simulation of twin pipes in ground was used to estimate the reduction in heat losses from replacing polyurethane foam with vacuum insulation panels for a twin pipe in field. The input data and boundary conditions are explained in Fig. 4 and Table 2.

In the twin pipe, the thermal bridge along the vacuum insulation panel disturbs the symmetry. One point of interest for implementation of the hybrid pipes is the effect of an overlap of the panel to reduce the heat flow through the thermal bridge by increasing its length. This was modelled in the twin pipe model as described in Fig. 5 which also show the definition of the thermal bridge length.

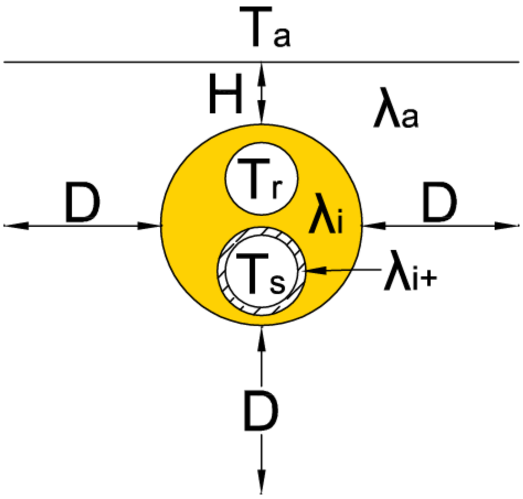

Fig. 4 Description of the boundary conditions material properties in the finite element model of twin pipes in the ground.

Table 2 Description of materials and boundary conditions for simulations of twin pipes in ground.

	Description	Set value
λ_i	Thermal conductivity of polyurethane	26 mW/(m·K)
λ_{i+}	Thermal conductivity of VIP	varies
λ_a	Thermal conductivity in ground	1.5 W/(m·K)
T_s	Supply water temperature	85°C
T_r	Return water temperature	55°C
T_a	Ambient temperature	5°C
D	Domain size	16 m
H	Burying depth	0.8 m

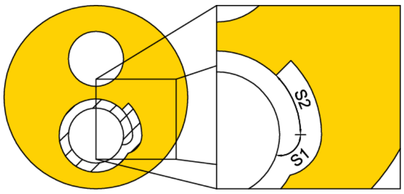

Fig. 5 The definition of overlap length used in some of the simulations. The thermal bridge length is defined as the sum of the distances S1 and S2.

The results of the simulations are shown in Fig. 9 to Fig. 12 in the results chapter.

Field measurements

In field, two hybrid insulation pipes have been connected to the district heating network in Varberg, a city on the southwest cost of Sweden. The district heating network is a low temperature network with maximum temperature in the supply pipe below 90°C.

In the pipes, thermocouples have been embedded into the polyurethane foam and measure the temperature at various positions in the pipe section. The temperatures have been measured every second hour since instalment in January 2012.

The first pipe of the two pipes has the dimensions DN 2*80/250 and the placements of the thermocouples are shown in Fig. 6. The second pipe has the dimensions DN 2*25/140 and the placement of the thermocouples are shown in Fig. 7.

The data from the field measurements have been analysed to get an estimate of the long time performance of the hybrid pipes.

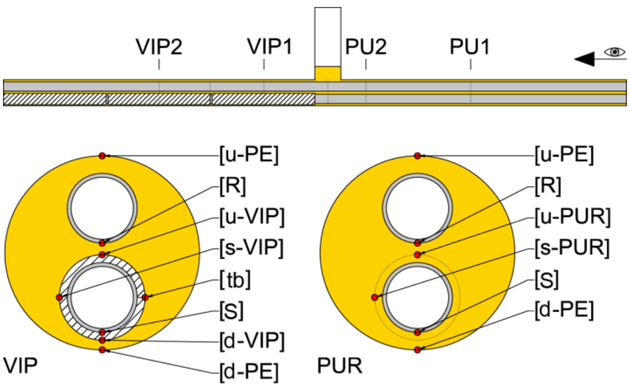

Fig. 6 Thermocouple placement for the DN 2*80/250 field measurement pipe. The uppercase S and R represent supply and return. The lowercase u, s and d represent the orientations up, side and down. VIP, PUR and PE represent the outside of the vacuum insulation panel, corresponding position in the Polyurethane foam and measurements on the polyethylene casing pipe. The term tb represents the thermal bridge along the panel.

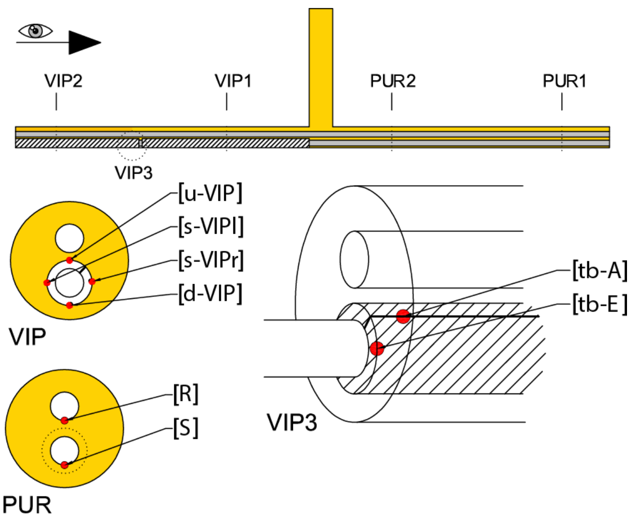

Fig. 7 Thermocouple placement for the DN 2*25/140 field measurement pipe. The uppercase S and R represent supply and return. The lowercase u, s and d represents the orientation up, side and down. VIP outside of the vacuum insulation panel and PUR represent a reference part of the pipe with only polyurethane foam. The terms tb-A and tb-E represents the thermal bridges along the panel and at the panel edge.

The results from the field measurements are shown in Fig. 13 to Fig. 15 in the results chapter.

RESULTS

The results can be divided into two main parts; first an analysis of the thermal performance of the hybrid pipes and how they compare to regular polyurethane foam pipes and secondly an analysis of the durability of vacuum panels under district heating temperatures.

The results from the “guarded hot pipe” measurements are shown in Fig. 8. For measurement number 1 in Fig. 8, two vacuum panels with a length of 0,5 m were used in opposite to 1 m long panels which were used in all the other measurements.

For measurements number 2-5 in Fig. 8, the panels were the same as those used in the field measurements. It is important to point out high apparent conductivities of measurement number 2 and number 5. For these two measurements, the vacuum insulation panels have probably collapsed and have become air filled. This illustrates a measurement problem where there is a difficulty ensure the correct location of the panels in the measurement pipes, creating a risk of perforating the panels during sample preparation. It is although important to see that the apparent thermal conductivity of the vacuum insulation panels are in the same order of magnitude as the polyurethane foam, even if they are air filled.

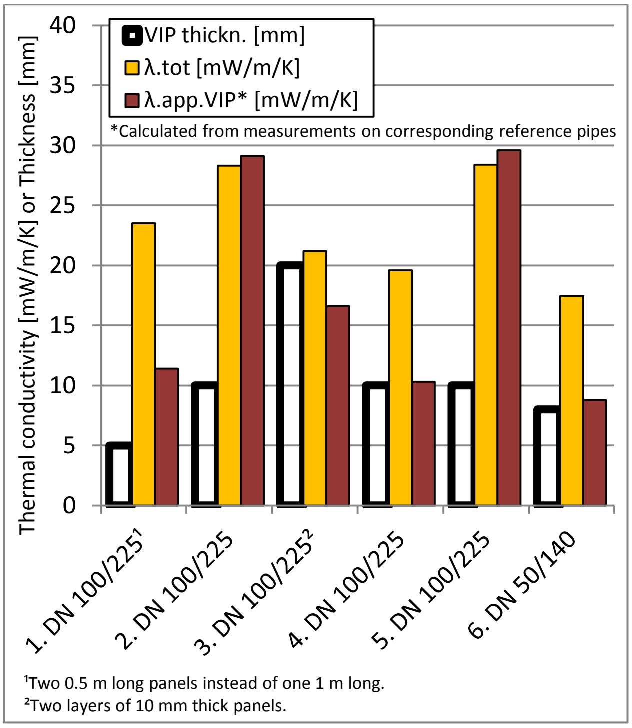

Fig. 8 Results from “guarded hot pipe” measurements of hybrid pipes. The figure shows the vacuum insulation panel thickness, the total thermal conductivity calculated according to EN 253:2009 and the effective conductivity of the vacuum insulation panels.

For measurement number 3 in Fig. 8, two layers of 10 mm thick vacuum insulation panels were used. The high apparent thermal conductivity indicates that one of the panels might be damaged.

The last measurement, number 6 in Fig. 8, is made for a pipe with a new improved type of vacuum insulation panel. That is why the measurements on pipe 6 have been used for the further analysis of the hybrid pipes.

The measured data from "guarded hot pipe" measurement number 6 in Fig. 8 was used as input data in the single pipe in laboratory model. The simulations gave an estimated thermal conductivity of 14.3 W/(m·K) for the envelope assuming an envelope thickness of 0.1 mm. This data was used in the twin pipe model to evaluate the effect of the overlap.

Pipes with a number of different dimensions between DN25 and DN 150 and a 8 mm thick vacuum insulation panel around the supply pipe were simulated in the twin pipe in field model. For each dimension three lengths on the overlap was modelled; 2 cm, 4 cm and 6 cm. A reference value for the pipes was also modelled, without the vacuum insulation and polyurethane foam in its place.

The results from the simulations are shown in Fig. 9 as the total energy loss from the pipe and in Fig. 10 as the reduction in energy loss compared a conventional pipe with polyurethane foam insulation. The results show a reduction of between 15% and 30% in the heat loss due to the addition of vacuum insulation panels.

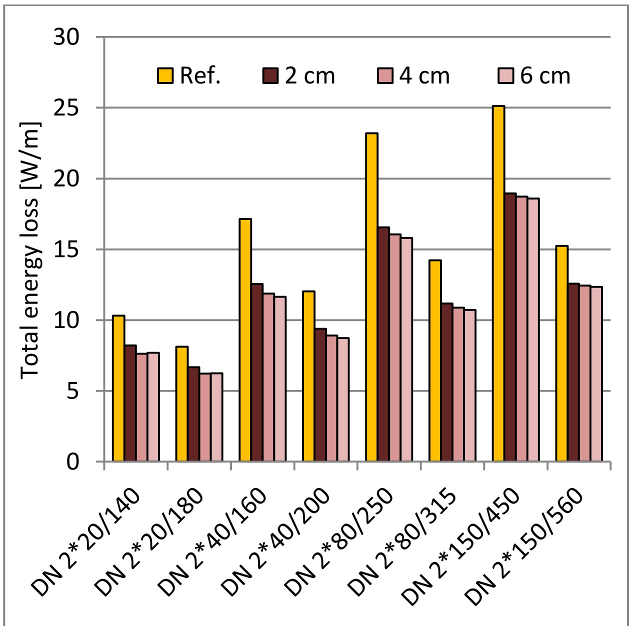

Fig. 9 Simulated total energy loss from twin pipes of different dimensions with a 8 mm vacuum insulation panel mounted around the supply pipe. The different colours represent different overlap in the vacuum insulation panel.

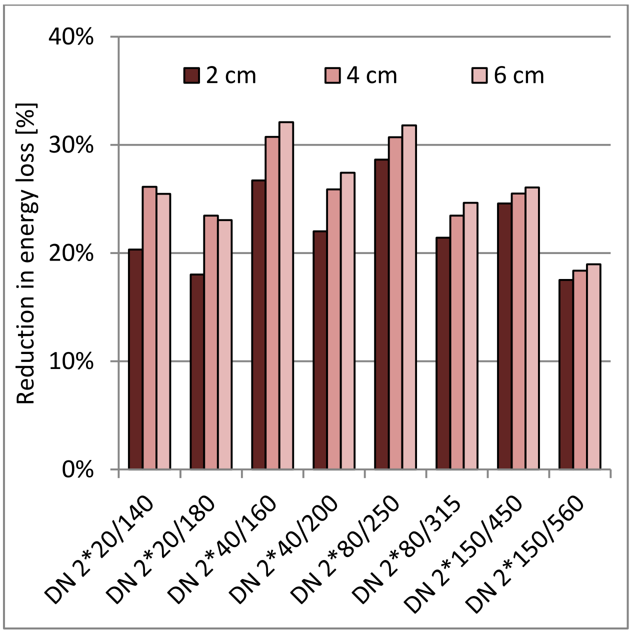

Fig. 10 The reduction in total energy losses when simulated results for hybrid pipes are compared to the result for a reference pipe with only polyurethane foam. The pipes are twin pipes of different dimensions with a 8 mm vacuum insulation panel mounted around the supply pipe.

In Fig. 10 it can be seen that for the small dimensions, the total energy loss increase for an overlap of 6 cm compared to a 4 cm overlap. This is due to a lower temperature where the thermal bridge reaches the polyurethane in the 4 cm case. While a longer overlap always decrease the loss from the supply pipe, the return pipe losses increases which makes the effect on the total loss complicated to predict.

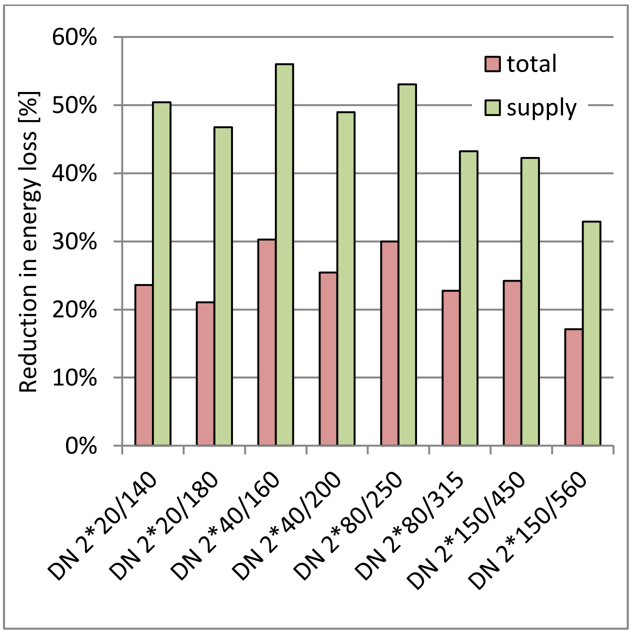

Fig. 11 A comparison between total losses and supply flow losses for twin pipes with a 8 mm thick vacuum insulation panel around the supply pipe.

The difference between the losses from the supply and the return pipes are shown in Fig. 11 for pipes with a 2 cm overlap. The results show that the reduction in heat losses from the supply pipe is almost twice the reduction of the total heat loss from both the supply and return pipes.

As the insulation effect is a combination of material properties and material thickness, the simulation results were compared to the results from simulations of conventional polyurethane pipes where the diameter was changed until it achieved the same thermal performance. The resulting diameters are shown in Fig. 12, which shows that a large reduction in size can be achieved, especially for small pipe dimensions. This would mean that less ground have to be removed for the pipe trenches and it would also make it easier to install the pipes in narrow areas as in central parts of a city.

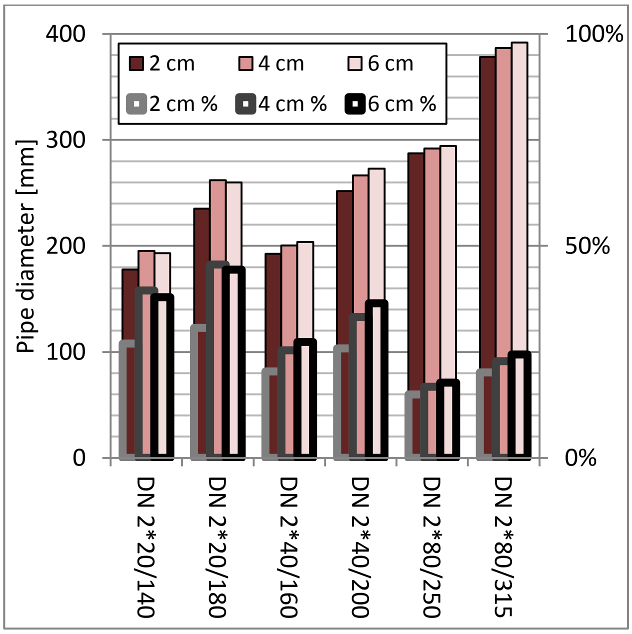

Fig. 12 The diameter for the polyurethane pipe, required to achieve the same thermal performance as the hybrid pipes. The results are shown both as absolute value and as relative values.

The temperature measurements from the field, are shown in Fig. 13 and Fig. 14 for the dimension DN 2*80/250, and in Fig. 15 for the dimension 2*25/140. All shown temperatures are the weekly mean temperature averaged from two or three measurement points at each position.

In Fig. 13, the temperature on the outside of the vacuum panels are shown together with corresponding positions in the reference part of the pipe, with only polyurethane foam, and the supply and return temperatures of the heat carrier. The temperature on the vacuum insulation panel (u-VIP and s-VIP) is significantly lower than the reference temperatures (u-PUR and s-PUR) which shows that the heat loss are smaller for this part of the pipe although the losses cannot be quantified from the temperatures.

A similar result can be seen in Fig. 14 where the temperature on the side of the vacuum insulation panel (s-VIP) is shown together with the temperature measured on the thermal bridge along the vacuum insulation panel (tba) and the reference measurement (s-PUR). The temperature in the thermal bridge is higher than the temperature on the middle of the panel, which is expected, but the temperature is lower than the reference temperature. This indicates that the vacuum insulation panel insulate better than the polyurethane foam even in its weakest spot, the thermal bridge.

For both pipe dimensions, DN 2*80/250 shown in Fig. 13 and DN 2*25/140 shown in Fig. 15, the temperatures on the vacuum panels (u-VIP s-VIP and d-VIP) seem to follow the variation in the temperatures of the supply and return pipes (S and R).There is no unique jump in temperature which would indicate damage in a panel. Over the time frame of the measurements, there is so far no visible slow increment in the temperatures from the diffusion of air through the envelope of the panels. This is a positive result for the vacuum insulation panels as the life span have been one of the main questions.

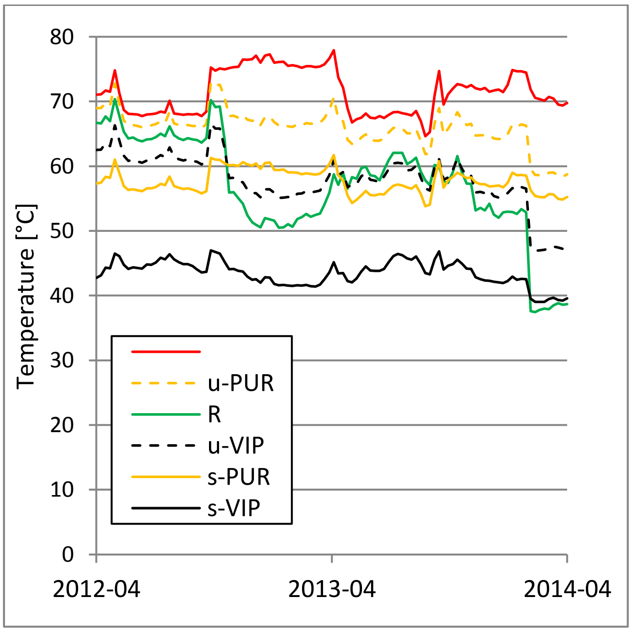

Fig. 13 Temperature measurements from the field measurements on the pipe with dimensions DN 2*80/250. The figure shows the temperature on the outside of the vacuum insulation panels together with the temperatures on corresponding positions in the polyurethane foam and the return and supply water temperatures.

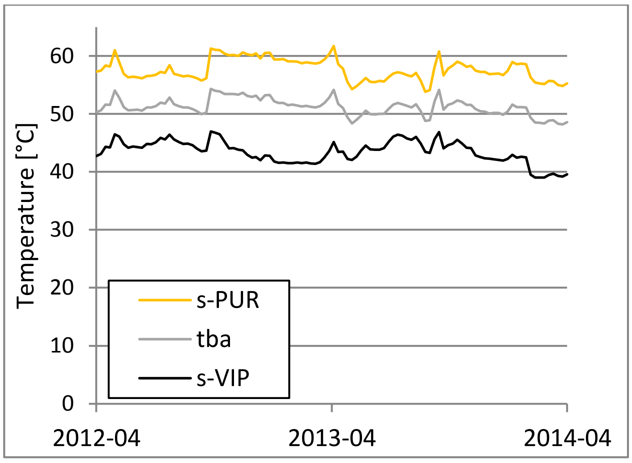

Fig. 14 Temperature measurements on the field measurements pipe with dimensions DN 2*80/250. The figure shows the temperature on the side of the vacuum insulation panels together with corresponding position in the polyurethane foam and the temperature at the position of the thermal bridge along the vacuum insulation panel.

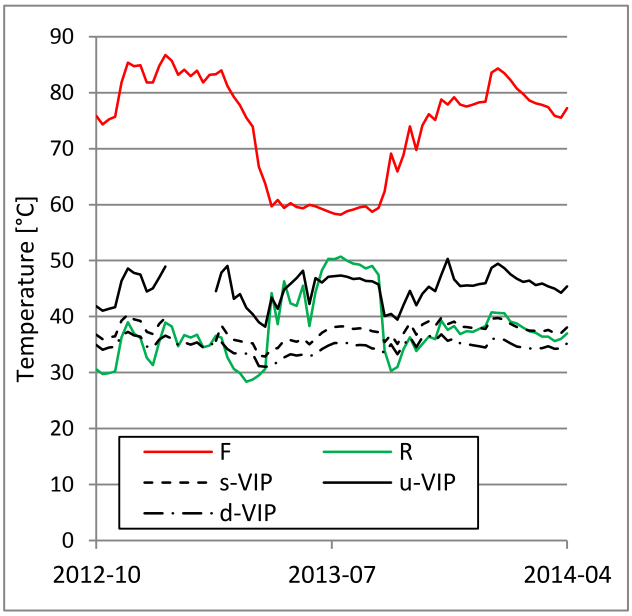

Fig. 15 Temperature measurements from the field measurements on the pipe with dimensions DN 2*25/140. The figure shows the temperature on the outside of the vacuum insulation panels together with the return and supply water temperatures.

The durability was also tested with the panels put in an oven at 70°C. The results are shown in Fig. 16. Under almost a year, the pressure have increased in average around 1,5 mbar. Panel D collapsed after 119 days. This is although contradicted by the field measurements where all panels have survived with no visible deterioration in the panels. This is an indication that the protected position in the polyurethane foam increases the vacuum insulation panel's life time. Also, in a pipe, the high temperature load will only affect one side of the panel. In the oven both sides were affected.

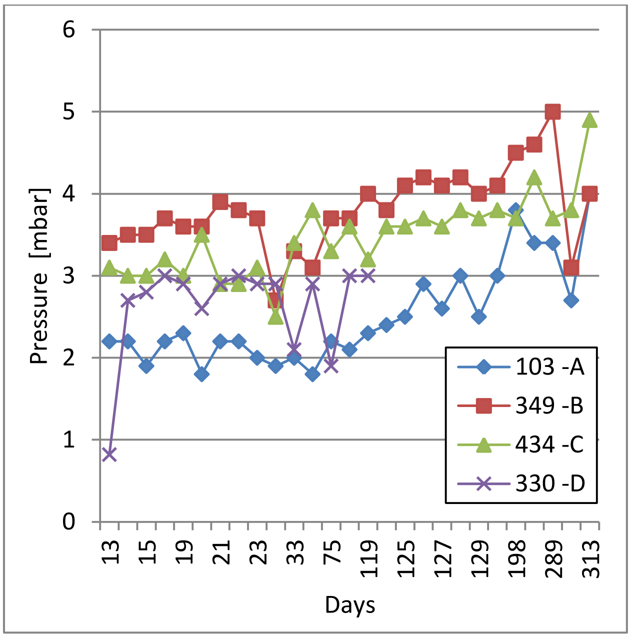

Fig. 16 Pressure measurements on vacuum insulation panels put in an oven at 70°C.

DISCUSSION

The results shown here are made for vacuum insulation panels adapted to room temperature applications. If the demand of high temperature applications would increase, the product development would follow. This could give an improved high temperature performance of the diffusion barrier.

For "guarded hot pipe" measurements there have been some problems with preparing the samples without damages to the vacuum insulation panels. Although, the panels mounted for field are shown to be undamaged.

The numerical simulations have been made in two dimensions with the effect on the edge of the panel baked into the panels overall performance. This is a simplification but it should have a small influence on the total performance since the edge thermal bridge follow the geometry of the panel.

OUTLOOK

The evaluation of the hybrid insulation concept will continue. More variations of the set-up of the vacuum insulation panel will be tested.

The thickness of the vacuum insulation layer and the orientation of the thermal bridges will be further studied for optimization.

A method for relative measurements of the thermal performance for twin pipes is under development. This will be used to validate the indicated thermal improvement seen in the simulations.

The durability of the vacuum insulation will also be investigated further.

CONCLUSIONS

The numerical simulations show a reduction in between 15% to 30% on the total losses from a twin pipe when an 8 mm vacuum insulation panel was added around the supply pipe. The losses from the supply pipe were reduced by more than 50%.

The field measurements show that the energy loss is reduced by the application of vacuum insulation. More important, there are no sudden large increases in the temperatures measured on the surface of the vacuum insulation panels, indicating a damaged panel, and so far there are no sign of the slow increment of the thermal conductivity of the vacuum insulation panels due to diffusion of gas into the panel. The experiments in an oven show a clear increment in the pressure but the influence on the temperature loggings in field can still not be seen.

These two conclusions show that the vacuum insulation panels can be used to decrease the energy losses from district heating distribution.

For single pipes with dimensions between DN 50 and DN 100 we saw a possible decrease in the calculated thermal conductivity from 26 mW/(m·K) for pure polyurethane to below 20 mW/(m·K) for a hybrid solution with around 10 mm vacuum insulation panel. For the best case, a DN 50/140 pipe with 8 mm vacuum insulation the calculated thermal conductivity was as low as 17.5 mW/(m·K). The calculated thermal conductivity directly correlates to the energy losses from the pipe, the improvement will be a little less in field since the thermal resistance in the ground will be the same for both cases, but the main part of the thermal resistance is in the pipe insulation.

The simulations show that the effect of the overlap of the vacuum insulation panel on the total energy losses is complex. The effect has to be examined more in detail to give good recommendations for optimization of the production.

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SELECTION OF STRAINERS: MINIMISE COST AND MAXIMISE PLANT EFFICIENCY

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W-FILTER / Waldow Engineering

ABSTRACT

Strainers and filters protect pumps, plant components and equipment against damage and malfunctioning caused by contamination.

Generally, a strainer is the only pipeline valve increasing its initial flow resistance while filtering debris and particles causing plant shut-down for maintenance. Hence, the selection of strainers requires a detailed consideration of efficiency and effectiveness lowering not only operational but overall cost of plants.

Standard strainers available in the market have been assessed and compared. On the one side respective pros and cons of those strainers have been analysed, either by the given data commercially available or through tests carried out in laboratories. On the other side, the experiences from the practical side have been gathered by discussing and interviewing plant operators or maintenance personnel. As a result ten points to consider for selecting strainers in plants have been summarized.

INTRODUCTION/PURPOSE

The past has shown that all too often, plant and equipment managers have set their sights on "big ticket" items (boilers, pumps, regulating valves, etc.), whilst neglecting "secondary" fittings, e.g. Strainers.

The results of the above are as following:

- Operating stoppage of the whole plant, because of repairs on "costly" equipment;
- Added expense through installation of strainers equipment with i.e. high flow resistance;
- Frequent plant operating interruptions caused by strainers that need to be constantly cleaned;
- Introduction of expensive, change-over strainer-valve units, to lengthen service intervals.

General requirements on strainers are given by:

- Dependable filtering effect;
- Large filtering volume and filter area;
- Insignificant pressure-drop in clean condition;
- Insignificant rise in pressure loss while dirty;
- Lengthen service intervals;
- Easy and time saving cleaning operation;
- Reasonable price.

In the present paper, the criteria for selecting strainers to achieve the optimum in plant operation/maintenance as well as saving overall cost will be explored.

STATE OF THE ART

Standard types of strainers are the Y-type (Y-Filter) or pot/basket strainers (T-Filter & W-Filter). In following those three types are introduced with respect to their individual characteristics, advantages/disadvantages when manufactured or in use/service.

Y-type (Y-FILTER)[1]:

The Y-FILTER in principle is utilising the casing of a slanted valve unit with a cylindrical sieve format.

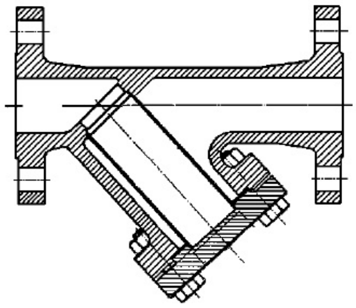


Fig. 1 Y-FILTER

Manufacturing (Y-FILTER):

- Advantages:
  + Reasonably priced casing, because of serial production with valve bodies;
  + Use of valve casings with damaged seats.
- Disadvantages:
  – Large deployment of sieve material compared to the effective filter area;
  – Additional cost for spacer sieve baskets;
  – Limitation in enlargement of the filter area.

When in use (Y-FILTER):

- Advantages:
  + Large deposition volume for particles which, separated from the flow, entered the dead zone and strike the sieve area at an angle;
  + Equally well suited for both horizontal and (from top to bottom) vertical flow.
- Disadvantages:
  – Increased pressure drop, caused by change in the flow direction;
  – Difficult handling of flange fittings;
  – Troublesome insertion of sealant during maintenance (overhead work, dripping);
  – Residual deposition area.

Pot / basket strainer (T-FILTER)[2]:

In principle a T-FILTER has the casing of a gate valve with a flat or half-cupped sieve.

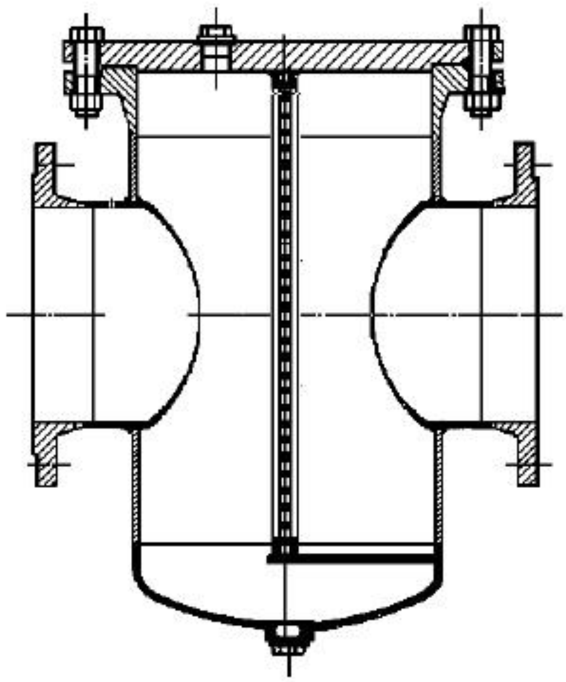


Fig. 2 T-FILTER

Manufacturing (T-FILTER):

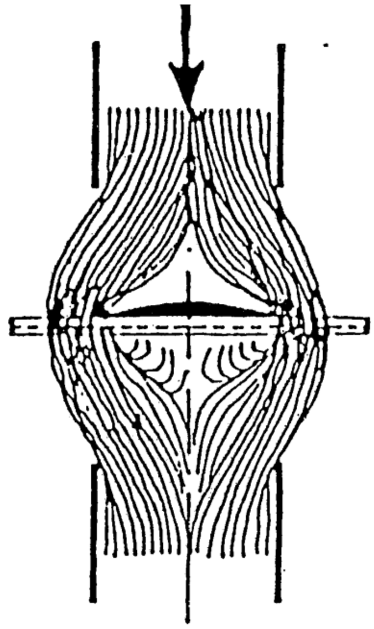
- Advantages:
  + A geometrically simple construction, welded or of cast iron;
  + Good possibility to extend filtering area.
- Disadvantages:
  – Extensive strengthening of sieve necessary, in order to create a unit withstanding pressure;
  – Additional cost, should the filtering of the dead zone be required.

When in use (T-FILTER):

- Advantages:
  + Negligible pressure drop when new, because of lack of flow turn-back;
  + Easy handling of flange fittings and sieve set, also with large ratings;
  + Easy assembly of gasket.
- Disadvantages:
  – The vertical flow clogs the sieve area quickly (especially when flow direction is from top to bottom), which causes a rapid increase of pressure drop;
  – Results are shortened maintenance intervals.

When dirty (T-FILTER sieve/screen):

Note the missing turnarounds and the extra reserve of available filter area.



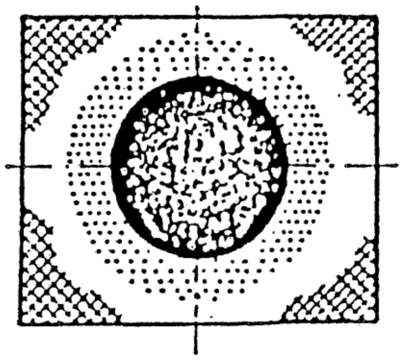


Fig. 3 T-FILTER: flow path under dirty conditions

Even though a large segment of the filter area remains not in use, the increase in pressure drop is of such magnitude that the strainer needs to be cleaned.

In horizontal flow position of the T-FILTER, the cleaning intervals are of longer duration (a large part of the dirt bounces off the sieve and is deposited in the dead zone of the dirt catcher).

However, also cleaning of the sieve is necessary, when the piping cross-section is blocked by “dirt disk” of equal size.

Basket strainer (W-FILTER)[3]:

The W-FILTER is in principle a T-FILTER, but without the disadvantages of the same.

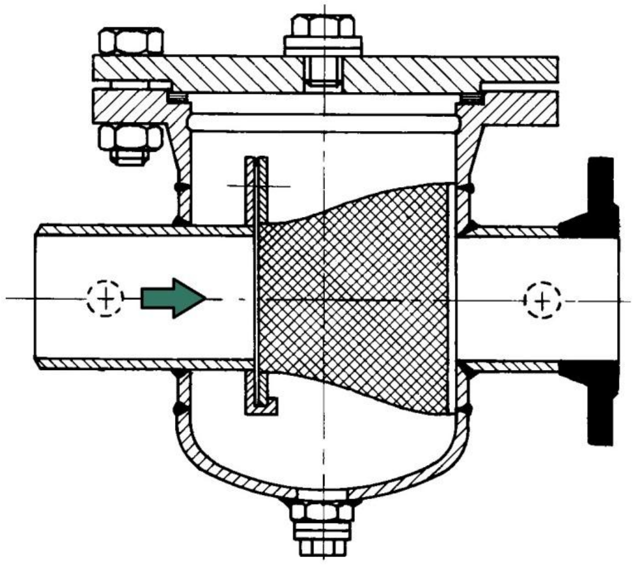


Fig. 4 W-FILTER: type SF (welded / flanged end)

The sieve is a wedge casing which is set in the flow direction of the medium.

This results in following advantages:

+ The inherent robustness of sieve body saves expensive re-enforcement and permits the use of reduced wire size for the same mesh format, which results in a larger open filter area;
+ Good dirt deposition through flat angle of impact of the dir particles;
+ Complete removal of filtered particles together with the extraction of the sieve unit;
+ Effective sealing between filter and sieve body – also with fine mesh format;
+ Negligible loss of pressure, also when unit is heavily clogged by dirt;
+ Lengthened intervals for maintenance, because of superior dirt separation;
+ Horizontal and vertical (top to bottom flow direction) mountings are about equally effective;
+ Reasonably priced model through low-cost manufacturing potential.

The "welding construction from commercial piping, bottles, sealant, screws and sieve meshing" takes the demands of the market fully into account, such as:

- Special dimensions;
- Units without flanges, with single side flange or flanges on both sides;
- High pressure capability through the thick-walled design;
- High, respectively low temperatures through use of selected materials;
- Short delivery periods – also for a limited number of orders.

When dirty (W-FILTER):

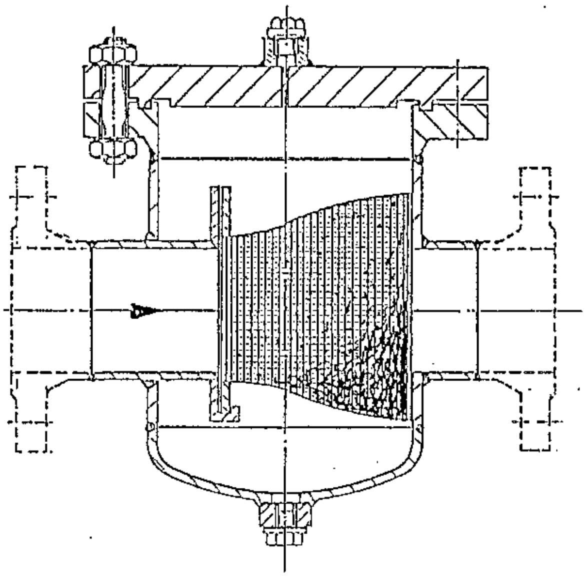


Fig. 5 W-FILTER (dirty) in horizontal flow path

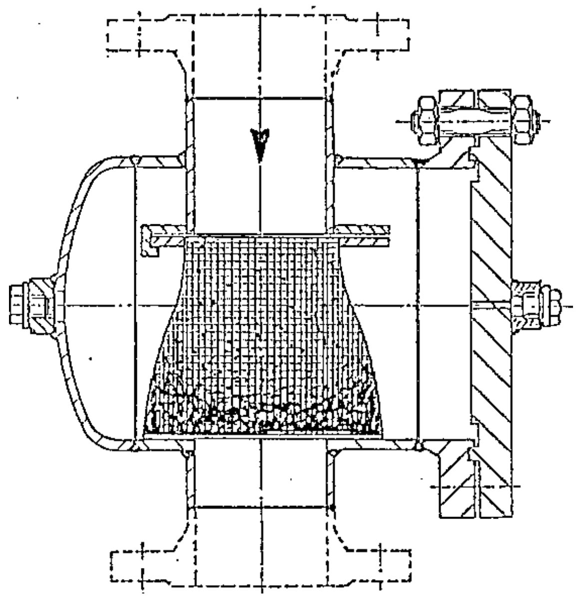


Fig. 6 W-FILTER (dirty) in vertical flow path

In both cases, the same degree of contamination is present as described under T-FILTER section (dirty).

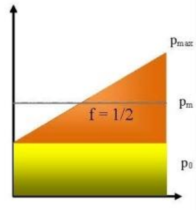
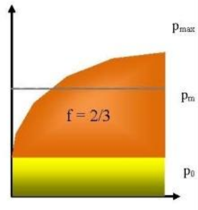
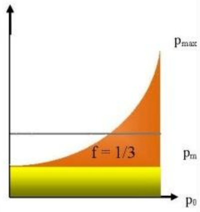
There is still a large and effective filter area available and the rise in pressure drop is so small that the cleaning of strainer remains unnecessary for some time to come.

Out of the experience by plant operators it is experienced, that the maintenance intervals of a W-FILTER are at minimum three times longer than of a conventional available T-FILTER

Often, the cost for filter cleaning, including plant operating stoppage, is higher than the price of a complete strainer unit.

Energy consumption in connection to the various resistance coefficient and pressure drop of the different strainers will increase and hence result in higher operating cost as shown in the following table (Table 1):

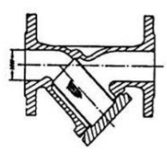
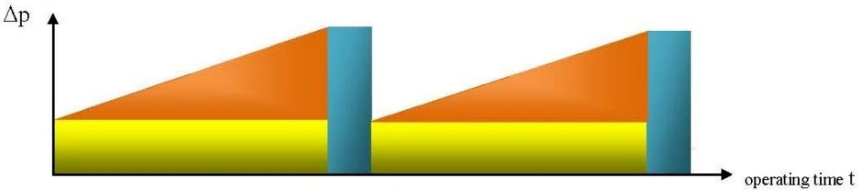
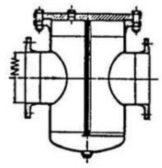
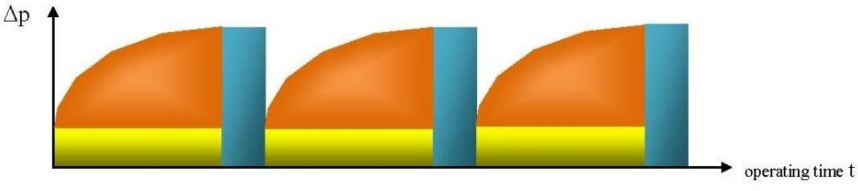
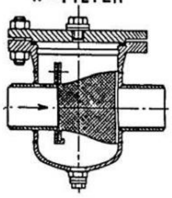
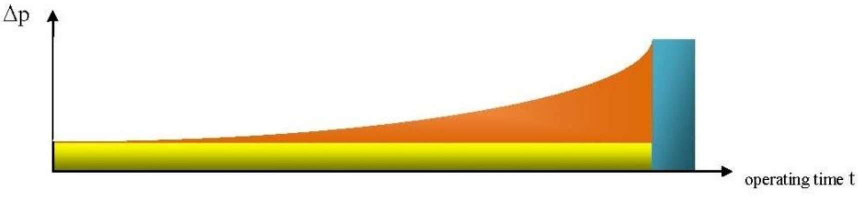
Table 1 Calculation of operating cost

Example: DN 200, Screen-mesh size 0.5 mm (flow rate: 365 m³/h hot water ≅ velocity 3 m/s) Energy cost: 0.10 €/kWh; screen cleaning at: $\Delta p = 10$ mWS ≅ 1 bar; $P_{max} = 13.25$ kW Cost per screen cleaning incl. of auxiliary material and production downtime: approx. €500.-			
Types of Filter	Y-Filter	T-Filter	W-Filter
Resistance coefficient (manufacturer's data)	$\zeta = 7.22$	$\zeta = 2.8$	$\zeta = 1.7$
Pressure drop Δp_o at clean screen filter ($\Delta p_o = \zeta\,(c^2/2g)\,\gamma$) [mWS]	3.32	1.29	0.78
Minimum pump capacity with $\eta_p = 0{,}75$ and at a clean screen filter (basic load) P_o [kW]	4.38	1.71	1.03
Maximum pump capacity P_{max} at Δp=10 mWS [kW]	13.25	13.25	13.25
Characteristic of pollution f (angle of impact, effective screen surface, etc.)			
Required average pump capacitiy until cleaning of filter: $P_m = P_o + f(P_{max} - P_o)$ [kW]	8.80	9.40	5.10
Average operating cost per hour [€]	0.88	0.94	0.51

Legend: **Δp at clean screen** **increase of Δp at dirty screen**

Cleaning intervals are different at constant pollutant quantities and maximum pressure drop (Δp max) – resulting in shut down, loss of production and maintenance cost, as visualized in the following table (Table 2):

Table 2 Cleaning intervals of different types of strainers

resulting in: **downtime of plant, loss of production and maintenance cost**! various filter types show different cleaning intervals at constant pollutant levels and maximum pressure drop (Δp_{max})		
Y-FILTER 		**2 times**
T-FILTER 		**2-3 times**
W-FILTER 		**1 time**

Legend: **Δp at clean screen** **increase of Δp at dirty screen** **cleaning procedure**

METHODS/METHODOLOGY

The datasheets of the three different types of strainers have acted as a basis for i.e. the cost calculation, based on the flow resistance figures (ζ-value)[1][2][3].

In addition, it was referred to literature on heat transfer technology for characteristics of pipelines and strainers determining the low resistance figures [4].

Physical tests on the flow resistance and differential pressure have been carried out on the W-FILTER DN200 in a closed piping circuit, consisting out of a pump that is transporting the medium (water) through the circular piping, a strainer and measuring equipment for the inlet and outlet pressure before and after the strainer. Additional physical tests utilising a high level tank, where water was transported through the vertical pipeline by gravity and the respective differential pressure detected at the measuring equipment before and after the strainer (W-FILTER DN80 and DN150).

Especially on the aspects of handling strainers, i.e. installation, maintenance intervals and maintenance work, plant operators and maintenance personnel from a variety of industries have provided a large number of important elements to bear in mind.

RESULTS

Out of all the above analysis and assessments, the following ten points to consider for selecting strainers in plants are recommended:

(1) Low resistance value (ζ)

Saving energy cost for the operator. Strainers with a high pressure drop show a higher level of energy consumption (kW) due to a higher utilization of the pump overcoming the respective pressure difference - summing up to a yearly amount higher than the initial price of the product!

(2) Large effective filtering area

The most important figure is the size of the filtering area which is provided into the stream, but not the installed filtering area. In most the technical brochures, one can find the total filtering area of the strainer. Similarly, plant engineers tender for an installed filtering area three or four times of the pipe connection. As we can see out of the flow and sieve characteristics of the different strainer, the effective filtering area can be much smaller.

(3) Angle of impact between flow and sieve

Sieves with an impact angle of 90º will clock easier as one with a flat impact angle. With the vertical impact angle, the particles with about the same dimensions as the mesh size will stick in the sieve and block the flow: cleaning and maintenance intervals are lengthened.

(4) Closed sieve-body

Using an open sieve, filtered particles will remain within the housing of a strainer, triggering additional cleaning cost. Utilizing a closed sieve, filtered particles will be removed together with the sieve – the filter mud is already cleaned and recyclable.

(5) Easy applicability of the strainer

Pipeline layout is simplified by installing a strainer both in horizontal and vertical position. Consider a strainer that can be installed both ways by providing the respective advantages of long maintenance intervals with the given low differential pressure.

(6) Good handling of top flange (‚cover‘)

Strainer of larger dimensions provide exhausting and time consuming maintenance, if cover, sealing and bolts are positioned head over or with an angel of <45º pointing down. Blind flanges (cover) of DN200 PN25 have already a weight of 23kg; handling those flanges will be easier by using a swivel/swing-arm so as to avoid the usage of a crane.

(7) Weld able housing material

Already in the design phase of plants, but-welded end strainer may be considered to lower cost by saving flanges, additional sealing and excluding potential leakage points. Even one-side flange types, strainers with stands, cover-mover and grips for measuring the differential pressure might be considered with the procurement of the strainer, so as to prevent additional installation cost later.

(8) Connections for manometers

A strainer increases its pressure drop during operation and has to be cleaned. Therefore, information on the level of dirt within the strainer should be gained and manometers installed. With the pre-set maximum pressure loss allowed in the pipeline, i.e. 1bar, these manometers could just indicate the level of dirt by a color code or via electronic indicators sending a signal at different levels of pressure drop.

(9) Filtering fineness

Filtering fineness of the sieve shall be “as course as necessary and as fine as possible!” Any mesh size which has been chosen too fine, results in an increased frequency of maintenance. You may operate your strainer with a finer mesh size of, i.e. 0.5mm, during startup of the plant and courser mesh size, i.e. 2.0mm, in continuous operation.

(10) Sealing of the top flange (cover)

The only consumable part of a good strainer shall be the sealing of the cover. Sometimes strainers are supplied with a company-specific seal. Therefore, installation of standard seals – available in the market - should be considered when procuring a strainer.

DISCUSSION

In this paper, a variety of aspects and considerations for selecting strainers to safe cost and increase efficiency of plants have been concluded.

The flow resistance figure ζ may vary with different brands of Y-FILTER due to their improvement in their flow deflection. Different ζ-values can be also found with the various T-FILTER or so-called basket strainer, using a curved sieve or a sieve basket. However, there was no strainer identified in the market with better values then the W-FILTER.

Basically, ζ-values should be increasing the larger a strainer in its dimension is. In the brochures of various manufacturers, however, one may find a discrepancy, as the values may increase first and then are lower with larger diameters.

Aspects for selecting strainer are mainly from the operational side and its respective cost, not the initial price. It is experienced, that due to the casted material, dimensions ≤DN200 of the Y-FILTER are cheaper than the others. Taking the life-cycle cost, including higher energy consumption and maintenance/labour cost into account, the initial saving in price is negligible.

OUTLOOK

Suggestions for the User of strainers:

Use wherever possible the strainers with welding ends, since there is little prospect of having to exchange the complete unit in the foreseeable future. Hence, save extra costs for reverse flange, gaskets and bolts which occur during flanging.

Should the adjacent component of the strainers have a flange connection (e.g. the suction part of a pump, a compensator, etc.), order a strainer with single-sided connecting flange.

In case you would like to change the type of strainer at a location already a less performing strainer had been utilised, order custom-made face-to-face dimension. If, for technical reasons, pipe connections of different values are to be found in front or behind the filter, ask for a custom-made solution for installation.

CONCLUSIONS

Generally, the longer the time between necessary maintenance, the more effective a plant is operating, due to less stoppage and more output. Limiting the resources carrying out the maintenance and also the handling will help to shorten also the time needed and going back to operation of the plant. You may even consider a swivel/swing-arm for handling the cover flange (>20kg), as this will allow you to remove the sieve without the need for a crane and hence will save you initial larger investment.

It is well known, that a lower friction in a pipeline, resulting from a low flow resistance figure ζ, will result in less energy a pump needs to transport a medium through the plant. Therefore, a mayor focus should be on selecting components with a low ζ-value.

We also learned that a focus on the effective filtering area shall be done. Assess the strainer you consider for installation in your plant under this aspect and do not let yourself be misleading by the given filtering area in the brochure.

If you like to take out the sludge together with the sieve, when cleaning, your focus should be on a closed sieve-body. Otherwise, you may have to install an additional device or cater for intermediate collection of the sludge.

Lastly, ensure that the cover seals used with the strainer can be obtained as a standard item from the market. Certain manufacturers only supply their own seals so as to bind their customers and may even ask for a premium price.

ACKNOWLEDGEMENT

We would like to thank KSB AG and ARI-Armaturen Albert Richter GmbH & Co. KG for their support regarding availability of their testing facilities and personnel in determining the pressure drop values.

Also we thank Mr. Jordan (EVONIK – former Hüls-Degussa), for the highly valuable information about the experiences in handling and maintenance of strainers of various types.

Furthermore, thanks to Mr. Kuch (EnviCon) on the confirmation about the flow resistance figures of the Filter Type W, as well as Mr. Bangerter and Mr. Larsen (VEKS Denmark) on their feed-back about the improvement of their District Heating operation in Amager/Denmark and the respective heat distribution by utilising the Filter Type W.

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SESSION 16

Urban energy systems, planning and development

ON THE USE OF SURPLUS ELECTRICITY IN DISTRICT HEATING SYSTEMS

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ABSTRACT

Maintained balance between supply and demand is a fundamental prerequisite for proper operation of electric power grids. For this end, power systems rely on accessibility to various balancing technologies and solutions by which fluctuations in supply and demand can be promptly met. In this paper, balancing approaches in the case of surplus electricity supply, due to long-term, seasonal, or short-term causes, are discussed on the basis mainly of compiled experiences from the Swedish national power grid. In Sweden, a structural long-term electricity surplus was created in the 1980s when several new nuclear plants were commissioned and built. One of four explicit domestic power-to-heat solutions initiated to maximize the utilization of this surplus electricity, as export capacities were limited, was the introduction of large scale electric boilers and compressor heat pumps in district heating systems. In retrospective, this solution not only satisfied the primary objective by providing additional electricity demand to balance the power grid, but represents today – from an energy systems perspective – a contemporary example of increased system flexibility by the attainment of higher integration levels between power and heat sectors. As European power supply will be reshaped to include higher proportions of fluctuating supply technologies (e.g. wind and solar), causing occasional but recurring short-term electricity surpluses, the unique Swedish experiences may provide valuable input in the development of rational responses to future balancing challenges. The main conclusions from this study are that district heating systems can add additional balancing capabilities to power systems, if equipped with electrical heat supply technologies, hereby contributing to higher energy system flexibility. Consequently, district heating systems also have a discrete but key role in the continued integration of renewable intermittent power supply technologies in the future European energy system.

INTRODUCTION/PURPOSE

District heating systems are mostly associated to combined heat and power (CHP), based on heat recovery from thermal power stations. This heat recovery is part of the basic fundamental idea of district heating [1]. This cogeneration of heat and power is based on the normal condition that electricity prices are considerable higher than heat prices. The exergy content in the fuel is then shaved off as electricity and exported to the power system. The remaining low-exergy and anergy parts are then used for heat generation supplying the district heating system. However, when electricity prices are low, the CHP advantage is lost and an opportunity appears for importing electricity to district heating systems for heat generation. This import direction of electricity to district heating systems is the basic theme for this article.

Low electricity prices are the result of some kind of surplus situation in the power system, when ordinary electricity customers cannot absorb the temporary supply surplus. If the power grid have high capacity power transmission cables to other regions, these temporary surpluses can be exported and substitute flexible power supply in these regions. If the export capacity to other regions is limited, the surplus must be absorbed in the region concerned. It can also be accomplished by using storage possibilities within the power systems as hydropower dams, batteries in future electric vehicles, or large compressed air storages.

The electricity surplus can also be absorbed outside the power system by export to heating systems for heat generation, either in individual heating systems or in district heating systems (power-to-heat solutions). The required flexibility in the power system from fast balancing power is then delivered from the heating systems. The obtained heat can then substitute ordinary flexible heat generation and local heat storages can also be used in order to supply the heat for later use. These heat storages can deliver flexibility to the power systems to a lower cost than most storage possibilities within the power system [2]. The competitive advantage for district heating systems compared to individual heating systems is that the absorption of surplus electricity can be implemented to a lower cost from economy-of-size. The electric surpluses can also be absorbed by gas generation technologies within the gas system (power-to-gas solutions). Hence, several competing solutions within the energy system can supply flexibility to the power system.

These electricity surpluses have different time scales from short-term (hours or days) to more long-term (one to many years). One example of short-term electricity surplus is supply peaks in the future power systems with high proportions of fluctuating wind and solar power during windy and sunny days. The future use of surplus electricity in district heating systems has been foreseen and discussed in [3] for Denmark, in [4, 5] for Germany, and in [6] for Russia.

Seasonal electricity surpluses appears in power systems dominated by hydropower plants from the variation from year to year with respect to precipitation received, also called dry and wet years. This annual variation initiated the introduction of Norwegian district heating systems in the 1980s, where requirements for

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sale of firm power[1] due to reliability was set to a minimum limit so that capacity on average was sufficient 27 years out of 30 years, thus creating a surplus of power on the majority of the years during a period of 30 years [7].

A more long-term electricity surplus appeared in early power systems when an initial major hydropower plant was built with a capacity much higher than the current electricity demand. Examples are the electric heating of the city hall in Borås in Sweden from the newly built and initially oversized Haby hydropower station in 1916 [8], the use of electric heating in Bergen, Norway [9], and the use of surplus hydropower electricity in two small district heating systems in Munich [10].

Another more structural long-term electricity surplus was created in Sweden in the 1980s, when many new nuclear power plants were commissioned. The possible supply of nuclear power became higher than the sum of the current electricity demand increase and the substituted thermal power plants using fossil fuels. The surplus could not be exported to other countries, since the current export capacity was too small, so the surplus had to be absorbed within the country. In order to maximize the utilization of the surplus, four activities were initiated: introduction of electric heating resistors in domestic oil boilers, general promotion of electric boilers and heat pumps for substitution of oil boilers in single-family houses, introduction of large electric boilers for industrial heat demands, and finally introduction of large electric boilers and large heat pumps in district heating systems.

The focus in this article is the documentation of the fourth activity above concerning district heating systems. The purpose is to provide experiences for other future power-to-heat solutions associated to district heating systems. First, the development in the Swedish power system is described. Second, the Power-to-heat technologies mainly used in district heating systems (large electric boilers, large heat pumps) are presented. Thirdly, the article aims to discuss general implications regarding the balancing role of district heating systems in highly integrated future energy systems. The added option in such systems, i.e. to use surplus electricity for heating purposes, may prove increasingly valuable as the proportion of intermittent power supply technologies escalate in the power supply mix.

SWEDISH POWER SUPPLY

Hydropower dominated initially according to Fig. 1 giving some national dependence of dry and wet years in the national power balance.

In the late 1940s, a future deficit of hydropower compared to demand was identified. This initiated many municipalities to start up district heating systems as heat sinks for future CHP plants. The first district heating systems was introduced in Karlstad 1948 [11]. Nine more cities started up district heating systems in the 1950s. In general, all early CHP plants used fuel oil as energy source.

Expanding electricity demands initiated also two major oil-fueled condensing power plants (Stenungsund and Karlshamn), also using fuel oil. This gave more space in the power balance for substituting the operation of these power plants with further CHP plants in both industries and district heating systems.

The first major Swedish nuclear power reactor was commissioned in 1972. During the following thirteen years, another eleven nuclear power reactors were commissioned; giving a considerable proportion in the Swedish power generation, see Fig. 1. This fast expansion of nuclear power created a surplus of electric power.

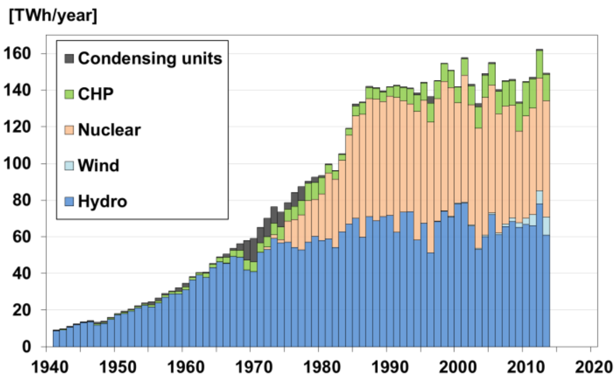

Fig. 1 Power generation in Sweden 1941-2011.

A major part of the temporary power generated, due to the surplus situation, was absorbed within district heating systems. During the period of 1985 to 1995, the relative proportion of temporary electricity supplied into district heating systems was 71 %. Industrial and residential/service sectors were also represented during the time period, but to a lower extent. They represented 27 % and 2 % respectively, see Fig. 2.

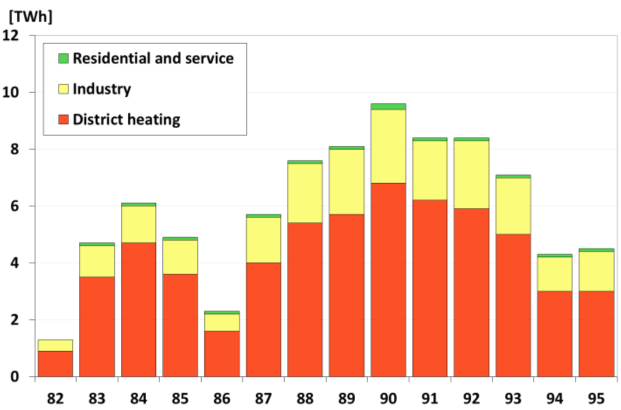

Fig. 2 The use of temporary electricity in the national electricity demand.

STATE OF THE ART: POWER-TO-HEAT IN DISTRICT HEATING SYSTEMS

In coherence with the national energy policy, surplus power was to be used as a replacement for fossil oil use. This goal was partly achieved by promotion of large electric boilers and use of large compression heat

[1] Firm power refers to electric power that is continuously available from the water stream, even in times of lowest flow and lowest head.

pumps for central use mainly in district heating systems.

Since power-to-heat reached its peak in 1990 with a 35 % proportion of heat supplied, see Fig. 3, there has been a steady decline of heat supply proportion from electric boilers into the district heating systems. The decline in proportion of heat supply from heat pumps is partly mitigated by the increase of heat supplied into district heating systems, see Fig. 4, and the expansion of biomass CHP plants. A reason for this development was that demand of electrical power caught up with supply, thus increasing the price; making power-to-heat solutions less viable.

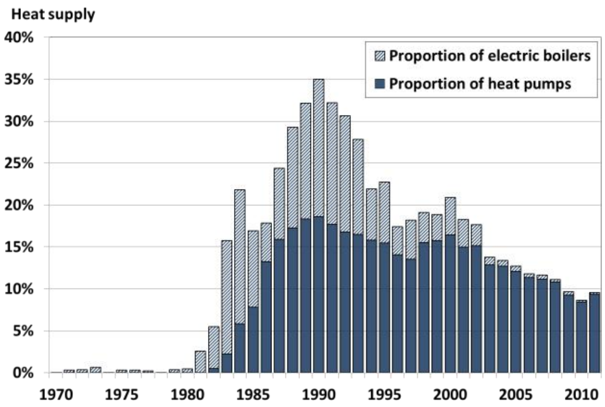

Fig. 3 Annual proportion of heat supplied from electric boilers and heat pumps, into district heating systems 1970-2011.

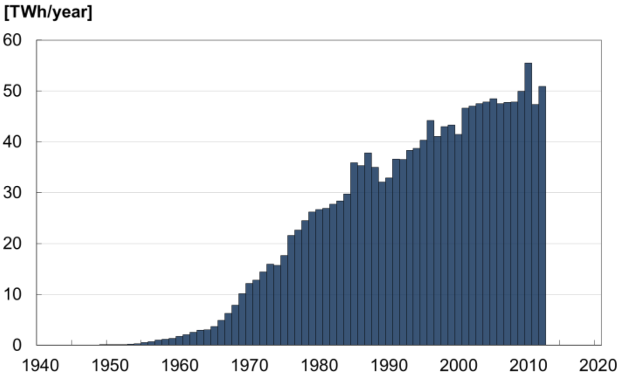

Fig. 4 Annual heat delivered from district heating systems 1949-2012.

Large electric boilers

For large electric boilers such promotion was partly introduced in the form of an energy tax reduction on electric energy. This tax reduction could be obtained during 1984 to 1991 [12]. Prerequisites to be entitled a tax reduction enclosed a special agreement with the electricity supplier about temporary power supply, which at any time could be interrupted due to power system reasons. In addition to be classified as temporary power, capacity of installed units was to exceed 1 MW of heat power, no oil-based power generation had occurred for a consecutive period of five days and there had to be an alternative source of heat for when the electric boiler was out of use [13].

Agreements for temporary power have existed in Sweden since 1950s. At this point in time power-to-heat was however rarely used; the exception was during wet years. It wasn't until the late 1970s and early 1980s that the use of large electric boilers, for temporary power, became a more common feature with the integration of nuclear power in the Swedish power system.

In order to ensure demand of surplus power, the Swedish state owned company Vattenfall promoted large electric boilers in two different ways. Investments could receive a grant of 100 SEK per installed kW, alternatively Vattenfall guaranteed a certain payoff time, and if the payoff time could not be achieved then Vattenfall paid the remaining sum.

Table 1. Electric boilers in industries and district heating systems for temporary power, above 30 MW in operation, December 1986

Owner	**Electric Power [MW]**	**Units**
Akalla Värmeverk	75	2
Drefvikens Energi AB	32	1
Edet AB	30	1
Gislaveds AB	30	1
Karlit AB	40	1
Karskärsverket, Gävle	40	1
Malmö Energiverk AB	105	3
Munksjö AB	32	1
St Kopparb-Bergvik	40	1
Stockholm Energi Värtaverket	150	3
Stockholm Energi Produktion	80	2
Stora Kraft, Kvarnsveden Papper	34	1
Stora Kraft, Skutskärsverken	40	1
Sundbybergs Energiverk	60	1
Sydkraft AB	35	1
UKAB	50	1
Vivstavarvs AB Timrå	50	1
Volvo AB	30	1
Västerås Stads kraftvärmeverk	60	2
Grand Total	**1013**	**26**

In the end of 1986, there was 422 units of electric boilers installed for temporary power equal to 3400 MW [13]. According to Table 1, approximately 6 % of the units corresponded to 30 % of installed capacity. A majority of the capacity was installed during a few years in early 1980s as can be seen in Fig. 3. In the beginning of 1986, Vattenfall withdrew any further promotion of large electric boilers.

Table 2. Heat capacity from heat pumps > 1 MW arranged by install year and heat source, value in MW, total number of facilities 114, total number of units 155 as of 1986 [14]

	Industrial excess heat	Sewage water	Ambient water	Groundwater	Air	Grand Total
1980					3	3
1981	4	3				8
1982	12	60	22			93
1983	31	106	38	3	8	186
1984	121	135	24	1	17	298
1985	28	53	86	20	3	190
1986	5	314	185	40	11	554
Grand Total	**201**	**671**	**355**	**63**	**41**	**1330**

Two statements can be made with this knowledge. First, it is unlikely that any more capacity of electric boilers was built. Second, it is questionable whether or not the rapid development of electric boilers was justified, with the consideration that too much capacity may have been installed.

Large heat pumps

As of 1987, there were 155 units of large heat pumps in use in Sweden[2], corresponding to 1330 MW of heat power. The growth rate was high during 1982 to 1986 as seen in Table 2. Thereafter, expansion decreased dramatically, the reason for this change of pace in expansion was the same as for electric boilers, market saturation. At this point in time a majority of the district heating companies had invested in a large heat pump. The decrease of proportion in heat supply from large heat pumps as seen in Fig. 3 depends partly on larger heat supply from district heating systems in general but a part of the decline is due to heat pumps which are decommissioned due to age. Also newly installed capacity in biomass combined heat and power plants preceded heat pumps in merit order depending on price of electricity.

Heat pumps were profitable on continuous operation and thus they required a continuous power supply whereas electric boilers relied on a recurring surplus. Heat pumps did neither share the tax benefits nor the investment guarantees of electric boilers. In addition it is of importance to note that large heat pumps cannot be operated as intermittently as electric boilers, due to mechanical wear during start-up, and time for start-up which amounts to minutes, while COP is low during start-up.

Potential heat sources for utilization in heat pumps ranged from: ambient water in seas, lakes, rivers, or groundwater, sewage water from sewage treatment plants (treated or untreated), geothermal heat from boreholes, industrial excess heat and solar heat. A prominent part of installed capacity from large heat pumps in Sweden used sewage water as heat source, see Table 2. The temperature level from sewage water is limited at a rather low temperature, though usually higher than temperature levels of ambient water. Performance of heat pumps is dependent on required increase of temperature, thus making a heat source with higher temperature levels more attractive. Even though this, coefficient of performance (COP) seen as an annual average has been kept at around three or above since the early 1980s, see Fig. 5. From an annual average perspective, it also seems that development in heat pump technology has been constant; since the difference in COP is marginal during the time period, see Fig. 5.

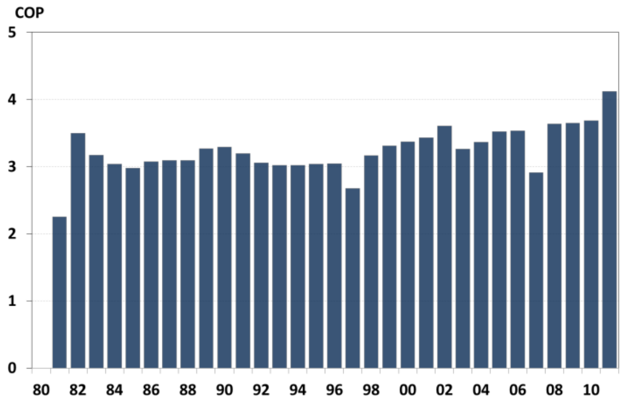

Fig. 5 National annual average COP for heat pumps in district heating systems 1981-2011.

DISCUSSION/OUTLOOK

Power-to-heat solutions can be beneficially implemented in power systems where electricity periodically occurs as a surplus, as is the case in countries with a high proportion of power generation associated with a varying degree of predictability such as hydro-, wind- and solar power. The key to unlocking power-to-heat at a large scale is district heating systems and with it, possibilities to occasionally even out fluctuations on an electric power grid.

In the past surplus power was usually based on seasonal and long-term sources, as was the case in Sweden, Norway and Germany during the early 20th century, where surplus of power lead to power-to-heat solutions in conjunction with hydropower. During the 1980s in Sweden, power-to-heat solutions once again flourished when the nuclear power was introduced. In the future however, a higher proportion of short-term surplus power from fluctuating sources is to be expected. Since surplus electricity once led to the expansion of district heating, as it did in Norway during the 1980s, it seems reasonable that power-to-heat

[2] Not only in district heating systems.

solutions once again should be introduced in already developed district heating systems.

Access to a long term recurring surplus of electrical power is an uncommon phenomenon. There is a need for large quantities of renewable energy sources, usually hydro- or geothermal power as seen from a historical perspective, but in the future, wind and solar power as well. Sweden is one of few countries that on a on and off basis has had documented access to surplus power during a time period of a century, thus there is large amount of experience to be gained from.

A compilation of Swedish historical experience on power-to-heat usage in district heating systems is a fundamental cornerstone to alleviate introduction of such solutions in future energy systems.

As the proportion of power-to-heat peaked in 1990 it is uncertain how much higher the share could have been with access to more surplus power, with regard to already installed capacity. Also to consider is the rapid decline of power-to-heat proportion in district heating systems over the following two decades. The development seems hasty and irrational, perhaps the possibilities of power-to-heat was greatly overestimated in correlation to the measurements taken to ensure their introduction. Thus creating a first come, first served situation, it could be considered that the benefits were too favorable and therefore allowed an excessive amount of capacity to be built.

Investments in energy systems are usually of long term character in nature. In the case of power-to-heat however, with focus on large electric boilers, the payback time were usually around two to three years and due to market saturation, economic life became short, only a few years for early investments and less for investments made at a later stage, while technical life of an electric boiler most likely could reach a few decades at least.

This paper gives a short general overview of large electric boilers and large heat pumps, mostly with regard to district heating systems. Continued work on this paper could include data on individual unit level, ensuring quality and quantity on data and to deliberate what the actual operating experiences has been, what to think of and which pitfalls to avoid.

CONCLUSIONS

The main conclusion of this paper is that power-to-heat solutions used in district heating systems can be a cost efficient way to introduce more flexibility to an energy system and thus allow a larger proportion of renewable power in an energy system. Power-to-heat is however dependent on low-cost electricity it should therefore primarily be used where a recurring electric power surplus occurs.

Further it has been shown that history is about to repeat itself, whereas in the past surplus power was generally supplied from hydro- and nuclear power while in the future new sources of surplus power is more likely to derive from wind- and solar power.

Sweden is historically one of the few countries together with Norway with substantial experience in the field of power-to-heat solutions and given its continued relevance in the energy system as a source of demand for balancing peaks in electric power systems, it is necessary to compile and document the experience for future reference.

ACKNOWLEDGEMENT

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SOLAR ELECTRICITY IN SWEDISH DISTRICT HEATING AREAS

– EFFECTIVE ENERGY MEASURES IN APARTMENT BUILDINGS TO INCREASE THE SHARE OF RENEWABLE ENERGY IN EUROPE

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ABSTRACT

To overcome the climate challenge is one of the greatest tasks of our time. In EU, renovating the existing building stock has been found an effective measure. In Swedish buildings with district heating, lowering heat demand could be questioned, because the energy used is mainly renewable bio energy or waste heat from industries. In addition many district heating systems cogenerate electricity, which could reduce the overall European greenhouse gas emissions.

The aim of this article is to find effective measures for Swedish apartment buildings, in order to increase the share of renewable energy in European energy consumption. As a basis we use a previous study of energy saving potentials in apartment buildings. Added to this we study the impact of heat savings in 30 of Sweden's largest district heating systems.

The results show that on average heat reductions will lead to a decreased share of renewable energy, while electricity reductions will lead to an increased share of renewables. Of the investigated measures, using photovoltaics for local solar electricity generation has the largest potential.

Our conclusion is that using the potential of solar electricity production should be considered in national energy policy and future building requirements. Heat reduction, on the other hand, could have lower priority in district heating areas, at least for existing buildings.

INTRODUCTION

A. THE CLIMATE CHALLENGE

The latest report from the International Panel on Climate Change (IPCC) shows that emissions of greenhouse gases must be reduced very dramatically in order to reach the 2 degree target of the 2010 UN Cancun Agreements [1], [2]. Ultimately the climate challenge is an act of will. The humanity has to ignore the possibility to use fossil fuels and leave them preserved – at least to a very large extent. The starting point of this article is a long term goal of a global energy system with 100% renewable energy (all sectors included), as described in the Ecofys Energy Scenario [3].

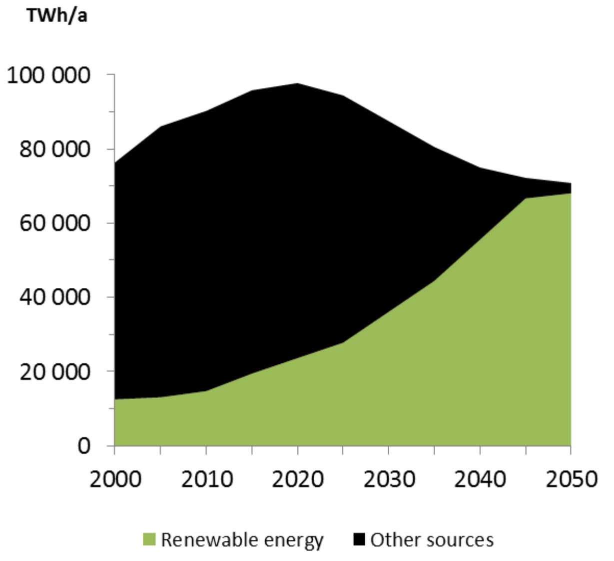

Fig. 1 Ecofys Energy Scenario, aggregated to renewable energy and other sources [3].

B. THE ENERGY SITUATION IN EUROPE

The situation in the European Union is about the same as on the global level, with a renewable energy share of about 14%. Buildings account for 40% of the total energy use, if the sectors Residential and Services are included, and 65% if also Industry is included [4].

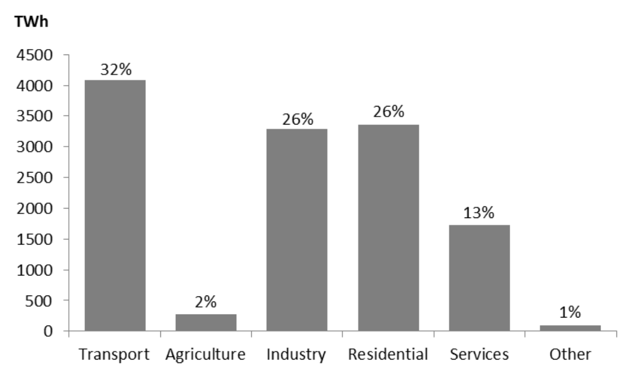

Fig. 2 Energy use in EU 2012 [4].

The share of renewable energy is lower in Transport and Agriculture, but the total use of non-renewable energy is larger in the built environment (including industry).

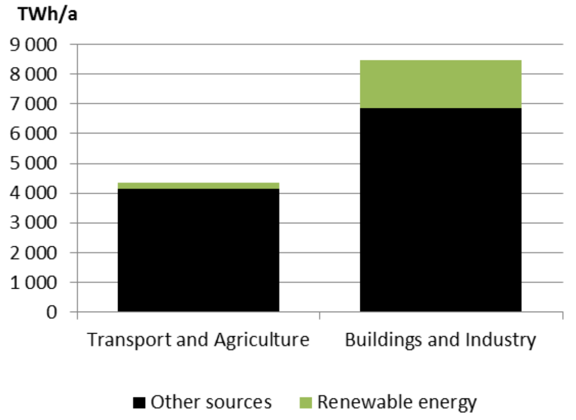

Fig. 3 Energy use in EU 2012. Processed statistics from Eurostat [4]. The share of renewable energy in agriculture is assumed to be zero.

To reach the goal of 100% renewables, the use of other sources has to be reduced as well as the overall energy consumption. According to the Energy Roadmap 2050 from the European Commission all sectors need to invest in energy efficiency [5].

In this work we will analyze the environmental benefits from energy reductions in buildings and to do this thorough we have to distinguish between the reduction of heat and electricity. From Eurostat statistics we have therefore calculated the shares of renewable energy used for producing heat and electricity, according to figure 4 [4].

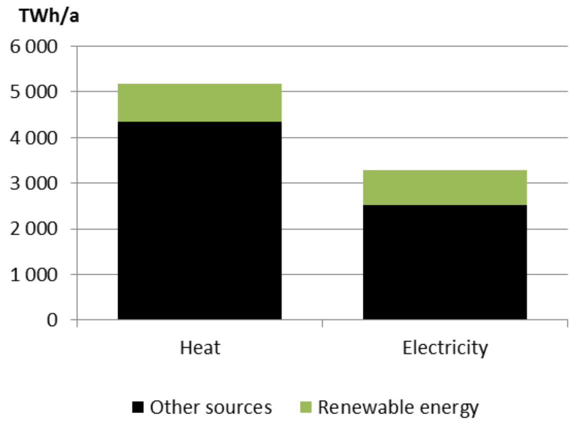

Fig. 4 Energy used in EU buildings and industry 2012. Processed statistics from Eurostat [4]. It is assumed that all energy used in these sectors can be characterized as either heat or electricity. In the calculations electricity used for transport and agriculture has been assumed to be zero.

It is also instructive to show the differences between countries, which make it obvious, that the most effective strategy might not be the same for all. Figure 5 is showing the renewable energy shares of energy used as heating and electricity in buildings and industry. Electricity used for transport and agriculture is assumed to be zero in the calculations.

Norway and Sweden stands out, with a very large use of electricity, which in turn has a large share of renewables (mainly hydro power). One can also see that the renewable energy share for heating is large in several countries, with Sweden outstanding.

C. ENVIRONMENTAL ASPECTS OF HEAT AND ELECTRICITY REDUCTIONS

Heat is always used locally or distributed in local areas, whereas electricity can be transited cross-borders. This makes the complexity of environmental issues regarding heat and electricity reductions very different.

The simplest case is heat produced with a boiler in the building. Reduction of heat in this building will of course correspond directly with reduced need of fuel to the boiler.

In a district heating system, the production of heat is usually done with a mix of fuels. Reduced heat demand will in this case generally correspond to a reduced need of the most expensive fuel, which can vary from time to time. In addition the district heating demand is in many cases used for cogeneration of electricity. This means that reduced heat demand could lead to reduced electricity production.

In the same way production of electricity is done with a mix of fuels. And since countries are interconnected, reduced electricity demand in one country may lead to reduced fuel need in another.

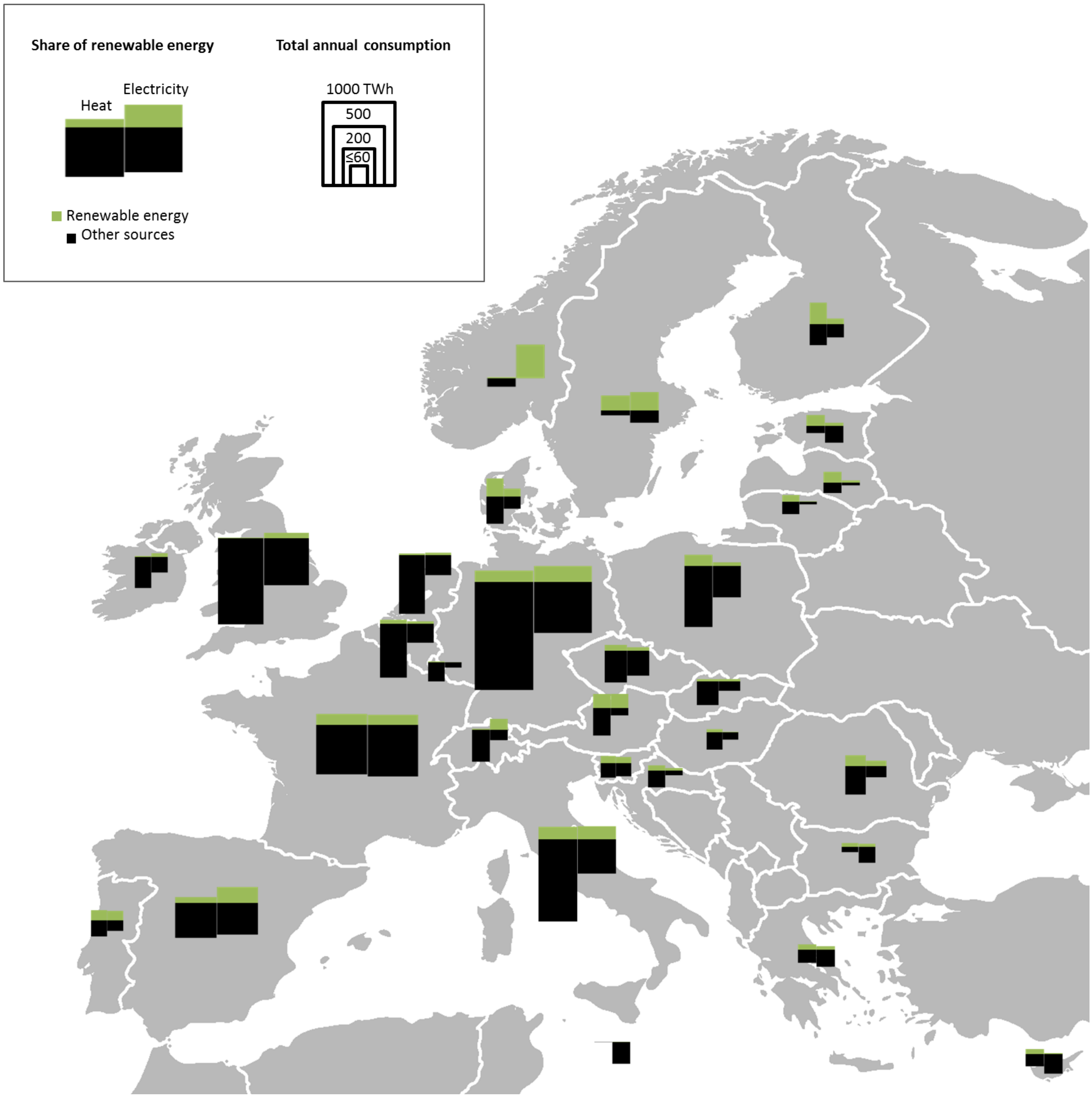

Fig. 5 Annual heat and electricity use in EU countries, Norway and Switzerland. Processed data [4],[6],[7]. All energy, which is not accounted for as electricity, is assumed to be used as heat. (Electricity used for transport and agriculture has been assumed to be zero in the processing. Renewable energy share in agriculture is assumed to be zero.)

D. ENERGY SAVING POTENTIALS

In our work we have focused on Swedish multi-dwelling residential buildings, which accommodate 55% of the total dwellings in Sweden and are usually connected to district heating [8], [9].

In a study from 2012, the energy savings potentials in 11 apartment buildings in mid Sweden were analysed [10]. Table 1 show average figures from this study.

Table 1 Avarage energy saving potentials for different energy measures in Swedish apartment buildings, processed figures [10]. Percentage of total energy used for space heating, tap water and ventialtion, and energy used per square meter heated area.

Measure	**Energy savings**	
	% of total	**kWh/m²**
Insulation on walls	17%	25
Insulation on attic	5%	10
New windows	10%	15
Heat recovery ventilation	10%	13
Solar collectors	9%	12
Photovoltaics	9%	13
Lighting	1%	1

Most of the measures are focusing on heat reduction; only photovoltaics and lighting will give reduced electricity use. Heat recovery ventilation will even give a slight increase in electricity use, which is not accounted for in the presented figures.

By definition, solar collectors and photovoltaics will supply energy to the building and not reduce the demand. However, with a traditional view of the energy system where buildings are consumers of energy, solar energy supplied to a building will have the same effect as energy reductions. In our work we therefor consider all presented measures to be energy saving measures.

E. PURPOSE OF THIS WORK

We want to investigate how owners of Swedish apartment buildings can contribute to reaching the goal of 100% renewable energy, which leads us to the following research questions:

- What is the difference between district heating and electricity savings, in terms of the impact on overall renewable energy shares?
- Which building related measures are the most effective to in the pursuit of reaching 100% renewables?

STATE OF THE ART

Climate benefits are generally quantified as reduced CO_2 emissions. This requires complex calculations in combination with trying to answer a series of questions about how to allocate emissions and how regulatory framework and market functions interact with your measures [11].

In order to reduce the complexity we only focus on the share of renewable energy. This will make the results less exact, but still indicative to formulate an appropriate strategy.

METHODS

A. DISTRICT HEATING SAVINGS

We have picked 30 of the largest Swedish district heating systems with a total heat delivery of 33 TWh in 2012, which is 60% of all heat deliveries in the statistics from the Swedish District Heating Association [12]. The energy mixes of these systems have been divided into four compounds; renewable energy, waste heat, electricity and other energy sources.

We have then estimated the effect of reduced heat demand, taking into account any cogeneration of electricity or use of heat pumps. The assumed ratio between cogenerated electricity and heat is 1:3 and the assumed ratio between input electricity and output heat in heat pumps is also 1:3.

The renewable energy content of waste fuels varies between district heating systems and is for instance 55% in Stockholm and 85% in Gothenburg [17], [18]. In our work waste fuels are considered to be 75% renewable and 25% fossil. Peat is considered as a non-renewable fuel.

In some cases heat is exchanged between district heating systems. This heat is considered to have been produced with 70% renewable energy and 30% energy from other sources.

The data used is annual figures, which is a limitation for the accuracy of the results. This will be further commented in the discussion.

B. ELECTRICITY SAVINGS

The effect of electricity savings has been investigated by many parties, among them Swedish Electrical Utilities' R & D Company (Elforsk). In their report it is stated that there are a number of approaches that can form the basis for environmental evaluations but that the concept of marginal electricity was concluded to be of central interest [13]. By marginal electricity they refer to the last used unit of electricity at any given point of time, which generally is supplied with the most costly means of generation in the generation merit order.

The nature of the marginal electricity thus can shift from time to time, but for reduced electricity use in Sweden the effect will most likely be reduced use of fossil fuels in condensing power plants, either in Sweden or in some of our neighbor countries, as shown in figure 6. Even though the power balancing is usually made with hydro power, the hydroelectric energy will be saved in the reservoir to be used later.

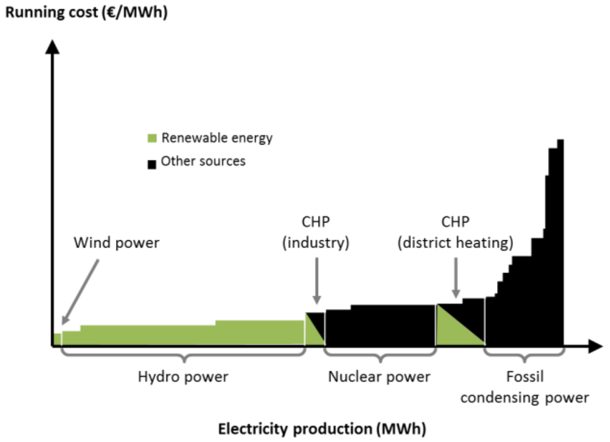

Fig. 6 Principle diagram of running costs for producing electricity, which is used in Sweden [14].

According to EIA the average efficiency of coal-fired plants was 32.5% in 2012 [15]. In our work the ratio between electricity produced and fuel energy used is assumed to be 1:3.

RESULTS

Figure 7 gives an overall view of the studied district heating systems, with fuel mixes along with import of waste heat from industries and net import/export of electricity. Renewable energy sources are dominating, but other sources are not neglectable in many cases (coal, oil, natural gas, peat and the fossil part of waste). Many of the bigger systems have cogeneration of electricity (resulting in electricity export) and a few systems depend highly on waste heat from industries. 9% of the total heat delivered is produced with heat pumps.

For each district heating system we calculate the average effect from heat reductions on fuel use and import/export of energy, according to (1).

$$\Delta E_F = \Delta E_H \left(\frac{E_R + E_W + \Delta E_E + E_O}{E_H} \right) \quad (1)$$

where ΔE_F is change in fuel use and import/export of energy,

ΔE_H is change in heat delivery,

E_R is total annual use of renewable fuels,

E_W is total annual use of waste heat,

ΔE_E is the total annual corresponding net use of electricity,

E_O is total annual use of other fuels

and E_H is total annual heat delivered.

The corresponding net use of electricity is in turn calculated according to (2).

$$\Delta E_E = \frac{E_{HP}}{3} + E_E - \frac{E_{PROD}}{3} \quad (2)$$

where E_{HP} is total annual electricity used in heat pumps,

E_E is total annual electricity used in electric boilers and other equipment

and E_{PROD} is total annual electricity production.

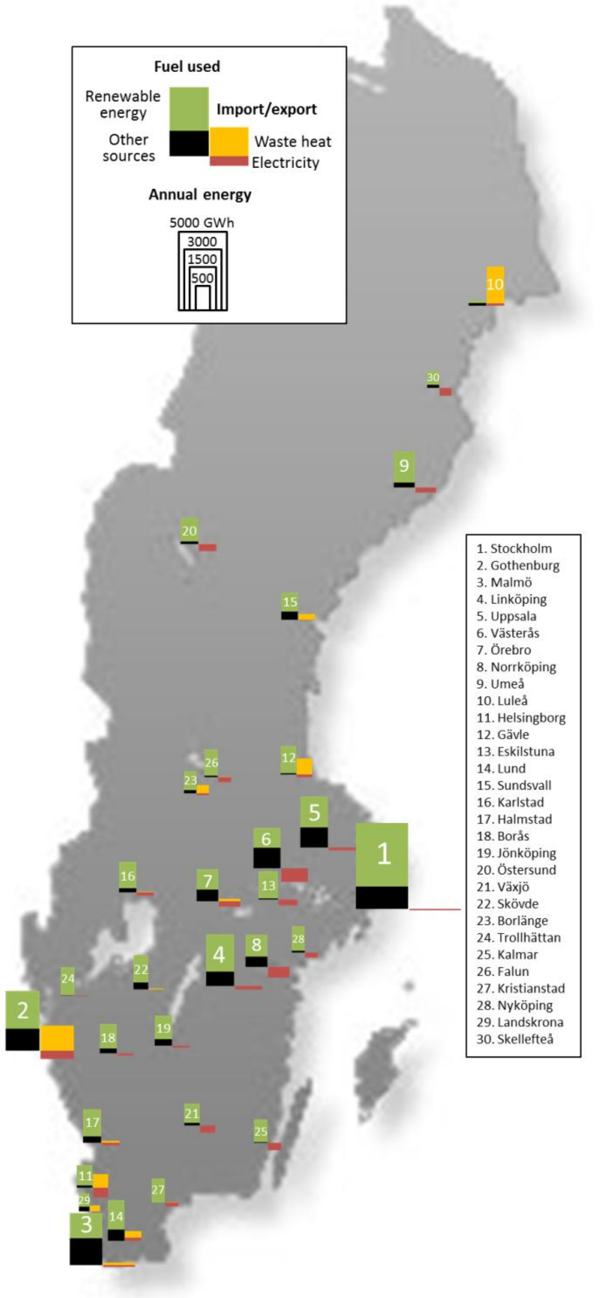

Fig. 7 Energy used for heat production in 30 Swedish district heating systems in 2012. Negative values show export of electricity due to production in combined heat and power plants [12].

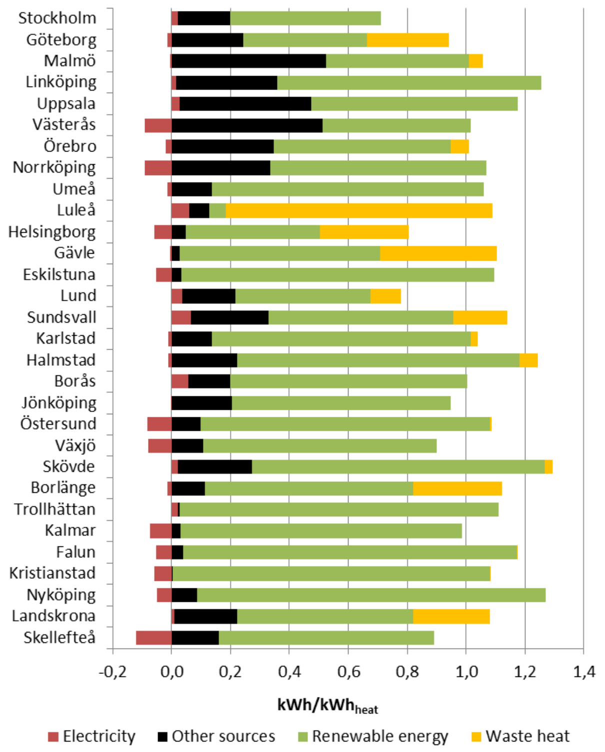

Fig. 8 Reduction of energy used for district heating production, when reducing heat demand. Negative values means that energy use increases. Calculated from annual figures for year 2012. [12]

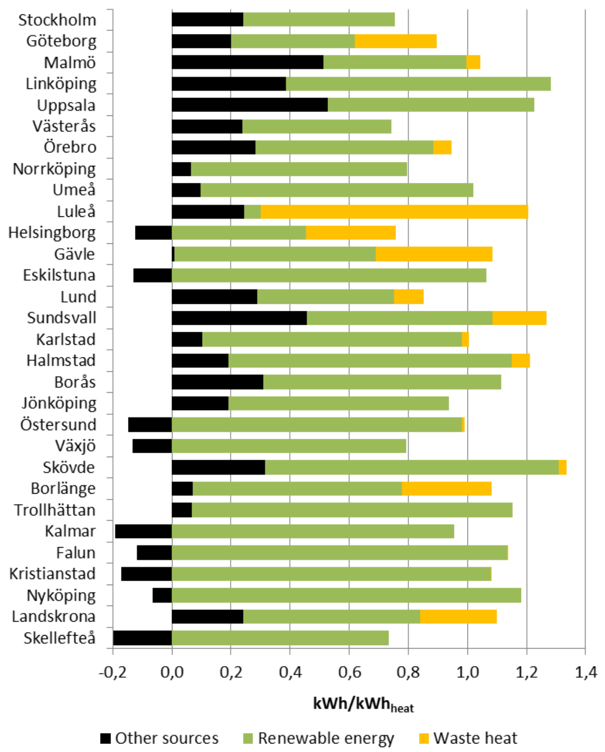

Fig. 9 Reduction of energy used for district heating production, when reducing heat demand. Assuming marginal electricity produced by fossil fuels. Negative values means that energy use increases. Calculated from annual figures for year 2012 [12].

Figure 8 shows the calculated changes in fuels used or waste heat and electricity imported, due to end user heat reduction. Positive values indicate reduced use of fuels or reduced import of waste heat and electricity. Negative values indicate reduced export of electricity from cogenerating plants.

The sum of changes might be >1 due to boiler losses or <1 due to use of heat pumps or to cogeneration of electricity.

In figure 9 values for electricity has been converted to fossil fuel, assuming marginal production in fossil-fired plants, according to (3).

$$\Delta E_{O,E} = 3 \cdot \Delta E_E \qquad (3)$$

where $\Delta E_{O,E}$ is the total annual net use of non-renewable energy sources corresponding to change in electricity use.

In some cases the amount of non-renewable fuel energy is reduced by 50% of the heat reduction, but in general heat reduction corresponds to less than 30% reduction of non-renewable fuels. In 9 cases heat reduction will lead to increased use of fossil fuels, because of reduced electricity production in cogenerating plants.

When using the average values of the 30 district heating systems studied, and comparing them with reduction of electricity, the result is according to figure 10.

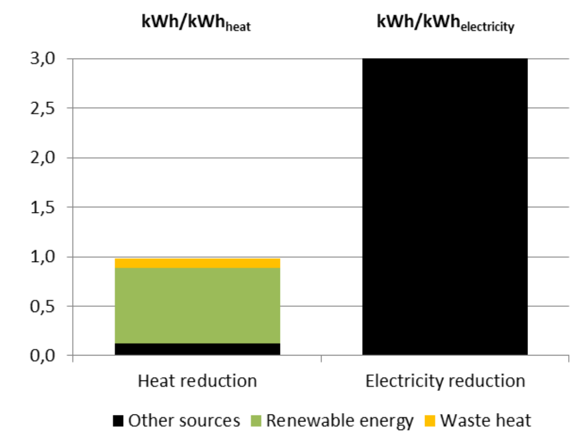

Fig. 10 Reduction of energy used for district heating production, when reducing heat demand (left) and reduction of energy used for electricity production, when reducing electricity demand (right). The left bar shows the average for the 30 district heating systems studied.

When we apply the results in figure 10 with the energy saving potentials in table 1, we get the resulting values in figure 11. For heat recovery ventilation an increased electricity use of 2 kWh per square meter heated area has been assumed.

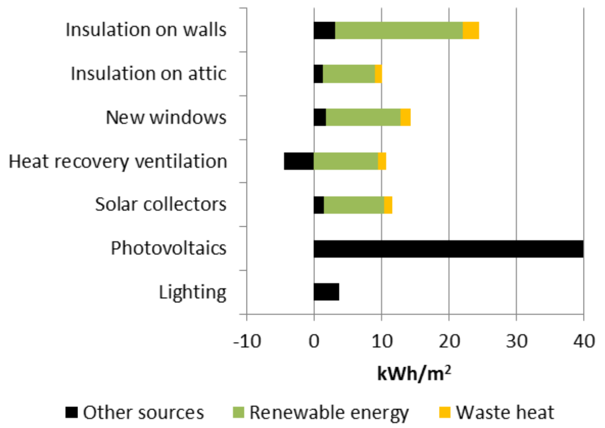

Fig. 11 Calculated effects on heat and electricity production from energy related measures in apartment buildings, per square meter heated area.

DISCUSSION

A. ACCURACY OF THE RESULTS

The analyzed effect on district heating from heat reductions was done with annual figures, which limits the accuracy of the results. Figure 12 show a principle duration curve for the delivered heat, where we assume that renewable energy or waste heat is used for base load and fossil fuels are used at peak load.

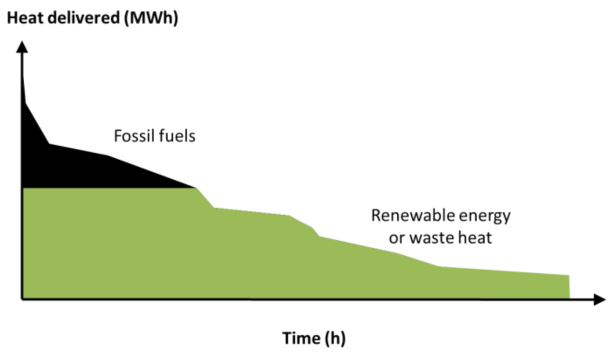

Fig. 12 Principle diagram of annual heat delivery duration and mix of fuels in a district heating system.

In this case any insulation measure in reality would give larger reductions of fossil fuels than calculated, since the heat reductions appear mainly in winter. On the contrary, solar collectors would lead to less reduction of fossil fuels than calculated, as the heat reductions in this case occur mainly in summer. Despite this, we believe our conclusions to be accurate.

More detailed analyses of particular Swedish district heating systems will be carried out within the Reesbe post-graduate school.

B. USING RESULTS IN FUTURE POLICY WORK

Many building owners put a lot of effort into reducing heat demand as a way to lower their environmental impact. This article shows that, within the studied Swedish district heating areas, reducing electricity demand is much more effective in order to increase the share of renewable energy. Installing photovoltaics has outstanding potential of the studied measures and a small measure like renewing the facility lighting may have the same reduction of non-renewable energy as insulating the walls.

In the longer perspective we most likely need near zero energy buildings to overcome the climate challenge and to be able to reach the goal of 100% renewable energy. This "near zero" on average can, however, at least in Sweden consist of new buildings which use very little energy and generate a lot of solar electricity – and of existing buildings which use more energy but also generate solar electricity. The new buildings will become "plus energy" buildings and the heat demand of the older ones will generate electricity through cogeneration in district heating plants.

To achieve this, one first step would be to strengthen the position of photovoltaics in Swedish building regulation code (BBR) by including household electricity as a basis for energy reductions and by calculating the net energy reductions from photo-voltaics on an annual basis [16].

In the very long perspective – when we have achieved a 100% renewable energy system in Europe – there will be no need for Swedish heat consuming buildings, but until then at least there should be a clear distinguish between district heating and electricity in national energy policy and in the building regulation code.

Danish regulations have a ratio between electricity and district heating of 2.5:1, which will be changed to 2.5:0.8 in 2015. Finnish regulations have ratios of 1.7:1.0:0.7 between electricity, fossil fuel and district heating. We propose that Sweden should introduce similar factors, for instance 3:1 as the ratio between electricity and district heating.

OUTLOOK

We expect the trends in Swedish district heating to be even higher shares of renewable energy and even more cogeneration of electricity, which will even further strengthen our conclusions.

One draw-back would be if some waste heat industries had to shut down, which would affect some of the studied district heating systems, and potentially lead to increased shares of fossil fuels in these areas.

CONCLUSIONS

Our conclusion is that building related energy measures generally should focus on reducing use of electricity rather than heat, within Swedish district heating areas. We have also found that installing photovoltaics is a building related measure with a large potential to increase the share of renewable energy.

ACKNOWLEDGEMENT

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NEXT GENERATION DISTRICT HEATING

-FINDINGS AND LESSONS FROM THE PROJECT

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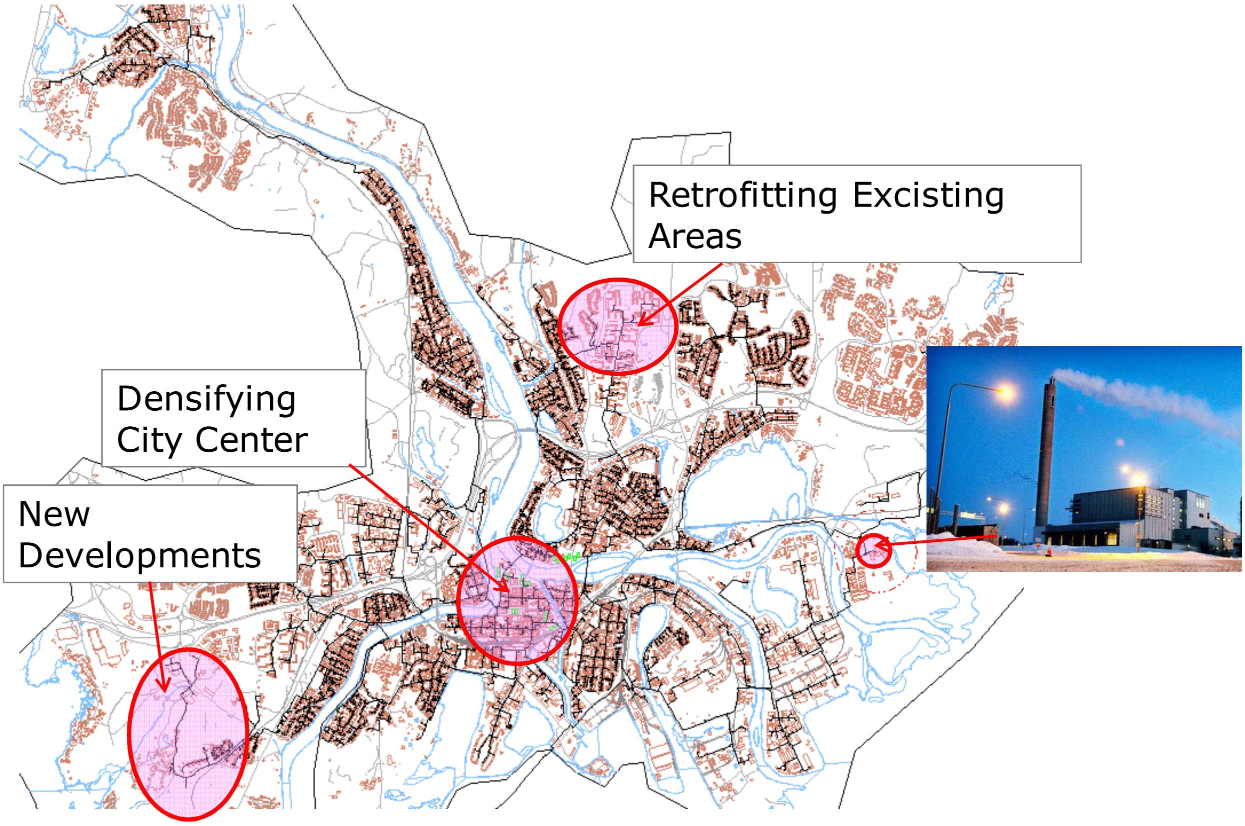

Fig. 1 Map of the Karlstad district heating net. Simulated areas are highlighted in red. Production plant to the right.

ABSTRACT

What will consequences for district heating be as more and more properties become energy efficient? We have investigated the impact of energy efficient buildings on environment, economy and district heating technology. Calculated building loads for existing, retrofitted or new buildings, some with integrated solar heating have been used in simulations of the Karlstad district heating net.

The energy efficiency measure with largest implication is installation of exhaust air heat pumps, leading to district heat mainly being used during times of high cost peak production.

“Plus houses”, where integrated solar panels provide more energy than the annual demand, can prove to be technically hazardous and costly for the district heating company as it requires considerably larger pipes than motivated by heating needs.

Trading margins will decrease, which makes optimal management of DH systems imperative. The future of district heating’s lies in a transition towards well insulated, low temperature nets; resulting in lower heat losses and ultimately better conditions for CHP production as well as opening up for more surplus energy.

For the implementation of lessons learned in this and other studies to be successful, collaboration between municipalities, local real estate owners and district heating companies must be established at an early phase of projects.

INTRODUCTION/PURPOSE

Trends in public opinion on environmental issues imply that we, in the next few years, will see a deviation from previous energy patterns. Energy will no longer be utilized merely at lowest possible cost, but people will place increasing demands on environment, third party impact and long term sustainability.

We can primarily expect a far-reaching reduction in energy use, but also, to some extent, self-production of heat in dwellings and other premises -some buildings will even become energy exporters. Energy efficiency and self-production of heat may not necessarily provide the lowest cost for the user, but will give a sense of independence and freedom of choice.

For district heating, this offers an opportunity to stand on the customers' side, offering flexible and environmental friendly energy solutions. In particular, this places new demands on design and operation of DH distribution, which to some extent will become bidirectional -with all that may entail in new systems, control and design models.

New buildings today and in the future will have much lower system temperatures for heating than previously. This, combined with a reduced energy profile in existing buildings, will in time give district heating companies the opportunity to lower their supply temperatures, resulting in reduced heat losses and increased CHP electricity production.

Energy use for heating and hot water in residential and commercial buildings in Sweden has decreased by 15-20 % in 15 years (Fig. 2). However, "free" energy from heat pumps is not included in the reported energy statistics -this means that the extensive installation of heat pumps has contributed to this reduction.

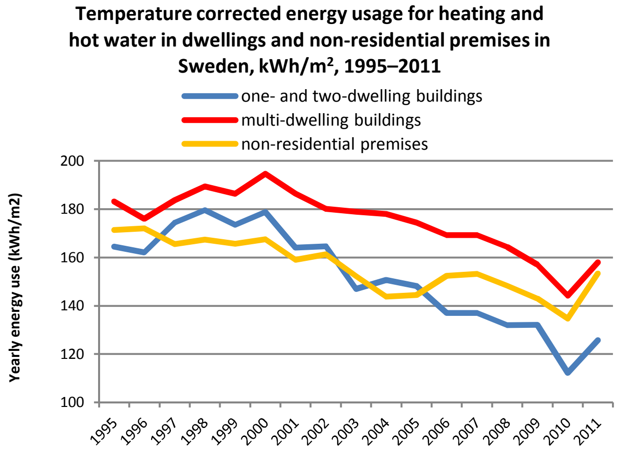

Fig. 2 Degree day adjusted energy consumption for heating and hot water in residential and commercial buildings, kWh/m^2, 1995-2011. (Energy In Sweden 2013)

It is important to identify how conditions for district heating distribution might change and find technical solutions to meet these changes, on network and on consumer level. The aim of this study has been to explore the demands that will be placed on the district heating system due to changing operating conditions in terms of energy efficiency, new low energy building schemes and customers supplying heat to the net (prosumers), including decentralized solar energy.

Some of these changes can already be observed in district heating networks, albeit to a relatively limited extent. How swift the transition will occur; the speed of renovation or new construction; will depend on policy instruments, general economic conditions and price trend on for instance electricity and district heating. Assuming the fulfilment of the EU 20-20-20 vision, we will, however, see significant changes within just the next 5-10 years.

How heating load will change and the technical and economic impacts on production and distribution costs are discussed in this study as well as the possibilities that exist in meeting this challenge.

A comparison between different types of exhaust heat recovery (air-to-air heat exchangers and exhaust air heat pumps) is made. Also, the importance of low system temperatures in the network and tools to reduce both the feed and return temperatures is demonstrated. Secondary connections to the district heating network, with low system temperatures are also studied.

Top concerns

- How does exhaust heat recovery in connected buildings affect network operation, economy and environment in a system perspective? What is the difference between types of heat recovery: air-to air heat exchanger or exhaust air heat pump, connected to the radiator system exclusively or to both the radiator and the hot water system?
- How can new low-energy areas be connected to the existing district heating system in a sustainable way, while maintaining good economy for customer and supplier?
- What technical challenges can be expected when the customer is allowed to supply district heating to the grid? How can these problems be prevented or managed?

STATE OF THE ART

District heating in was instigated in Sweden in the late 40s/ early 50s, but did not really take off until the oil crises in the 70s. The production of district heat has adapted to surrounding conditions over the years; and has moved towards environmentally friendly fuels, cogeneration and waste heat recovery.

The distribution of district heating, however, works for the most part in the same way as it did when district heating was established in the country. Tube heat exchangers has been replaced with plate heat exchangers and, to a large extent, prefabricated substations, but network temperature and pressure levels has remained largely unchanged. We see that the built community is about to embark on a transformation where energy efficiency is taken to a higher level. If district heating is to compete with local energy solutions, technology must be greatly modified.

METHODS/METHODOLOGY

To get an idea of how altered network conditions will affect operating parameters, such as temperature, pressure and flow; simulations of different scenarios have been conducted in NetSim®, which is a grid simulation software for district heating, widely used by Swedish DH companies. By using inserted district heating pipes and production data and with detailed data on customer consumption and return temperatures, it is possible to simulate network behaviour in various operating conditions.

For this study, we used a network model of the district heating system in Karlstad, Sweden. The locations of simulated areas are selected in consultation with Karlstad Energy, in order to get as realistic case scenarios as possible. A schematic diagram of simulated areas is shown in Fig. 1.

Simulated areas

Some different area types that already exist to some extent in the built environment, but in the future will become increasingly common, has been simulated in the study:

1. Energy efficiency retrofitting of an existing multi-dwelling (Million Programme) area.
2. New low energy single dwelling area; Half of the about 50 houses have solar panels for own domestic hot water (DHW) use.
3. New multi dwelling area (about 1000 apartments), consisting of houses built according to low energy and Passivhaus standard. Some of the buildings are solar energy exporters; “plus houses”.

1. Energy efficiency retrofit of a Million Programme area

Fig. 3 Million programme buildings in Rud, Karlstad; recently retrofitted.

The Million Programme[1] was an ambitious housing programme implemented in Sweden between 1965 and 1974 to provide affordable homes for all. The aim of the programme was to build a million new dwellings in a 10-year period (hence the project's name). Today, many of these dwellings have large renovation needs and strong measures are taken to ensure that they are retrofitted. How extensive these renovations or retrofittings will become, and what measures will be implemented, will vary, of course.

In Karlstad, the renovations of a Million Programme area (all in all 855 dwellings) in Rud has begun; (Fig. 3 and Fig. 5). In conjunction with raising the apartment standard, a number of energy-saving measures have been implemented, including balcony glazing, energy efficient windows, adjustment of heating systems and exhaust air heat pumps for domestic hot water and space heating. Degree day adjusted monthly consumptions of heating prior and after renovation of the first of four areas (Horsensgatan 100-127) are displayed in Fig. 4. After measures were completed in spring 2011 there is, as expected, a significant reduction in heating demand. Due to teething problems with the exhaust air heat pump, district heating consumption was higher than expected during the summer months, though.

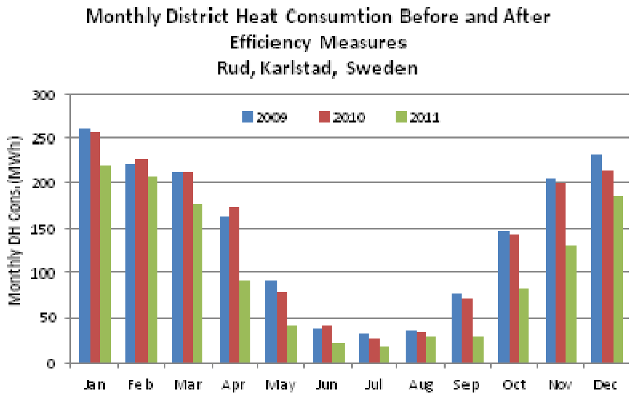

Fig. 4 Degree day adjusted monthly district heat consumption for Horsensgatan 100-127 in Karlstad, before and after retrofit in spring of 2011.

The baseline for our net simulations is an existing million programme area in the DH network, where the heat load changes in accordance with what can be expected of this type of building when energy efficiency measures are applied. We have studied how a variety of measures would affect the consumption of heat and electricity. Since this is an existing area in the network, there were no changes made in DH pipe size or material.

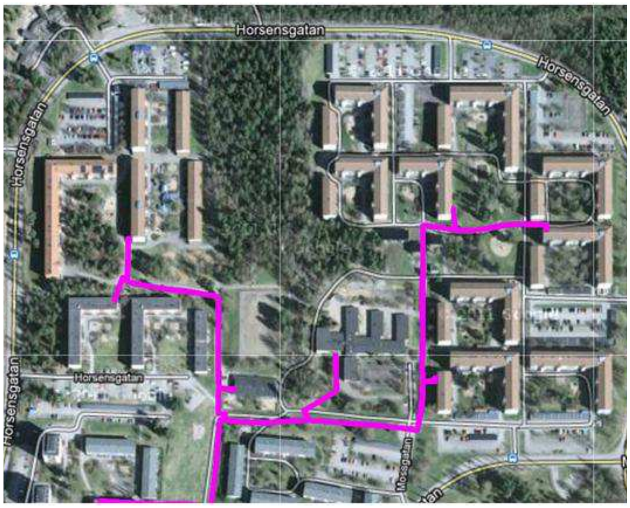

Fig. 5 Aerial view of residential Rud in Karlstad, with district heating network in purple. (Google Maps with own editing). Horsensgatan 100-127 at top left.

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[1] Miljonprogrammet in Swedish

2. New low energy single dwelling area

The area is connected to the periphery of the DH network (Fig. 1 and Fig. 6); both primary and secondary connections are simulated.

Fig. 6 DH piping for single dwelling area. Houses on right side of streets are fitted with solar collectors for domestic hot water.

Case 2A: Reference area. Primary connection with prefabricated substations and storage for solar and district heat

The simulated network consists of steel pipes with standard insulation, class 2. In line with Swedish custom, parallel plate heat exchangers are used for connection; DHW and space heating respectively. In addition, houses with solar panels will have a combined heat storage for solar and district heating (Fig. 7). Solar houses service pipes are dimensioned for space heating demand plus required DHW charging load. Other service pipes were designed for DHW needs. Smallest possible pipe size was set to DN20, in order to avoid clogging of pipes.

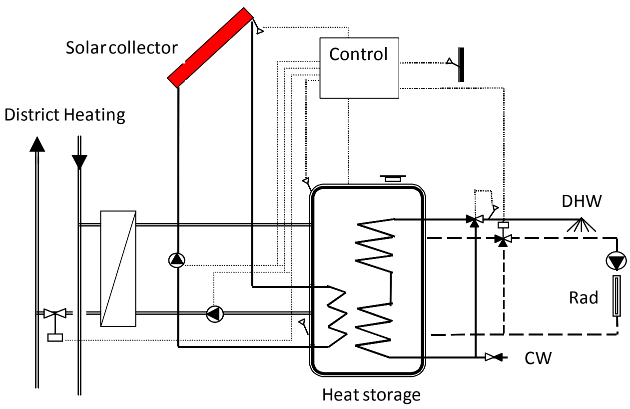

Fig. 7 Heat storage for solar and district heating for single dwelling (Zinko, 2003).

Case 2B: Primary Connection with prefabricated substations and DHW storage

Although heat demand for domestic hot water also can be assumed to decrease slightly in the future, DHW demand will in future buildings have a significantly larger share of the total heat load than today. Furthermore, large instantaneous peak loads can occur when hot water is drawn. To avoid having to design service pipes to accommodate this, DHW storage is installed in each substation, which facilitates the use of smaller pipes.

This reduces heat losses in the distribution network, but increases installation costs in substations. In areas with low heat density, this extra investment may be worthwhile, since long distribution culvert make pipe heat losses more critical.

In this simulated case all houses are provided with DHW storage; solar and non-solar. Service pipes are dimensioned in the same way as for buildings with solar heating in the reference case (2A).

As in the reference case, the pipes are steel with standard insulation, class 2. However, in an attempt to trim pipe sizes, the smallest dimension is set to DN15 and clogging is avoided by installing filters at area connection point. This results in a lower average pipe diameter than in the reference case (24.8 mm compared to 28.4 mm). The difference is not dramatically large, partly because half of the houses in the case 2A already are equipped with storage tanks.

Case 2C: Low temperature secondary net (~60 °C)

There are several advantages of a secondary connected network:

- The area is less sensitive to available differential pressure, 1-1.5 bar is enough at area substation.
- For a new-built area a supply temperature of 60-65 °C is sufficient, which causes a significant impact on distribution losses.
- The pressure level in the secondary network can be kept lower (PN6, compared to PN16). Lower pressure and temperature allows the use of pex pipes, which provides more flexibility in choice of system and enables lower installation costs. A lower pressure rating also contributes to lower civil engineering costs.

The secondary network design has 65 °C supply temperature of and 30 °C return temperature. The network consists of well-insulated PEX pipes, designed for low heat density DH. Total pipe length is slightly more than for the steel pipe systems (1671 m compared to 1666 m for case 2A and 2B).

Table 1 Mean inner pipe diameter (D_i) and heat loss coefficient for single dwelling areas in study. Total number of pipes for all cases is 200.

Simulation case	Di (mm)	Heat loss coefficient (W/m°C)
1. Reference area	28,4	0,26
2. DHW storage	24,8	0,24
3. Secondary net	28	0,15

3. New apartment block area

Simulations of a new development consisting of multi dwelling buildings with low energy and Passivhaus standard and "plus houses" (see definition below); 7 Passivhaus buildings, 7 low energy and 6 plus houses are connected to the district heating network. For comparison, an area without solar heating is also simulated; i.e. 7 Passivhaus and 13 low-energy houses.

Plus house

The definition of a plus house is that it generates more energy than it consumes. The energy typically comes from sun or wind. Plus houses that deliver a surplus to the district heating network are not common yet, but in Växjö, Sweden, a single-family plus house, supplying energy to the electric and district heating grid both has been in operation since April 2013 (Smålandsposten, 2014). In this study, we chose not to include single dwelling plus houses, as required installation costs were considered too expensive relative to the produced heat. They are, however, included in the multi-dwelling areas.

Each building is simulated with 500 m^2 of vacuum tube solar panels, which is close to the limit of the buildings' available roof area. The building has no separate storage tank; instead it's using the DH net to handle excess solar energy. For the houses to qualify as plus houses, they should also have a net surplus of electricity to be supplied to the grid. The electricity, in this case, needs to come from a source other than roof mounted PV cells, as the available space already is occupied by the vacuum tube panels. Possible solutions are wind turbines, for buildings in city periphery, or solar panels on the walls. Combined heat and electric solar panels could also be a way to maximize use of the roof area. Further analysis of plus house electricity is not included in this study.

Load distribution of DH use and solar heat generation was calculated in VIP-Energy®, and is presented in Fig. 8. For the house to be able to deliver a net surplus of heat, on an annual basis, the buildings heating requirement must be close to Passivhaus standard.

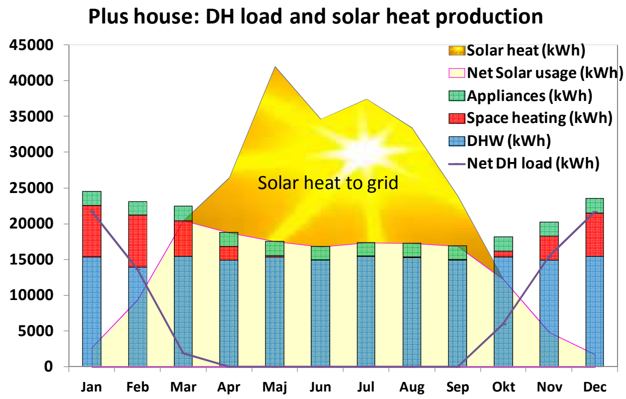

Fig. 8 Monthly heat demand and produced solar heat for a simulated plus house.

Multi dwelling area with plus houses, with primarily (3A) and secondary (3B) connection

Building integrated solar collectors on the plus houses deliver excess heat to the DH supply pipe, which also mean that when the collected solar heat exceeds the total heat demand from other buildings in the area, the area becomes a heat exporter to the rest of the DH network. The main network will then serve as heat storage and, to some extent, level out load variations.

One characteristic that will affect the operating conditions is that the area's buildings during hot summer days will make the area self-sufficient in heat, while still needing full heating power in winter, which is supplied via district heating.

For plus houses, the design of service pipes are decided by the flow needed to deploy solar heat to the distribution pipes. In addition to solar flux, the flow requirements also depend on the return temperature that the plus houses get from the DH net. For the simulated area there is a major difference between the main network return temperature (about 60 °C) and the return temperature from the other new buildings in the area (33 °C). This means that plus houses closer to the main network must have service pipes that can handle a higher flow rate than those further away.

Service pipes to the other buildings in this scheme are dimensioned for the domestic hot water requirements, which is the dominating design load.

Both cases are simulated with standard steel twin pipes, insulation class 2. Overall length of pipe network is 2880 m and the average pipe diameter is 78,2 mm.

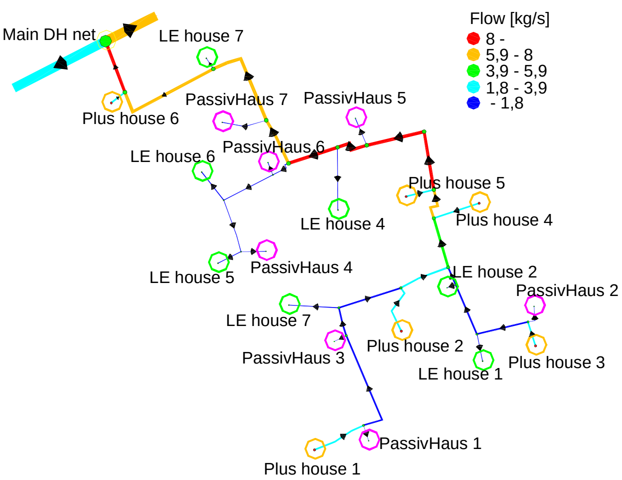

Fig. 9 Multi-dwelling area with Passivhaus, low energy and plus houses. Simulation of dimensioning solar heat delivery to the network (300 kW/house), at 20 ° C outdoor temperature. The figure shows pipe flow rates and flow direction.

For this simulation, the area's pipe system has been designed for sufficient network capacity to transfer heat from the plus houses to the main network. In addition to increased sizes for plus house service pipes, virtually all distribution pipes are larger than needed for the building's heating needs solely. This in turn leads to higher installation costs and more heat losses than the area would otherwise have had.

Furthermore, for the plus houses, thermal bypasses become necessary to achieve high enough supply temperature at substations, even at the design space heating load. Among other things, this leads to higher return temperatures in the area.

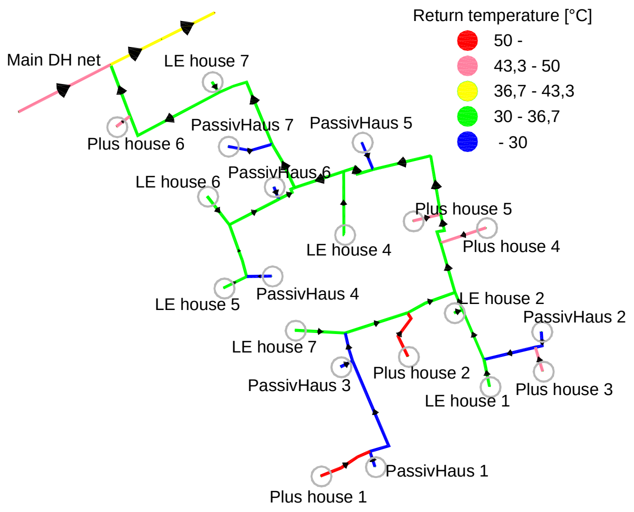

Fig. 10 Return temperatures in plus house area, at design heat load (-23 ° C)

Multi dwelling area with Passivhaus and low energy houses only

Since the pipe diameters and thus the total network volume becomes significantly larger with plus houses in the area, a simulation was made for the same area, where the plus houses were replaced with low-energy buildings. The overall pipe length for the network was not affected by this, but the average diameter of the pipes went from 78.2 mm to 48.5 mm, compared with the plus house area. Thus, if the network is dimensioned for the buildings heating load only, the network volume will be cut in less than half (15 m^3 compared to 39 m^3 for the plus house area).

DH driven appliances

Transferring energy use from electricity to district heating can increase the heat load for low-energy and passive houses. DH heated appliances are, since a number of years, in operation in a demonstration house in Gothenburg (Zinko, 2006), and have been installed in a couple of new areas in Sweden, including Västerås and Växjö. In our simulations, we have equipped the new development dwellings with dishwashers, washing machines and dryers equal to the ones of the Gothenburg house.

DH driven appliances can contribute to the overall target of environmental friendly district heating, without significantly increasing the customer's energy costs (we assume that some increase in cost can be accepted if comfort is also increased). There are two major problems associated with district heating distribution in areas with low heat density; 1) low annual heating load makes it harder to write down investments in the distribution system, and 2) low summer heat load makes it harder for district heat distribution to function well. This makes it interesting to seek ways to increase heat load and promote sustainable use of district heating; such as applying techniques where electricity is replaced with district heating. As long as coal condensing is the marginal electricity production, a reduced use of electricity will have a significant impact on CO_2 emissions and associated climate ramification.

Heat driven appliances are also suitable for other renewable energy sources, like solar and bio fuels which, combined with the widespread use of these devices, makes it important to keep exploring the possibility of using heat instead of electricity in these machines.

RESULTS

1. Energy efficiency retrofit of a Million Programme area

A reduction of the area's heating needs does not influence the operation of the network to any great extent. Something that may well adversely affect the district heating distribution, however, is when exhaust air heat pumps almost completely removes the summertime district heating load. This could lead to unsatisfactory low supply temperature at the substation. The problems can be reduced by increasing flow and thus reduce cooling due to pipe heat losses. In order to maintain a high enough flow, bypass valves may have to be installed at the ends of service pipes. These can be of various types; most are manual valves or thermostatic valves. Manual valves will usually provide too high bypass flows, as they are difficult to adjust. Additionally, a flow that is correct at one load period, say in winter, can be too small in summertime. Thermostatic valves work better, but not always entirely satisfactory and experience have shown that they often malfunction after some time in use. An alternative solution can be a regulated control valve with a set supply temperature. For buildings with PLCs regulating the system, the existing control valve for domestic hot water can be used for this purpose.

The district heating supply water temperature during summer operation in Rud is shown in Fig. 11. It is assumed that the connected properties have exhaust air heat pumps for domestic hot water preparation and temperature controlled bypasses with a supply temperature set point of 55 °C. Despite a certain recirculation flow, the supply temperature drops 20 °C before reaching the substations at the outer edge. The flows necessary to maintain adequate supply temperature do not need to be excessively high; mainly due to the fact that the supply temperature holds a pretty high level right up to Rud. Areas in the further outskirts of the district heating net may need significantly higher bypass flows.

Although increased flow will ensure that required supply temperature level is held, it should be noted that this will also result in higher distribution heat losses.

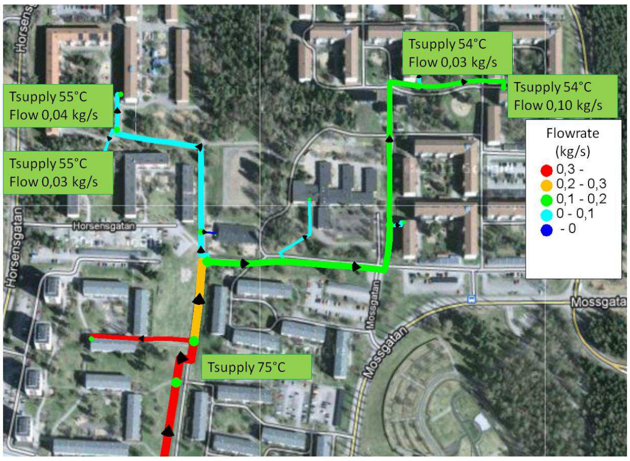

Fig. 11 Flow temperature and bypass flows for Rud. Summer load with exhaust air heat pumps in all connected buildings.

In our scenario, retrofitting the building envelope alone reduces heating consumption by about 24% (see Table 2). If air-to-air heat recovery is added, district heat demand is reduced by 41% and when exhaust air heat pumps are connected to the radiator system, the district heating load is lowered by 49%. With exhaust air heat pumps providing heat to both domestic hot water and space heating, over 60% of the district heating load disappears. However, when increased electricity consumption is taken into consideration, the energy reduction for the different exhaust air recuperation systems do not differ as much.

A calculation of the primary energy consumption was also made, where DH production was assumed to consist of a biomass fuelled CHP plant for the base load, and biomass HOB plus an oil boiler for peak loads. Produced electricity was assumed to replace fossil electricity and credited with a factor 2,6 (see Table 2). These calculations show that, in this DH system, heat recuperation with air-to-air heat exchangers is, by far, most energy efficient, when primary energy is considered. Air-to-air HEX used less than half the primary energy that the heat pump did (1802 MWh compared to 3735 MWh, annually).

Also, having previously accounted for about 5 % of the total heating load, the relative distribution heat losses increases to about 12 % or more if exhaust air heat pumps are installed.

Table 2 Annual energy demands in a Million Programme area with about 855 apartments, after different measures.

District heat (DH) demand after various measures in Million Programme area				
Measure	**DH MWh**	**Electr. use MWh**	**Energy, tot MWh**	**Primary energy MWh[2]**
None	6600	132	6732	2819
Retrofit only	5015	100	5115	2142
Retrofit plus air-to-air heat exchangers	3872	135	4007	1802
Retrofit plus exhaust air heat pumps -DHW and space heating	2898	905	3803	3735
Retrofit plus exhaust air heat pumps -space heating only	3392	717	4109	3560
Distribution pipe losses	341	N/A		

2. New low energy single dwelling area

In Fig. 12 we see a summary of the area's heating needs (split into space heating, DHW and appliances). The building's heating needs were assumed to be the same regardless of connection method. Pipe heat losses are also included in the diagram.

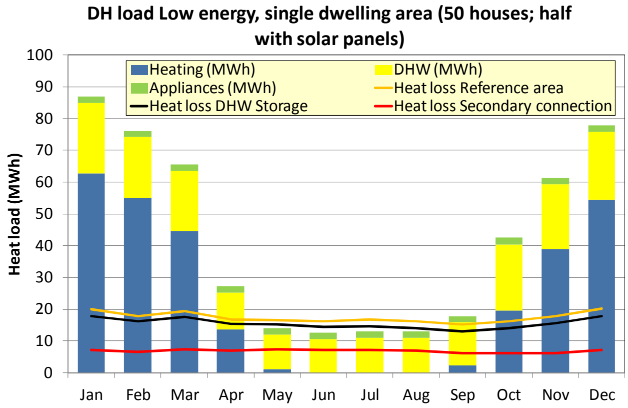

Fig. 12 Monthly district heat sale in a single-dwelling area with low-energy buildings and houses with solar panels. Heat losses for the different connection options are displayed as lines on the chart.

Because of the areas low heat density, the heat losses are expected to be rather high relative to the load. The reference area has the highest heat losses; 29% of

[2] Primary energy use was calculated in a system perspective with the main DH production from a biomass fuelled CHP plant. Produced electricity was accredited with a factor 2,6.

produced heat is lost in distribution. The heat losses for secondary connected area is significantly lower; 14%. The major reasons for this are lowered system temperatures and considerably better pipe insulation.

3. New apartment block area –"Plus houses"

The monthly consumption of district heat in the plus house area is compared with corresponding monthly consumption for a dwelling area without plus houses in Fig. 13. Not only has the latter area a higher heating demand, which means that relative distribution heat losses are lower; 10%, compared to 16% for the plus house area. Fig. 13 also shows the heat losses for a secondary connection for the plus house area. This clearly shows the importance of low system temperatures. Without any other measures, heat loss decreases from 16% to 12%. Admittedly, one should take into account that lower system temperatures, in this case, also means lower temperature difference (DT) between supply and return pipes, which requires higher flows. However, because hot water loads and supplied solar heat will. in this case, set the design for service and distribution pipes, dimensions will be sufficient to cope with this flow.

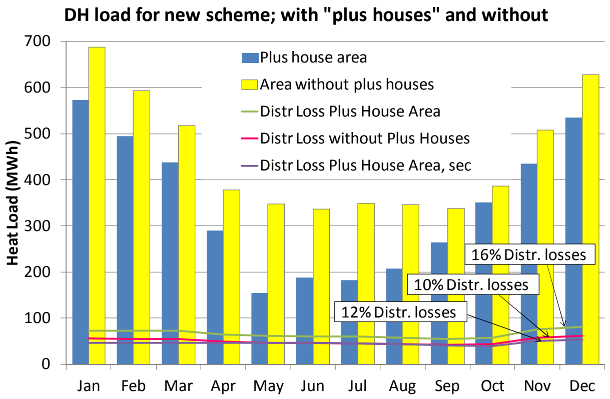

Fig. 13 Monthly heat sales in a multi-dwelling area with Passivhaus, low energy and plus houses relative to the same area with only Passivhaus and low energy houses. Heat losses for the different connection options (including secondary connection) are displayed as lines.

DISCUSSION

Despite changes in the built environment, district heating will still be an important part of a sustainable future. District heating sales are predicted to go down, which forces DH companies to reduce cost and, possibly, find new ways of increasing revenue. Some ways to do this are:

- More effective grid operation; optimize temperature and pressure levels, make sure consumers do not use excessive DH flow, ensure good insulation and don't over-size pipe dimensions.
- Lowering production costs; lower supply temperature will increase CHP electricity production, lower return temperature will increase potential heat recovery from flue gases; both will facilitate greater use of surplus energy.
- Cooperation and planning with local authorities, developers and property owners at an early stage of each project, to coordinate procurements and also find energy solutions that are financially, technically and environmentally sustainable from a systems perspective as well as for individual parties.

OUTLOOK

Special features of the next generation of district heating will be:

• Lower energy consumption in buildings compared to before

• Low temperature levels in the district heating network (down to 60 °C or lower)

• Flexible supply of heat to the district heating network, with or without third party access

CONCLUSIONS

Exhaust heat recovery

If all properties in a Million programme area gets exhaust air heat pumps connected to both space heating and domestic hot water, the entire heating load for the area will disappear for almost half the year (spring, summer and fall). That part of the network could either be completely shut down (the impact of this would need to be investigated further), or a bypass flow will be needed to keep the supply temperature high enough. Quite possibly, one or two customers in the area will still have a need for district heating, and for them it is necessary to ensure delivery. These bypass flows will increase heat losses as the district heating return not will be cooled off in the substations.

The far better alternative to exhaust air heat pumps is exhaust air-to-air HEX. They will use less primary energy than the heat pump; peak loads will be reduced, while summer load will be unchanged and, provided the price of DH is low enough, will have lower running costs.

Plus houses

For the simulated house to be able to, on an annual basis, deliver a net surplus of thermal energy to the grid, it's required that essentially all of the available roof area is covered with solar panels, while the building's own heat load is close to Passivhaus standard.

In order to deliver heat from the solar panels to the net each plus house must have adequate pumping capa-city to drive the heat out to the supply pipe and, equally important; service and distribution pipes for district heating must be designed for the required flow. This implies both a higher installation cost, and higher heat losses in the network. In our simulations, this meant DN65 service pipes. With service pipes designed for the building's heat load instead, they would've been DN32. For the area, this meant that, due to larger pipe dimensions, the distribution heat losses were more than 30% higher than with pipes designed for the buildings heat load. The Swedish pipe installation cost catalogue (Kulvertkostnadskatalogen, 2007) indicates that also pipe installation costs increased correspondingly.

Our recommendation, if solar heating for supply to the DH net is to be installed, is that the solar installation should be designed so that excess heat can be transferred in pipes that are designed for the building's heat demand. The “vacant” roof surfaces can be used for PV-cells. This is probably even more viable in other European countries, where electricity prices are higher than in Sweden and/or the revenue for selling electricity back to the grid is better. For those who still choose to install plus houses with over-sized pipes, in order to manage solar heat delivery; it would be fair for the extra expenditures incurred in the form of higher installation costs and higher heat losses to be covered by the owner of the solar installation.

New low energy developments

The simulations show that it will still be possible to connect single dwellings to the district heating network, but perhaps not in the traditional way, through primary connection. The main economic factors here are to increase revenues and to reduce installation costs (fixed costs) and heat losses (annual costs). The scope for increasing revenues is relatively limited in a single-family area. In order for customers to choose district heating, it must be price competitive with the alternatives and the DH price trends must also be favourable. One way is to increase sales is by installing heat-powered appliances, something that also lowers electricity consumption. To get low heat losses, the temperature level in the network needs to be as low as possible. Another important contributing factor is pipes with good insulation properties, which however results in higher installation costs. The pipes used in the simulations for a secondary connected area are relatively well balanced in terms of heat loss versus installation cost, but there are several factors to consider in each case, such as pipe lengths and dimensions, heat production and distribution costs and current piping prices. Thus, it is crucial that the one responsible for pipe installation also takes responsibility for the future operation of the secondary network.

Apartment building areas are also best connected secondary to the district heating network. By creating "islands" of low temperature DH nets within the larger DH network, the entire system gets prepared for a gradual transition to a low temperature system for the entire network. In addition to lower heat losses, favourable electricity production in cogeneration and other production and distribution advantages, this enables utilization of waste heat from lower temperatures. 60-70 ° C is enough in the secondary system simulated in this study, but it is theoretically possible to go even lower in temperature, provided that the risk of Legionella growth can be eliminated.

Previous studies have also shown that it is of great importance to the overall distribution economy to select as small pipe dimensions as possible, and proper design of service pipes is not to be neglected (Zinko, 2008). Earlier research in programmes sponsored by the Swedish District Heating Association (Pohl and Klingemann, 2006) have demonstrated methods to hold installation costs down, such as shallower pipe depth; collocation with other systems, single procurements or alternative installation methods.

ACKNOWLEDGEMENT

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http://www.svenskfjarrvarme.se/Fjarrsyn/Forskning--Resultat/Ny-kunskapresultat/Rapporter/Teknik/Nasta-generations-fjarrvarme/

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ENERGY SCENARIOS FOR NEW BUILDINGS WITH DISTRICT OR SOLAR HEATING

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ABSTRACT

District heating (DH) may be useful for low-energy buildings if DH utilises resources that cannot be used in individual buildings.

Energy scenarios for a new district in a Swedish town were elaborated. In scenario A, *normal* buildings have external energy supply. Scenario B has low-energy buildings using external and solar energy. DH supplies household appliances and solar electricity, but not heat, is produced to make DH viable despite low heating demand. Scenario C has almost self-sufficient nearly zero-energy houses.

Scenarios were outlined, components chosen and energy use simulated. The MODEST model optimised city-wide DH production. Waste is the main DH fuel but biomass covers new demand.

Scenarios A and B have similar annual DH use. B, using some DH for washing instead of heating, has less seasonal variations. In C, without DH, solar energy is the main supply.

B and C use least primary energy. Using carbon-lean electricity, CO_2 emissions are lowest in C, lacking DH-fuel emissions, and solar heating is more climate-friendly than DH.

With fossil electricity, scenario B, using little electricity but much DH, has lowest CO_2 emissions, emphasized by CHP electricity displacing coal-based power. B uses less primary than final energy, also with partly nuclear electricity.

INTRODUCTION

Societal transitions are required to reduce resource consumption in industrial countries to sustainable levels. Some desired changes concern the built environment. Many new buildings need little energy and all new houses in the European Union are supposed to be so called nearly zero-energy buildings in a few years. Low energy demand means that buildings can be more self-sufficient in energy, which indicates less dependence on the surrounding world. But connections to surrounding energy systems may level differences between energy demand and energy extraction ("energy production") in, for example, solar cells that produce electricity. District-heating systems also make it possible to utilise energy resources that are difficult to use directly in individual buildings, such as municipal waste and unrefined solid biomass. Therefore, it may be beneficial to use district heating at least in densely built areas even if the buildings have low heat demand.

In this paper, three energy scenarios for the new development (city district) *Södra Butängen* in the Swedish town *Norrköping* are presented [1]. The scenarios include electricity, heat and cooling and range from completely external energy supply to almost self-sufficient buildings. The study served as a step in the spatial planning process for the district. How energy issues can be considered in spatial planning has previously been studied by e.g. [2], [3].

Estimated energy extraction, supply and use in the district are presented. It is also shown which approximate primary energy use and carbon-dioxide (CO_2) emissions the scenarios would cause depending on how the use of various energy carriers is considered to influence the surrounding energy system.

STATE OF THE ART

New buildings can have low energy demand and high energy extraction, primarily of solar heat and electricity. It may be argued that new houses connected to district-heating networks only can have modest insulation because it would not be cost-effective to have high capital costs for supply as well as end-use technologies [4]. On the other hand, it has been shown that low-temperature district-heating networks, which have low losses, can supply low-energy buildings at competitive costs [5].

Reductions of space-heating demand in existing buildings can even be combined with switching to district heating and reduce CO_2 emissions and socioeconomic costs [6]. Heat demand reductions in present buildings supplied by district heating can decrease heat-only production more than combined heat and power (CHP) production and reduce CO_2 emissions [7].

It is important to have a comprehensive view on energy issues and to consider how solutions influence resource use, which can be represented by primary energy. The primary energy use for an electrically heated *passive* house may be higher than for a district-heated *normal* building [8]. Biomass is sometimes seen as an unlimited resource and individual wood-pellet-fuelled boilers as an environmentally benign alternative to district heating. However, individual renewable heating with biomass may consume a larger fraction of the limited biomass resources than supplying heat demand with district heating, which can utilise, for example, industrial surplus heat [9].

METHODS

Main scenario differences were outlined and appropriate building components were chosen for each scenario based on, for example, the energy-efficiency ambitions for the scenarios. The approximate energy use was calculated with a simplified building simulation model.

Concerning the power and district-heating systems that surround the studied area, the average and marginal production of electricity and heat were considered. Primary energy use and CO_2 emissions due to electricity, as well as district heating and cooling supply to the new development were calculated for the average and marginal supply. Average electricity is assumed to come from the mixed sources that produce electricity in Sweden, whereas marginal electricity comes from the power plants in operation with highest operation costs, which is the electricity generation that is reduced and increased depending on demand.

Roughly, hydro and nuclear power each produce almost one-half of Swedish electricity. Due to the wasted heat from the nuclear condensing power plants, the primary factor 2.0 is used as average for the electricity generated in Sweden (i.e. two units of primary energy are needed per unit of electricity), whereas the CO_2 emissions are 10 kg per MWh of electricity due to the small fraction of fossil fuels used in CHP plants. Marginal electricity is assumed to originate from coal-fired condensing power plants having 33% efficiency and emitting 1000 kg of CO_2 per MWh of produced electricity.

The impact of heat use on district-heating production was analysed with the MODEST energy system optimisation model, which calculates how energy demand is satisfied at lowest possible cost (e.g. [10]). Here, the operational costs for covering district-heating and steam demand in Norrköping with existing plants were minimised under consideration of revenues from waste reception and electricity sales. The total heat production for the city-wide district heating system was optimised with and without district-heating supply to the new development.

Average district-heating supply corresponds to the total heat production, whereas marginal district-heating supply is the additional production required to supply heat to the new development. For average district-heating supply, the electricity generated in CHP plants is considered to displace average electricity and for marginal heat supply, CHP electricity displaces

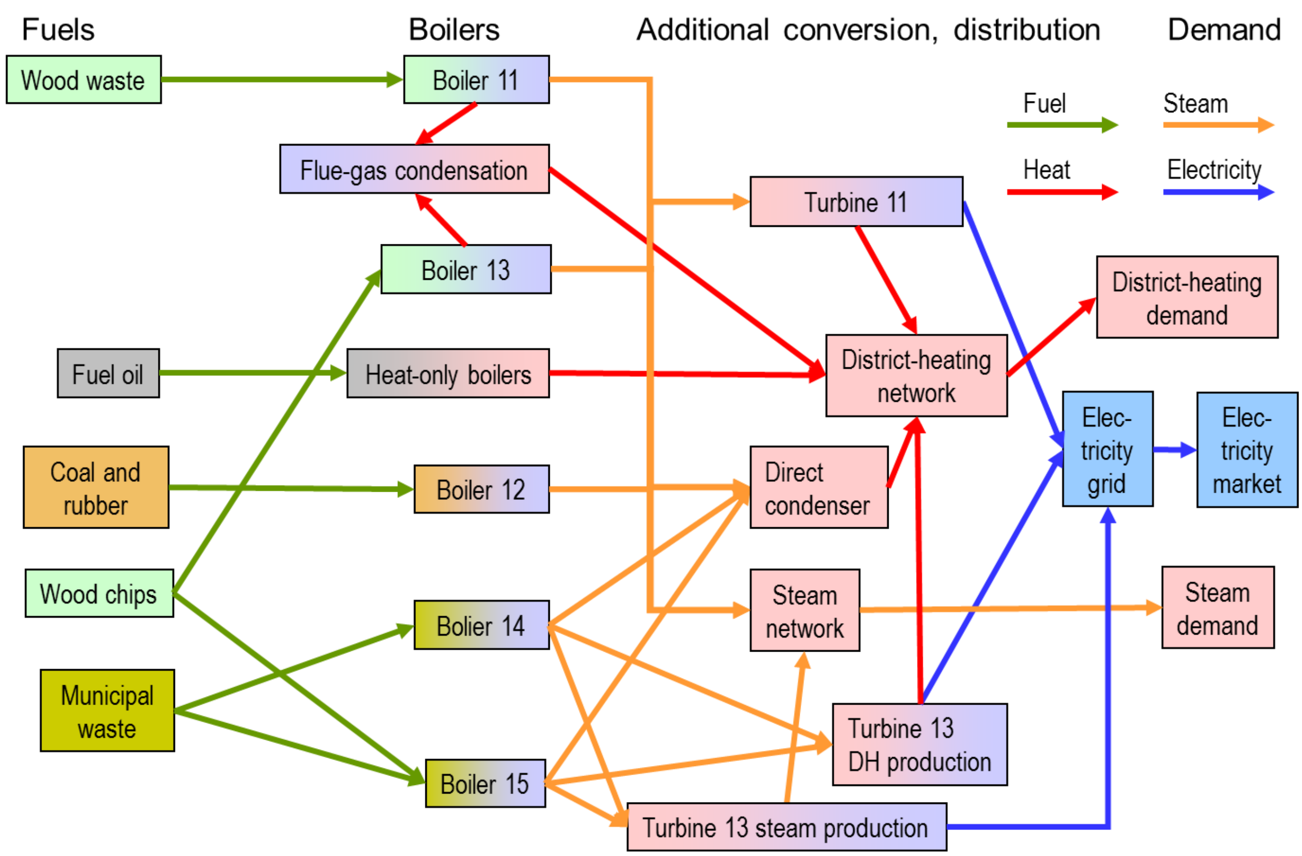

Fig. 1 Plants and energy flows in the model of heat, steam and electricity production for the city-wide district-heating system in Norrköping

marginal electricity. Local primary energy use and CO_2 emissions for district heating are calculated but reduced with the reductions of primary energy and CO_2 emissions that CHP electricity achieves in other power plants. District cooling is mainly produced using electricity and has corresponding average and marginal properties.

DISTRICT-HEATING PRODUCTION

Figure 1 shows the E.ON city-wide district-heating system in Norrköping and how it is described in the MODEST model (cf. [11]). Fuels feed boilers that produce steam, which primarily is used for electricity generation in two turbines but also can be used directly to cover the steam demand or for district-heating production in the condenser. Two boilers have flue-gas condensation that yields district heating. Both turbines co-produce electricity and district heating. Turbine 13 also produces most of the steam, which is used for production of automotive bio ethanol. The steam production mode is modelled as a parallel unit (Fig. 1). Electricity can be sold in the market when it is profitable.

In the district-heating model, variations in, primarily, heat demand and electricity prices are reflected through a time division that is more detailed for occasions with high demand (e.g. single peak hours in winter) than for periods with low demand, such as July, because at high demand, boiler capacities are crucial.

SCENARIOS

The outlined energy scenarios describe different alternatives for energy supply, extraction and use for the new development, which are considered technically possible. The scenarios reflect a future situation for this district but outlined solutions are mainly general and can also illustrate energy concepts for other developments.

It is planned that 6 000 persons will work and 6 000 people will live in this city district. In all scenarios, 170 six-floor buildings of 3 000 m^2 heated floor area cover the 650 000 m^2 of ground in the district. The floor area is divided into 64% apartments, 25% offices and 11% shops. The whole buildings have ventilation with heat recovery through heat exchangers. Offices and shops have comfort cooling.

In scenario A, future *normal* houses are built, which have higher energy standard than current normal buildings. The low-energy buildings in scenario B have solar cells and are supplied by district-heating (Fig. 2). In scenario C, energy use is as low as possible and energy extraction as large as possible.

In scenarios A and B, the buildings have rectangular shape, whereas the houses are square-shaped in scenario C to obtain small wall areas and, thus, lower heat losses. Building envelopes differ between scenarios concerning wall, attic and ground insulation, window heat transfer and air tightness, which results in different heat losses. Scenarios B and C include water-lean taps and other outlets, which reduce domestic hot water use, and additional hot-water-pipe insulation reducing losses.

In scenario B, district-heating is used for all heat demand in the household appliances (Fig. 2) dishwashers, washing machines, tumble dryers and towel dryers. There are also district-heating-driven absorption-cooling refrigerators, which, on the contrary to the other equipment, is not a mature technology. The fridges are assumed to use district heating continuously, whereas the other appliances are used with the same variations as domestic hot water. Solar energy is in scenario B used for electricity generation in solar cells instead of heat production. These district-heating applications and this solar energy utilisation help making district heating viable despite low space-heating demand.

Solar cells cover in scenarios B and C the upper half of the facades facing south (170 m^2 per building). In B, they also cover the whole roof and in C most of the roof (30° inclination in both cases). Surplus electricity is supplied to the grid (Fig.2).

In scenarios B and C, there is more efficient ventilation and present-controlled lighting, as well as electricity-lean household, consumer and business appliances, such as freezers, TV sets and computers, respectively.

Scenario C generally includes the best available technologies. Vacuum solar collectors (inclined 45°) on the roof area not covered by solar cells produce heat, which is complemented by wood-pellet-fired boilers. Outdoor air can often be used as *free* cooling, which reduces operation of electric cooling equipment. Heat is recovered from sewage pipes to hot-water pipes. Office and shop surplus heat is used elsewhere in the buildings. There are heat and cooling storages and electricity load management, which decouple energy use from supply. There is also individual measurement and charging of domestic hot-water use in scenario C (Fig. 2).

RESULTS

Energy supply, extraction and use for the scenarios have been estimated, as well as approximate impact of the energy solutions on district-heating production, primary energy use and CO_2 emissions from different viewpoints concerning how the external energy systems are influenced.

Energy use

The energy use consists of space heating, domestic hot water, comfort cooling, building electricity for ventilation etc. and household and business electricity, that is, electricity used in households and offices & shops, respectively, for computers, etc.

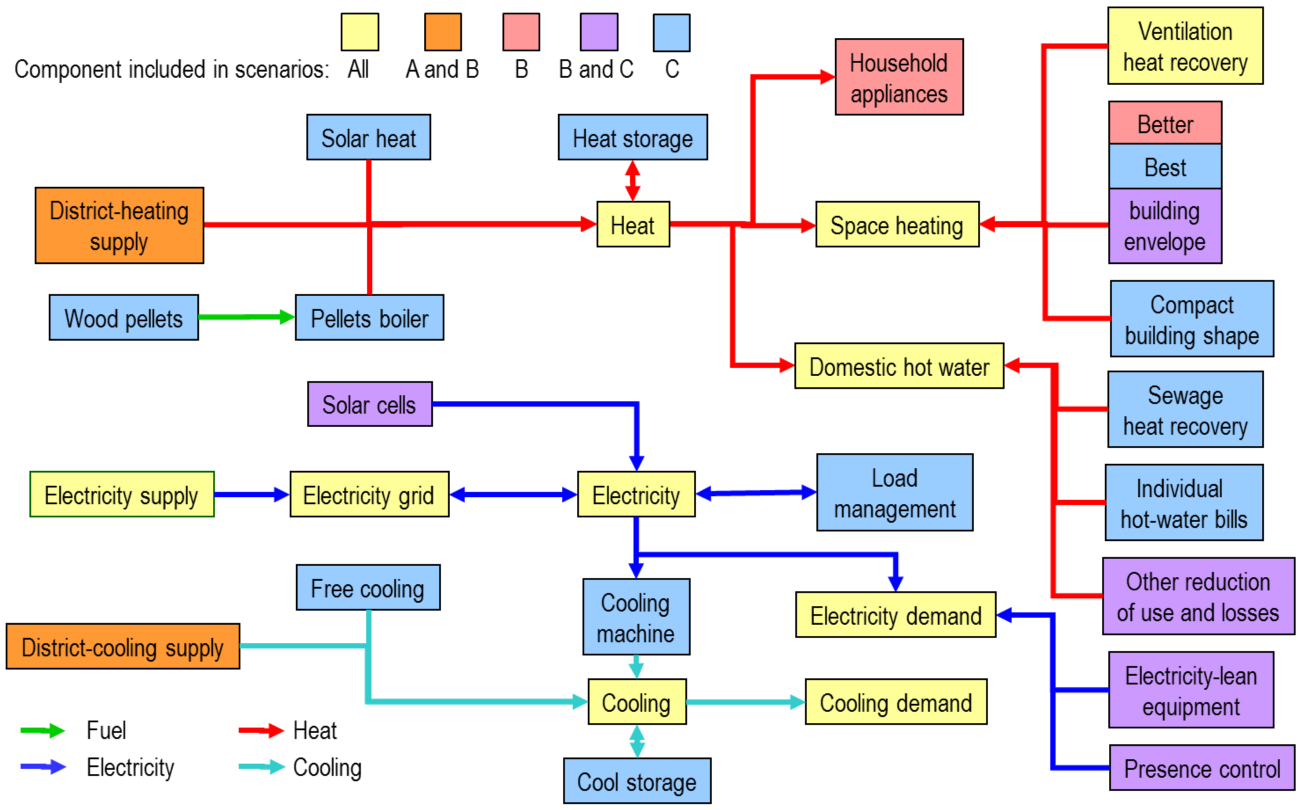

Fig. 2 Energy supply and use components for the buildings in the new development in scenarios A, B and C.

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Figure 3 shows estimated final energy use in relation to total heated floor area (A_{temp}). Space-heating demand differs between scenarios primarily due to the energy standard of the building envelopes. Energy demand for preparation of domestic hot water is lower in scenarios B and C due to water-lean outlets, additional hot-water-pipe insulation and, in C, individual hot-water bills and sewage heat recovery, as well as dishwashers etc. using little water, which together with little space heating make total heat demand lowest in scenario C. Scenario C generally reflects estimated minimum achievable energy use.

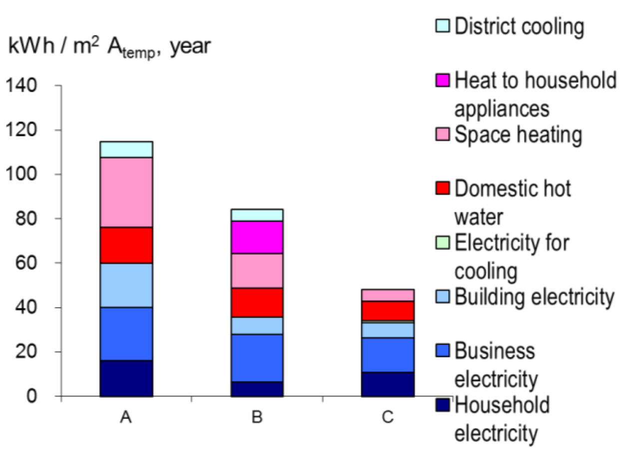

Fig. 3 Annual final energy use per square meter of total heated floor area in scenarios A, B and C

Figure 3 shows all energy use in the buildings, including electricity consumption of building users. Household electricity use is lowest in B because district-heating is used for some household appliances. Electricity use is lower in scenarios B and C due to more efficient equipment. Cooling demand is therefore lower due to less heat losses but it should be noticed that for scenario C the *electricity* used for cooling is indicated but hardly visible in Fig. 3, which anyhow is less than the district cooling shown for scenarios A and B.

District heating is the mostly used energy carrier in scenario B, because district-heating replaces electricity in several household appliances. Total district-heating use is almost equal in both scenarios but the heat utilised in appliances in B, which partly contributes to space heating, only covers additional space-heating demand in A.

Figure 3 is based on the total heated floor area in the buildings. Household and business electricity, as well as office and shop cooling related to corresponding floor areas can be obtained by dividing the values in Fig. 3 with the fractions of total floor area, which are 64 and 36% for households and business, respectively.

Energy extraction

Energy extraction is dominated by solar electricity generation on the roofs and the facades to the south (Fig. 4). In scenario C, solar collectors placed on about one-half of the roof area yield most of the needed heat and solar cells covering the rest of the roofs and the south-facing facades cover one-third of the electricity demand. In Fig. 4, the usable solar heat is indicated, considering losses when storage is required. Total solar energy is larger in Scenario C because it is estimated that twice as much solar heat as solar electricity can be extracted per unit of roof area.

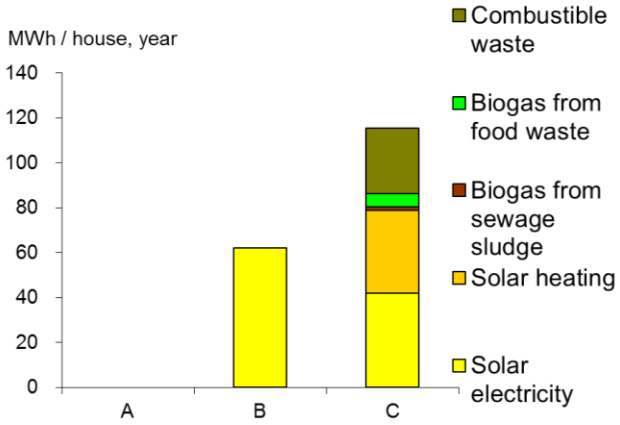

Fig. 4 Annual energy extraction for one building in scenarios A, B and C.

Energy can also be extracted from waste produced in the development in all scenarios but it is only indicated for scenario C in Fig. 4. The combustible waste is used in the CHP plant producing district heating.

Energy supply

In Fig. 5, energy supply and extraction are shown above the horizontal axis and energy use is indicated below the axis. In scenario A, all energy is externally supplied. Electricity is supplied to the area in all scenarios, least in scenario B and most in scenario A. District cooling is used more in scenario A than B because high electricity use causes undesired heating.

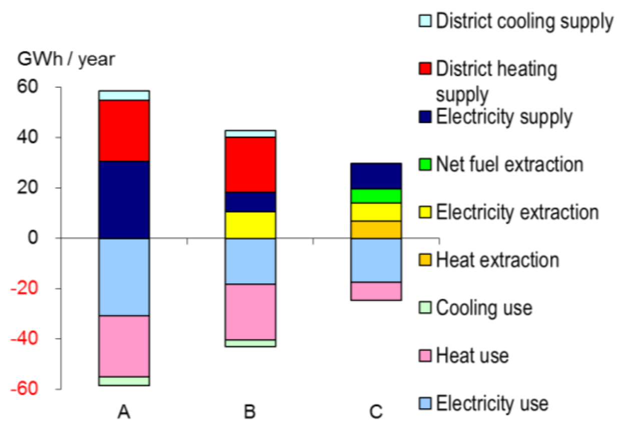

Fig. 5 Annual energy supply, extraction and use for the new development in scenarios A, B and C.

In scenario C, wood pellets complement the solar heat and in total some 20% of the energy use is covered by net external supply when the solar-energy and waste extraction (Fig. 4) in the development is considered. Net fuel extraction is only indicated for scenario C in Fig. 5 and represents extracted waste energy minus supplied wood-pellets energy. In that scenario, some electricity is used for comfort cooling.

District-heating production

District heating is primarily produced through waste-fuelled CHP production. Figure 6 shows calculated present fuel use for production of district heating, steam and electricity. Fuels with higher costs are used when the capacities of the boilers for low-cost fuels, primarily waste, are fully utilised. Waste-incineration capacity is reduced in summer due to maintenance. Some virgin wood-chips are co-burned with waste. In reality, some oil is used, which is not shown in Fig. 6.

In total, 1.1 TWh of district heating and 430 GWh of electricity are produced annually. 51 MW of steam are also continuously generated.

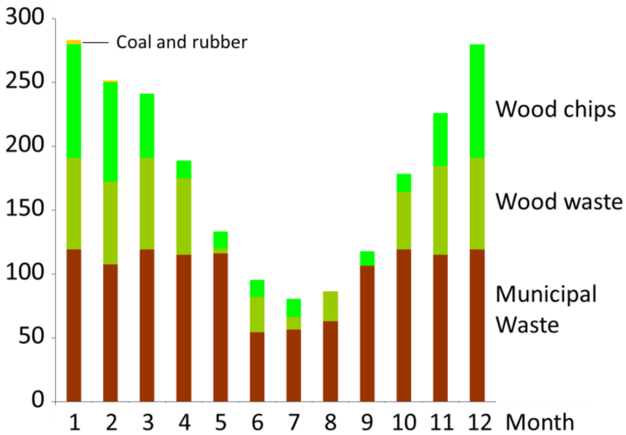

Fig. 6 Present district-heating fuel use (GWh).

Figures 7 and 8 show the additional fuel that is needed to supply district heating to the new development in scenarios A and B. It includes the fuel use for co-produced electricity (8 GWh/year). Total fuel use is almost equal for both scenarios but district heating supply has less seasonal variations in scenario B than in A because a smaller fraction of the supply covers space heating.

Waste dominates the total district-heating production (Fig. 6), whereas the district-heating demand in the new development primarily would be covered by virgin wood chips. But in scenario B, which has a more seasonally levelled district-heating demand, a larger fraction of the supply to the new development can be based on the low-cost fuels municipal waste and building-wood waste (Fig. 8). In scenario A, district-heating supply is larger in winter (Fig. 7) when most of the boiler capacity for these low-cost fuels is used already today. But in May and September, waste-incineration capacity is not fully utilised today and can

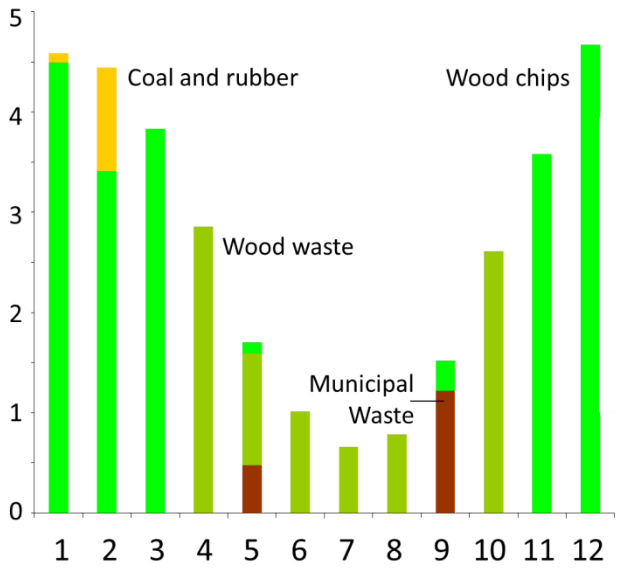

Fig. 7 Monthly district-heating fuel use for the new development in scenario A (GWh).

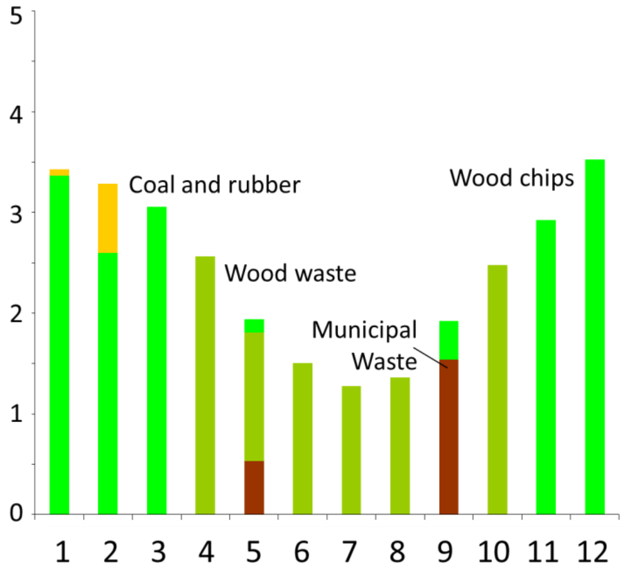

Fig. 8 Monthly district-heating fuel use for the new development in scenario B (GWh).

be used for production of district heating to the new development in both scenarios.

Primary energy and CO_2 emissions

Various levels for primary energy use and CO_2 emissions due to energy use in the development are estimated depending on how energy carriers are assumed to impact upon the surrounding energy system. The average and marginal production of electricity, as well as district heating and cooling are considered.

District-heating model results include local primary energy use and CO_2 emissions, which both mainly are due to waste incineration for present (average) district heating production. Because less waste (of fossil origin) is used for producing district heating for the new development, local CO_2 emissions are lower for this marginal district-heating production.

Considering the reductions of primary energy use and CO_2 emissions that CHP electricity achieves in other power plants, the values in Table 1 are estimated.

The primary energy factor is the amount of primary energy required per unit of district heating. The differences between average and marginal district-heating supply primarily depend on the characteristics of average and marginal electricity (cf. Section Methods).

Table 1. Properties of average and marginal district-heating supply

	Average	Marginal
Primary energy factor	0.65	0.22
CO_2 emissions (kg/MWh)	52	-250

Primary energy use is highest in scenario A (Fig. 9) from the average as well as the marginal viewpoint for external energy supply due to large total energy use and a high electricity fraction.

Scenarios B and C have similar primary energy use with C having the lowest use with average external energy supply but B using least primary energy if marginal supply is considered. Especially with that perspective, scenario B has very low primary energy use compared to final energy use because little electricity but much district heating is used and the latter is largely produced in CHP plants together with electricity, which can displace power production in nuclear (average) or coal-fired (marginal) condensing power plants. To obtain the marginal primary energy use for scenario B in Fig. 9, the 1 GWh negative bar, due to replacement of coal condensing power, should be subtracted from the positive bar.

In scenario C, no district heating is used and all primary energy use is due to electricity supply. Waste extracted from the development is not considered in Fig. 9 to balance primary energy use except partly in scenario C where wood-pellet supply is left out because waste extraction is larger.

Figure 10 shows CO_2 emissions due to external energy supply. Emissions from average district cooling and electricity are too small to be visible in Fig. 10. Marginal district heating causes negative emissions (Table 1). To obtain total marginal emissions from Fig. 10, average district-heating should be excluded and the negative bars for marginal district heating should be subtracted from the remaining positive bars. This results in 145 annual tonnes of CO_2 for one building in scenario A and 13 tonnes in B.

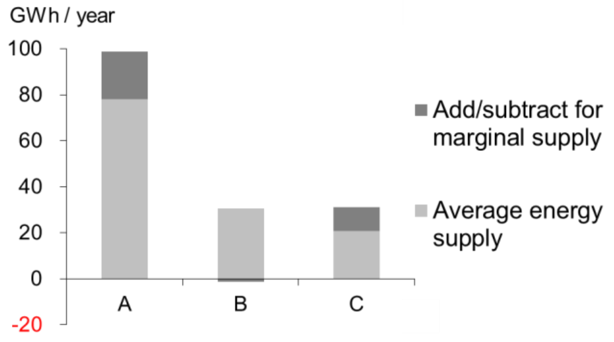

Fig. 9 Annual primary energy use due to energy supplied to the new development in scenarios A, B and C.

Scenario A yields the highest CO_2 emissions with the average as well as the marginal perspective (Fig. 10). From the average viewpoint, CO_2 emissions are low in all cases and are dominated by district-heating fuel because Swedish electricity production has very low emissions. With this perspective, scenario B causes almost as large emissions as scenario A, whereas case C, where no district heating is used, has very low emissions. Hence, considering average externally supplied energy, scenario C, where solar energy covers one-half of the energy demand, causes the lowest climate impact.

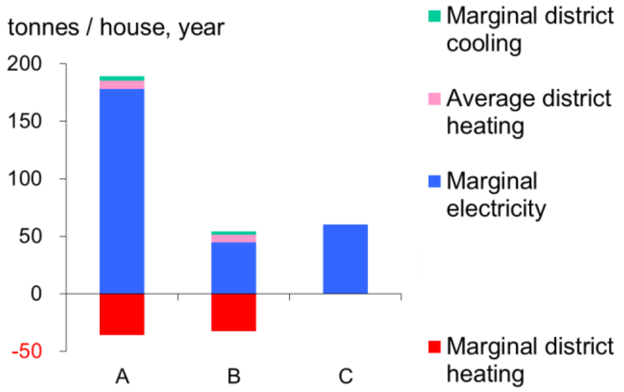

Fig. 10 Annual CO_2 emissions due to energy supplied to one building in scenarios A, B and C.

By consideration of marginal electricity and district-heating supply, CO_2 emissions are lowest in scenario B with low electricity demand and a high district-heating share of the low total energy demand. This is emphasized by a large production of CHP electricity that can reduce power production in coal-fired condensing plants and their CO_2 emissions, but also without considering this interplay marginal CO_2 emissions are lowest for scenario B (Fig. 10).

DISCUSSION

In this study, input data are approximate and calculations are simplified and the results are uncertain but they still show relations between different solutions and perspectives concerning, for example, primary energy use and CO_2 emissions.

Some scenario characteristics may seem extreme but reflect an ambition to present cases with apparent differences. For example, the commercially not available technology refrigerators with absorption cooling uses much district heating in scenario B, which exaggerates the impact of using district heating for household appliances. The district-heating use in fridges could be interpreted as district heating used in an industrial manufacturing process.

The solar heat that can be utilised may be smaller than shown due to worse storage characteristics than assumed. If the buildings in scenario C were connected to the district-heating network, which could absorb surplus solar heating in summer, the houses could be net self-sufficient in energy by using the whole roofs for solar heating production.

The values used for primary energy and CO_2 emissions for average and marginal electricity are not exact but are considered to be sufficiently correct for the comparisons between energy solutions and perspectives on the surrounding energy system made in this analysis.

The purpose of this study is to outline technically possible solutions for energy use, extraction and supply and the consequences for resource use and climate impact. No economic evaluation of the scenarios was made. Therefore, the district-heating demand in scenario B should not be understood as the lowest that is viable to cover by district heating.

In a corresponding way as electricity produced in CHP plants is affecting primary energy use and CO_2 emissions in other power plants, consumed non-fossil fuels could be considered to cause CO_2 emissions elsewhere because if they were not used in the studied district-heating system they could replace fossil fuels and reduce CO_2 emissions some other place. This interplay is regarded concerning primary energy by giving biomass and waste the same primary energy value as other fuels, which is not always the case, but not for climate impact.

OUTLOOK

The outlined scenarios can illustrate more or less sustainable energy solutions for new developments in other towns and countries as well. The study may serve as a general inspiration for city planners and building proprietors concerning possible energy concepts.

To deploy district heating in areas with energy-efficient buildings is a demanding task that can be facilitated through early co-operation among several actors including local authorities, district-heating companies, architects and adjacent land owners. Together, they may achieve comprehensive sustainable systems before parties have prepared individual solutions that do not fit together.

District heating should have a role to play also for low-energy buildings because it is not only an energy distribution system but a means to expand the supplies of utilisable energy resources, such as waste and waste heat. To develop district heating, it also needs to be used for new purposes.

CONCLUSIONS

Energy scenarios for a new development in a Swedish town have shown completely external energy supply, as well as next-to self-sufficiency in energy.

It has been shown how new customers with traditional and novel heat use influence district-heating production. Low-energy buildings with electricity-generating solar cells, but no heat-producing solar collectors, as well as district-heating use in household appliances can facilitate deployment of a district-heating network despite low space-heating demand. Such buildings have a more seasonally levelled heat use than *normal* buildings. This heat use can to a larger extent be covered by low-cost district-heating supply than if a larger share of the heat demand is for space heating.

Heat and electricity use can be very low due to a building envelope of high standard and a compact building shape, which hamper heat losses, and efficient electric appliances, as well as sewage heat recovery and other measures reducing heat demand for domestic hot water. Solar energy can cover one-half of the total energy demand, including household and business electricity, in such buildings.

District heating that supplies buildings with low energy demand and low electricity use but higher heat use can achieve very low primary energy use compared to final energy use if the district heating is co-produced with electricity, which can reduce operation of inefficient nuclear or coal-fired condensing power plants. The low primary energy use is partly due to the use of resource-efficient district heating instead of resource-demanding electricity, for example, in household appliances.

Considering average supplied energy, including nuclear electricity, nearly zero-energy buildings primarily using solar energy cause the lowest climate impact but by consideration of marginal energy supply, including coal-fired condensing power plants, CO_2 emissions are lowest with district-heating supplying buildings with low energy demand. Due to low electricity use, this solution has the lowest CO_2 emissions also without regarding that CHP production can reduce emissions from other power production.

The study shows that it is important to consider how energy solutions influence the rest of the energy system.

ACKNOWLEDGEMENT

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POSTER SESSION

CHP operation scheduling under uncertainty

Estimating the value of thermal energy storage

Ilias Dimoulkas & Mikael Amelin

1 Introduction

The power plant short-term operation scheduling is a field of extensive and continuous research. Many methodologies and optimization techniques have been proposed that try to solve the problem of optimal unit commitment and power dispatch [1]. The deregulation of electricity markets in many countries has altered the objectives of power producers. While previously they were caring about how to follow a specific electrical load at the minimum cost, now the target is to maximize the profits by selling the electricity in the markets. In this economic environment the plant operators have to schedule their production under the uncertainty of electricity prices. Furthermore, the increased use of renewable energy sources in the grid results in higher volatility of electricity prices and higher demand for regulating power due to the intermittent power production. Therefore there is a need for new tools and techniques to be developed in order to handle all these new challenges.

Combined heat and power (CHP) plants can produce power and useful heat. Traditionally they find application in the industry or in residential district heating networks. The simultaneous power and heat production, however, makes the operation scheduling problem harder to solve compared to a conventional power plant as more restrictions are applied. A survey of the various methods proposed for the optimal CHP short-term operation is given in [2]. In this work, a model is proposed for the optimal short-term (24-hours ahead) operation planning of a CHP system under the uncertain parameters of electricity prices and heat demand. The uncertain parameters are incorporated into the model through a number of scenarios and stochastic programming framework is used for modeling the problem. To test the performance of the model, a case study is conducted.

2 Mathematical formulation of the problem

The formulation of the problem is done in three discrete steps: first the decision framework is considered, then the scenarios of the stochastic parameters are made and finally the mathematical model is formulated. These steps are described in the following subsections.

2.1 The decision framework

In the stochastic programming framework the decisions are divided into the decisions that have to be made before any stochastic parameter is realized (here-and-now) and decisions that are made with knowledge of the outcome (wait-and-see). This decision making process is formulated into a scenario tree with many stages where each stage represents a time point when decisions are made. The stages on the left refer to earlier decisions. The proposed model derives the optimal power and heat production during the next day. The first stage decisions are made after the clearing of the spot market. At that time point the CHP producer knows exactly how much power has to produce next day (Day-1). This is equivalent to covering a specific load and the decision is about how to distribute the load among the units. Therefore the first stage variables are the unit commitment and power output of the units. The second stage variable is the heat output of the units during Day-1. This decision has not to be taken in advance but the producer can wait till the hour of the heat delivery to decide how much heat will be produced according to the heat demand. Finally, the third stage variables are the power offer in the market and the heat production after two days (Day-2). This third stage is used in order to derive optimal unit commitment decisions for the final hour of Day-1 (ending conditions), a method suggested in [3]. The scenario tree of the model is depicted in fig.1.

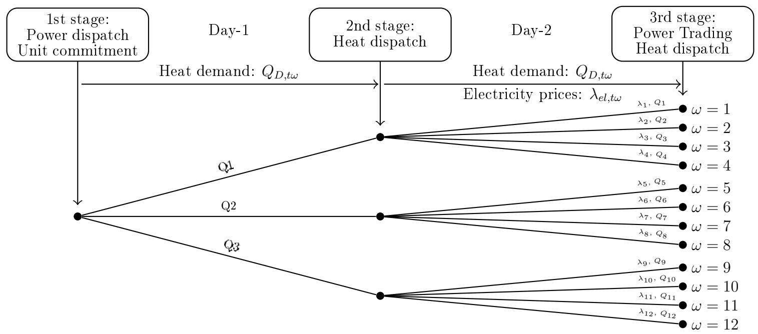

Figure 1: Scenario tree of the proposed model

2.2 The scenarios

The scenario making is divided in two steps. In the first step a forecasting method is used in order to build a model that can predict future values of the stochastic parameters. There are many forecasting methods like time series analysis, neural networks, hybrid methods etc. In this work time series analysis is used to build a model that can predict future values of spot market prices and heat demand in a district heating network. In the second step Monte Carlo simulation is used to produce the scenarios using the previous model. Then the scenarios are combined so as to correspond to the scenario tree. A third step which is not followed here is the scenario reduction which is done when the problem cannon be solved due to its size.

2.3 The model

Objective function: The objective function of the problem (1) is to maximize the profits of the CHP producer which consist of the revenues from the power sold in the spot market during the 2$^{\text{nd}}$day of the planning horizon (A) minus the variable production costs (B), the start-up costs (C) and the shut down costs (D) during the whole planning horizon.

$$Maximize:$$

$$\sum_{\omega=1}^{N_\Omega} \pi_\omega \left(\sum_{t=N_T+1}^{2N_T} \sum_{g=1}^{N_G} \underbrace{\lambda_{el,t\omega} P_{gt\omega}}_{A} - \sum_{t=1}^{2N_T} \sum_{g=1}^{N_G} \left(\underbrace{\lambda_{f,g} P_{fuel,gt\omega}}_{B} + \underbrace{c_{start,g} y_{gt\omega}}_{C} + \underbrace{c_{stop,g} z_{gt\omega}}_{D} \right) \right) \tag{1}$$

Non-anticipativity constraints: These constraints ensure that the structure of the scenario tree is applied into the problem. This means that the variables referred to common scenarios have to be assigned the same values.

$$P_{gt\omega} = P_{gt\omega+1} \qquad \forall g, t = 1, ..., N_T, \omega = 1, ..., N_\Omega - 1 \tag{2}$$

$$u_{gt\omega} = u_{gt\omega+1} \qquad \forall g, t = 1, ..., N_T, \omega = 1, ..., N_\Omega - 1 \tag{3}$$

$$Q_{gt\omega} = Q_{gt\omega+1} \qquad \forall g, t = 1, ..., N_T, \omega = 1, ..., N_\Omega - 1: \quad if\, Q_{D,t\omega} = Q_{D,t\omega+1} \tag{4}$$

Operational constraints: These constraints apply the operational limits of the CHP units. The most common type of steam turbine used in large CHP systems is the extraction condensing steam turbine. It is characterized for its flexibility. The feasible zone is described by (5-8). The fuel consumption is given by (9). In many CHP plants there are only heat producing boilers that are usually used during peak heat demand hours. The operational limits for these boilers are given by (10) and the fuel consumption by (11).

$$\beta_{el,g}P_{gt\omega} + \beta_{th,g}Q_{gt\omega} \leqslant \beta_{el,g}P_{max,g}u_{gt\omega} \quad \forall g, \forall t, \forall \omega \tag{5}$$

$$\beta_{el,g}P_{gt\omega} + \beta_{th,g}Q_{gt\omega} \geqslant \left(\beta_{el,g} + \beta_{th,g}/r_{min,g}\right) P_{min,g}u_{gt\omega} \quad \forall g, \forall t, \forall \omega \tag{6}$$

$$Q_{gt\omega} \leqslant Q_{max,g} \quad \forall g, \forall t, \forall \omega \tag{7}$$

$$P_{gt\omega} \geqslant r_{min,g}Q_{gt\omega} \quad \forall g, \forall t, \forall \omega \tag{8}$$

$$P_{fuel,gt\omega} = \beta_{el,g}P_{gt\omega} + \beta_{th,g}Q_{gt\omega} + \beta_{0,g}u_{gt\omega} \quad \forall g, \forall t, \forall \omega \tag{9}$$

$$Q_{min,g}u_{gt\omega} \leqslant Q_{gt\omega} \leqslant Q_{max,g}u_{gt\omega} \quad \forall g, \forall t, \forall \omega \tag{10}$$

$$P_{fuel,gt\omega} = \frac{Q_{gt\omega}}{\eta_{boiler,g}} \quad \forall g, \forall t, \forall \omega \tag{11}$$

Heat balance constraints: The heat load balance constraint ensures that the total heat production is equal to the total heat demand including the changes in the content of the heat storage tank (12-13). The capacity of the tank (14) limits the maximum heat content.

$$V_{t+1\omega} = V_{t\omega} + \sum_{g=1}^{N_G} Q_{gt\omega} - Q_{D,t\omega} \quad t = 1, ..., 2N_T - 1, \forall \omega \tag{12}$$

$$V_{1\omega} = V_{2N_T\omega} + \sum_{g=1}^{N_G} Q_{g2N_T\omega} - Q_{D,2N_T\omega} \quad \forall \omega \tag{13}$$

$$V_{t\omega} \leqslant V_{max} \quad \forall t, \forall \omega \tag{14}$$

Power balance constraints: The power balance constraint is applied during the 1^{st}day of the planning horizon according to the decision framework. It simply says that the total power output must satisfy the load.

$$\sum_{g=1}^{N_G} P_{gt\omega} \geqslant P_{S,t} \quad t = 1, ..., N_T, \forall \omega \tag{15}$$

Unit commitment constraints: These constraints assign values to the binary variables u, y and z which keep the state of the units, operating, starting-up or shuting down respectively.

$$y_{gt\omega} \leqslant u_{gt\omega}, \quad y_{gt\omega} \leqslant 1 - u_{gt-1\omega}, \quad y_{gt\omega} \geqslant u_{gt\omega} - u_{gt-1\omega} \quad \forall g, \forall t, \forall \omega \tag{16}$$

$$z_{gt\omega} \leqslant u_{gt-1\omega}, \quad z_{gt\omega} \leqslant 1 - u_{gt\omega}, \quad z_{gt\omega} \geqslant u_{gt-1\omega} - u_{gt\omega} \quad \forall g, \forall t, \forall \omega \tag{17}$$

Minimum up and down time constraints: These constraints (18-23) are applied to avoid the frequent transitions from on state to off state and vice versa.

$$\sum_{t=1}^{L_g} (1 - u_{gt\omega}) = 0 \quad \forall g, \forall \omega \tag{18}$$

$$\sum_{\tau=t}^{t+UT_g-1} u_{g\tau\omega} \geqslant UT_g y_{gt\omega} \quad \forall g, t = L_g + 1, ..., 2N_T - UT_g + 1, \forall \omega \tag{19}$$

$$\sum_{\tau=t}^{2N_T} (u_{g\tau\omega} - y_{gt\omega}) \geqslant 0 \quad \forall g, t = 2N_T - UT_g + 2, ..., 2N_T, \forall \omega \tag{20}$$

$$\sum_{t=1}^{F_g} u_{gt\omega} = 0 \quad \forall g, \forall \omega \tag{21}$$

$$\sum_{\tau=t}^{t+DT_g-1} (1 - u_{g\tau\omega}) \geqslant DT_g z_{gt\omega} \quad \forall g, t = F_g + 1, ..., 2N_T - DT_g + 1, \forall \omega \tag{22}$$

$$\sum_{\tau=t}^{2N_T} (1 - u_{g\tau\omega} - z_{gt\omega}) \geqslant 0 \quad \forall g, t = 2N_T - DT_g + 2, ..., 2N_T, \forall \omega \tag{23}$$

where $L_g = min\left\{2N_T, \left(UT_g - T^0_{up,g}\right) u^0_g\right\}$ and $F_g = min\left\{2N_T, \left(DT_g - T^0_{down,g}\right)\left(1 - u^0_g\right)\right\}$ are the hours in the beginning of the planning horizon that the unit is restricted to operate or to be offline respectively due to initial conditions.

3 Results

The system in the case study consists of two CHP units, one heat producing boiler and a heat storage tank. The parameters of the units are given in Appendix B. In fig. 2 the scheduling of heat production is given. Because heat production is scenario dependent, this figure depicts one possible outcome. The existence of heat storage capacity increases the flexibility of the system. For example the use of the expensive heat boiler is avoided (e.g. hours 5-7) and the second unit can stop its operation when electricity prices are forecasted to be low (e.g. hours 41-43).

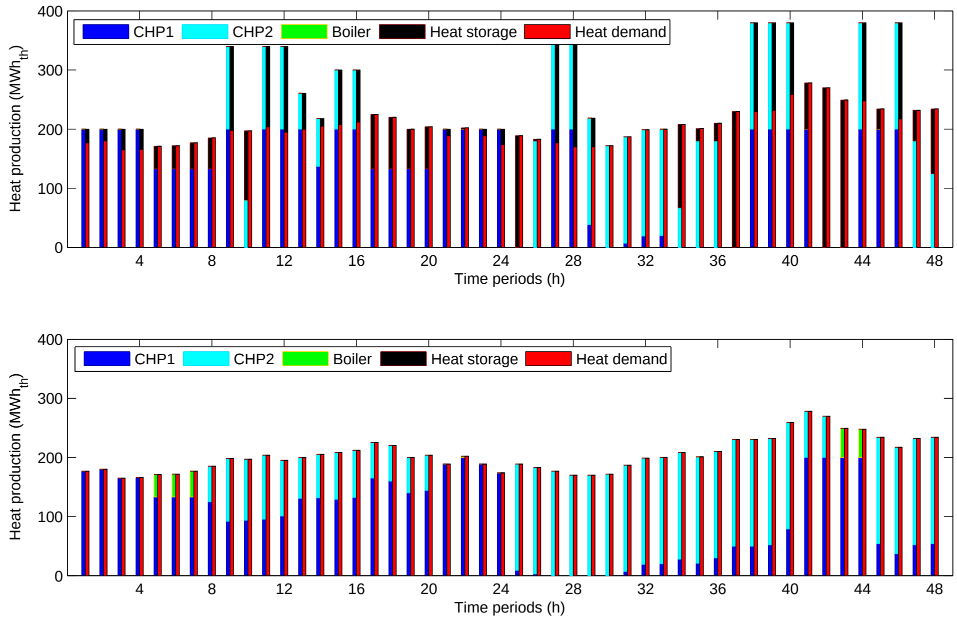

Figure 2: Heat production scheduling with (up) and without (down) heat storage capacity

To estimate the value of heat storage, the model is solved with different amounts of storage capacity, running from 0 to 1000 MWh/h. The results show an increasing optimal value with decreasing change rate. It must be noted that the optimal value is negative as the objective function does not include the income from power sold in Day-1 and the income from heat sold.

Capacity (MWh$_{th}$/h)	0	200	400	600	800	1000
Optimal value (€)	-94499	-91330	-90201	-89621	-89174	-88788

Table 1: Change of optimal value in accordance with the heat storage capacity

Acknowledgement

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Appendix A: Nomenclature

Indices and Numbers:

g	Index of units, running from 1 to $\mathrm{N_G}$
t	Index of time periods in hourly resolution, running from 1 to $2\mathrm{N_T}$
ω	Index of scenarios, running from 1 to $\mathrm{N_\Omega}$

Parameters

π_ω	Probability of occurrence of scenario ω
$\lambda_{el,t\omega}$	Day-ahead market price in period t and scenario ω, (€/MWh)
$Q_{D,t\omega}$	Heat demand in period t and scenario ω, ($\mathrm{MW_{th}}$)
$P_{S,t}$	Power load in period t, (MW)
$\lambda_{f,g}$	Fuel price of unit g, (€/MWh)
$c_{start,g}$	Start-up cost of unit g, (€)
$c_{stop,g}$	Shut down cost of unit g, (€)
$\beta_{el,g}$	Marginal fuel consumption for power production of unit g
$\beta_{th,g}$	Marginal fuel consumption for heat production of unit g
$\beta_{0,g}$	Fuel consumption at minimum output of unit g, (MW)
$r_{min,g}$	Minimum power-to-heat ratio of unit g
$\eta_{boiler,g}$	Efficiency of boiler unit g
$P_{min,g}, P_{max,g}$	Power production limits of unit g, (MW)
$Q_{min,g}, Q_{max,g}$	Heat production limits of unit g, ($\mathrm{MW_{th}}$)
V_{max}	Heat storage capacity, (MWh/h)
UT_g	Minimum up time of unit g, (h)
DT_g	Minimum down time of unit g, (h)
u_g^0, y_g^0, z_g^0	Initial state of binary variables $u_{gt\omega}$, $y_{gt\omega}$and $z_{gt\omega}$
$T_{up,g}^0$	Time periods of unit$g$ has been on in the beginning of the planning horizon, (h)
$T_{down,g}^0$	Time periods of unit$g$ has been off in the beginning of the planning horizon, (h)

Variables

$P_{gt\omega}$	Power produced by unit g in period t and scenario ω, (MW)
$Q_{gt\omega}$	Heat produced by unit g in period t and scenario ω, ($\mathrm{MW_{th}}$)
$P_{fuel,gt\omega}$	Fuel consumption of unit g in period t and scenario ω, (MWh/h)
$V_{t\omega}$	Heat storage content in period t and scenario ω, (MWh/h)
$u_{gt\omega}$	Binary variable for the on/off status of unit g in period t and scenario ω
$y_{gt\omega}$	Binary variable for the start-up of unit g in period t and scenario ω
$z_{gt\omega}$	Binary variable for the shut down of unit g in period t and scenario ω

Appendix B: Case study parameters

Table 2: CHP parameters used in the case study

CHP units	Unit1/Unit2	**Heat boiler**	
Fuel	Gas	Fuel	Gas
Fuel price, (€/MWh)	10	Fuel price, (€/MWh)	10
Min. power output, (MW)	35/30	Min. heat output, ($\mathrm{MW_{th}}$)	0
Max. power output, (MW)	140/120	Max. heat output, ($\mathrm{MW_{th}}$)	100
Max. heat output, ($\mathrm{MW_{th}}$)	200/180	Efficiency	0.9
Marg. fuel consump. for power prod.	2.4/2.5		
Marg. fuel consump. for heat prod.	0.36/0.37		
Fuel consump. at min output, (MW)	40/35		
Minimum power-to-heat ratio	0.5/0.5		
Start-up cost, (€)	10000	**Heat storage tank**	
Minimum up time, (h)	1/1	Capacity, (MWh/h)	0 - 600
Minimum down time, (h)	1/1		

CHP operation scheduling under uncertainty

Estimating the value of thermal energy storage

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1 Introduction

The power plant short-term operation scheduling is a field of extensive and continuous research. Many methodologies and optimization techniques have been proposed that try to solve the problem of optimal unit commitment and power dispatch [1]. The deregulation of electricity markets in many countries has altered the objectives of power producers. While previously they were caring about how to follow a specific electrical load at the minimum cost, now the target is to maximize the profits by selling the electricity in the markets. In this economic environment the plant operators have to schedule their production under the uncertainty of electricity prices. Furthermore, the increased use of renewable energy sources in the grid results in higher volatility of electricity prices and higher demand for regulating power due to the intermittent power production. Therefore there is a need for new tools and techniques to be developed in order to handle all these new challenges.

Combined heat and power (CHP) plants can produce power and useful heat. Traditionally they find application in the industry or in residential district heating networks. The simultaneous power and heat production, however, makes the operation scheduling problem harder to solve compared to a conventional power plant as more restrictions are applied. A survey of the various methods proposed for the optimal CHP short-term operation is given in [2]. In this work, a model is proposed for the optimal short-term (24-hours ahead) operation planning of a CHP system under the uncertain parameters of electricity prices and heat demand. The uncertain parameters are incorporated into the model through a number of scenarios and stochastic programming framework is used for modeling the problem. To test the performance of the model, a case study is conducted.

2 Mathematical formulation of the problem

The formulation of the problem is done in three discrete steps: first the decision framework is considered, then the scenarios of the stochastic parameters are made and finally the mathematical model is formulated and solved. These steps are described in the following subsections.

2.1 The decision framework

In the stochastic programming framework the decisions are divided into decisions that have to be made before any stochastic parameter is realized (here-and-now) and decisions that are made with knowledge of the outcome (wait-and-see). This decision making process is formulated into a scenario tree with many stages where each stage represents a time point when decisions are made (fig.1). The stages on the left refer to earlier decisions. The proposed model derives the optimal power and heat production during the next day. The first stage decisions are made after the clearing of the spot market. At that time point the CHP producer knows exactly how much power has to produce next day (Day-1). This is equivalent to covering a specific load and the decision is about how to distribute the load among the units. Therefore the first stage variables are the unit commitment and power output of the units. The second stage variable is the heat output of the units during Day-1. This decision has not to be taken in advance but the producer can wait till the hour of the heat delivery to decide how much heat will be produced according to the heat demand. Finally, the third stage variables are the power offer in the spot market and the heat production the following day (Day-2). This third stage is used in order to derive optimal unit commitment decisions for the final hour of Day-1, a method suggested in [3]. The scenario tree of the model is depicted in fig.1.

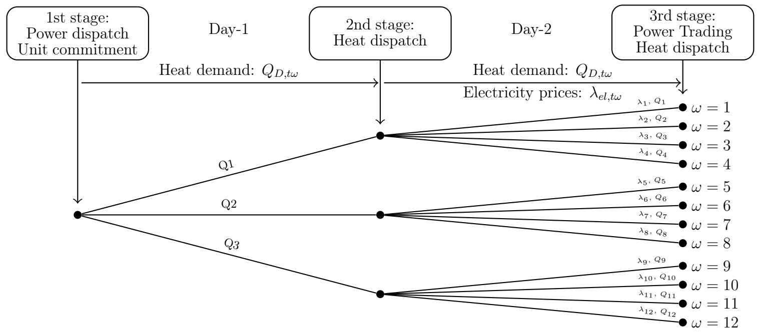

Figure 1: Scenario tree of the proposed model

2.2 The scenarios

The scenario making is divided in two steps. In the first step a forecasting method is used to build a model that can predict future values of the stochastic parameters. There are many forecasting methods like time series analysis, neural networks, hybrid methods etc. In this work time series analysis is used to build a model that can predict future values of spot market prices and heat demand in a district heating network. A SARIMA model is used for the spot market prices and a SARIMAX for the heat demand where the external parameter is the outdoor temperature. In the second step Monte Carlo simulation is used to produce the scenarios using the previous models. Then the scenarios are combined to correspond to the scenario tree.

2.3 The model

Objective function: The objective function of the problem (1) is to maximize the profits of the CHP producer which consist of the revenues from the power sold in the spot market during the 2^{nd}day of the planning horizon (A) minus the variable production costs (B), the start-up costs (C) and the shut down costs (D) during the whole planning horizon.

$$Maximize:$$

$$\sum_{\omega=1}^{N_\Omega} \pi_\omega \left(\sum_{t=N_T+1}^{2N_T} \sum_{g=1}^{N_G} \underbrace{\lambda_{el,t\omega} P_{gt\omega}}_{A} - \sum_{t=1}^{2N_T} \sum_{g=1}^{N_G} \left(\underbrace{\lambda_{f,g} P_{fuel,gt\omega}}_{B} + \underbrace{c_{start,g} y_{gt\omega}}_{C} + \underbrace{c_{stop,g} z_{gt\omega}}_{D} \right) \right) \tag{1}$$

Non-anticipativity constraints: These constraints (2-4) ensure that the structure of the scenario tree is applied into the problem. This means that the variables referred to common scenarios have to be assigned the same values.

$$P_{gt\omega} = P_{gt\omega+1} \qquad \forall g, t = 1, ..., N_T, \omega = 1, ..., N_\Omega - 1 \tag{2}$$

$$u_{gt\omega} = u_{gt\omega+1} \qquad \forall g, t = 1, ..., N_T, \omega = 1, ..., N_\Omega - 1 \tag{3}$$

$$Q_{gt\omega} = Q_{gt\omega+1} \qquad \forall g, t = 1, ..., N_T, \omega = 1, ..., N_\Omega - 1 : \quad if\, Q_{D,t\omega} = Q_{D,t\omega+1} \tag{4}$$

Operational constraints: These constraints apply the operational limits of the CHP units. The most common type of steam turbine used in large CHP systems is the extraction condensing steam turbine. It is characterized for its flexibility. The feasible zone is described by (5-8). The fuel consumption is given by (9). In many CHP plants there are only heat producing boilers that are usually used during peak heat demand hours. The operational limits for these boilers are given by (10) and the fuel consumption by (11).

$$\beta_{el,g}P_{gt\omega} + \beta_{th,g}Q_{gt\omega} \leqslant \beta_{el,g}P_{max,g}u_{gt\omega} \quad \forall g, \forall t, \forall \omega \tag{5}$$

$$\beta_{el,g}P_{gt\omega} + \beta_{th,g}Q_{gt\omega} \geqslant \left(\beta_{el,g} + {}^{\beta_{th,g}}/{}_{r_{min,g}}\right) P_{min,g}u_{gt\omega} \quad \forall g, \forall t, \forall \omega \tag{6}$$

$$Q_{gt\omega} \leqslant Q_{max,g} \quad \forall g, \forall t, \forall \omega \tag{7}$$

$$P_{gt\omega} \geqslant r_{min,g}Q_{gt\omega} \quad \forall g, \forall t, \forall \omega \tag{8}$$

$$P_{fuel,gt\omega} = \beta_{el,g}P_{gt\omega} + \beta_{th,g}Q_{gt\omega} + \beta_{0,g}u_{gt\omega} \quad \forall g, \forall t, \forall \omega \tag{9}$$

$$Q_{min,g}u_{gt\omega} \leqslant Q_{gt\omega} \leqslant Q_{max,g}u_{gt\omega} \quad \forall g, \forall t, \forall \omega \tag{10}$$

$$P_{fuel,gt\omega} = \frac{Q_{gt\omega}}{\eta_{boiler,g}} \quad \forall g, \forall t, \forall \omega \tag{11}$$

Heat balance constraints: The heat load balance constraint ensures that the total heat production is equal to the total heat demand including the changes in the content of the heat storage tank (12-13). The capacity of the tank (14) limits the maximum heat content.

$$V_{t+1\omega} = V_{t\omega} + \sum_{g=1}^{N_G} Q_{gt\omega} - Q_{D,t\omega} \quad t = 1, ..., 2N_T - 1, \forall \omega \tag{12}$$

$$V_{1\omega} = V_{2N_T\omega} + \sum_{g=1}^{N_G} Q_{g2N_T\omega} - Q_{D,2N_T\omega} \quad \forall \omega \tag{13}$$

$$V_{t\omega} \leqslant V_{max} \quad \forall t, \forall \omega \tag{14}$$

Power balance constraint: The power balance constraint (15) is applied during the 1st day of the planning horizon according to the decision framework. It simply says that the total power output must satisfy the load.

$$\sum_{g=1}^{N_G} P_{gt\omega} \geqslant P_{S,t} \quad t = 1, ..., N_T, \forall \omega \tag{15}$$

Unit commitment constraints: These constraints (16-17) assign values to the binary variables u, y and z which keep the state of the units, operating, starting-up or shutting down respectively.

$$y_{gt\omega} \leqslant u_{gt\omega}, \quad y_{gt\omega} \leqslant 1 - u_{gt-1\omega}, \quad y_{gt\omega} \geqslant u_{gt\omega} - u_{gt-1\omega} \quad \forall g, \forall t, \forall \omega \tag{16}$$

$$z_{gt\omega} \leqslant u_{gt-1\omega}, \quad z_{gt\omega} \leqslant 1 - u_{gt\omega}, \quad z_{gt\omega} \geqslant u_{gt-1\omega} - u_{gt\omega} \quad \forall g, \forall t, \forall \omega \tag{17}$$

Minimum up and down time constraints: These constraints (18-23) are applied to avoid the frequent transitions from on state to off state and vice versa.

$$\sum_{t=1}^{L_g} (1 - u_{gt\omega}) = 0 \quad \forall g, \forall \omega \tag{18}$$

$$\sum_{\tau=t}^{t+UT_g-1} u_{g\tau\omega} \geqslant UT_g y_{gt\omega} \quad \forall g, t = L_g + 1, ..., 2N_T - UT_g + 1, \forall \omega \tag{19}$$

$$\sum_{\tau=t}^{2N_T} (u_{g\tau\omega} - y_{gt\omega}) \geqslant 0 \quad \forall g, t = 2N_T - UT_g + 2, ..., 2N_T, \forall \omega \tag{20}$$

$$\sum_{t=1}^{F_g} u_{gt\omega} = 0 \quad \forall g, \forall \omega \tag{21}$$

$$\sum_{\tau=t}^{t+DT_g-1} (1 - u_{g\tau\omega}) \geqslant DT_g z_{gt\omega} \quad \forall g, t = F_g + 1, ..., 2N_T - DT_g + 1, \forall \omega \tag{22}$$

$$\sum_{\tau=t}^{2N_T} (1 - u_{g\tau\omega} - z_{gt\omega}) \geqslant 0 \quad \forall g, t = 2N_T - DT_g + 2, ..., 2N_T, \forall \omega \tag{23}$$

where $L_g = min\left\{2N_T, \left(UT_g - T^0_{up,g}\right) u^0_g\right\}$ and $F_g = min\left\{2N_T, \left(DT_g - T^0_{down,g}\right)\left(1 - u^0_g\right)\right\}$ are the hours in the beginning of the planning horizon that the unit is restricted to operate or to be offline respectively due to initial conditions.

3 Results

The system in the case study consists of two CHP units, one heat producing boiler and a heat storage tank. The parameters of the units are given in Appendix B. In fig.2 the scheduling of heat production is given. Because heat production is scenario dependent, this figure depicts one possible outcome. The existence of heat storage capacity increases the flexibility of the system. For example the use of the expensive heat boiler is avoided (e.g. hours 5-7) and the second unit can stop its operation when electricity prices are forecasted to be low (e.g. hours 41-43).

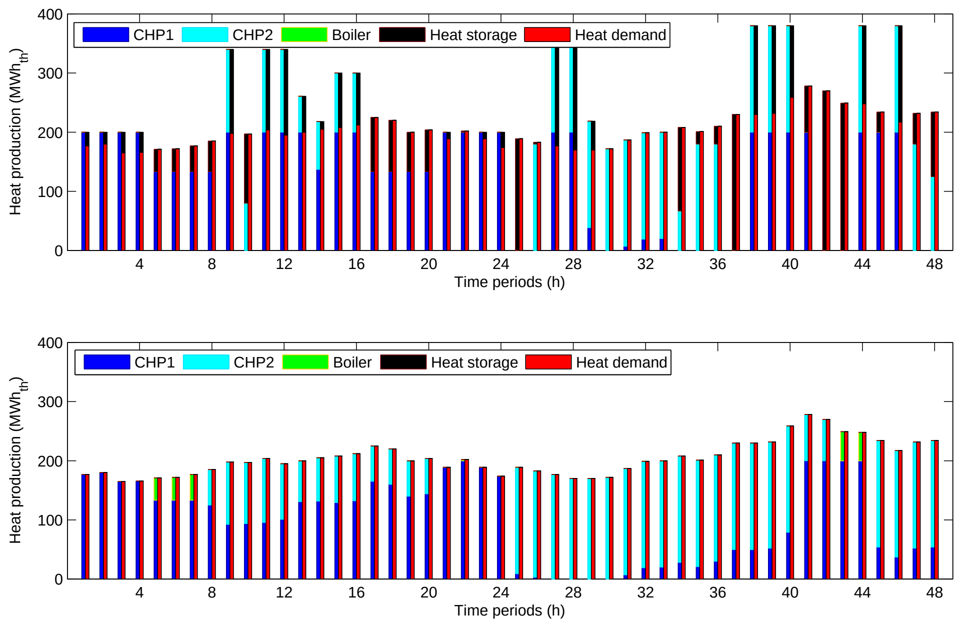

Figure 2: Heat production scheduling with (up) and without (down) heat storage capacity

To estimate the value of heat storage, the model is solved with different amounts of storage capacity, running from 0 to 1000 MWh/h. The results show an increasing optimal value with decreasing change rate. It must be noted that the optimal value is negative as the objective function does not include the income from power sold in Day-1 and the income from heat sold. These incomes are fixed and do not affect the optimal solution.

Capacity (MWh$_{th}$/h)	0	200	400	600	800	1000
Optimal value (€)	-94499	-91330	-90201	-89621	-89174	-88788

Table 1: Change of optimal value in accordance with the heat storage capacity

Acknowledgement

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Appendix A: Nomenclature

Indices and Numbers:

g	Index of units, running from 1 to $\mathrm{N_G}$
t	Index of time periods in hourly resolution, running from 1 to $2\mathrm{N_T}$
ω	Index of scenarios, running from 1 to $\mathrm{N_\Omega}$

Parameters

π_ω	Probability of occurrence of scenario ω
$\lambda_{el,t\omega}$	Day-ahead market price in period t and scenario ω, (€/MWh)
$Q_{D,t\omega}$	Heat demand in period t and scenario ω, ($\mathrm{MW_{th}}$)
$P_{S,t}$	Power load in period t, (MW)
$\lambda_{f,g}$	Fuel price of unit g, (€/MWh)
$c_{start,g}$	Start-up cost of unit g, (€)
$c_{stop,g}$	Shut down cost of unit g, (€)
$\beta_{el,g}$	Marginal fuel consumption for power production of unit g
$\beta_{th,g}$	Marginal fuel consumption for heat production of unit g
$\beta_{0,g}$	Fuel consumption at minimum output of unit g, (MW)
$r_{min,g}$	Minimum power-to-heat ratio of unit g
$\eta_{boiler,g}$	Efficiency of boiler unit g
$P_{min,g}, P_{max,g}$	Power production limits of unit g, (MW)
$Q_{min,g}, Q_{max,g}$	Heat production limits of unit g, ($\mathrm{MW_{th}}$)
V_{max}	Heat storage capacity, (MWh/h)
UT_g	Minimum up time of unit g, (h)
DT_g	Minimum down time of unit g, (h)
u_g^0, y_g^0, z_g^0	Initial state of binary variables $u_{gt\omega}$, $y_{gt\omega}$and $z_{gt\omega}$
$T_{up,g}^0$	Time periods of unit$g$ has been on in the beginning of the planning horizon, (h)
$T_{down,g}^0$	Time periods of unit$g$ has been off in the beginning of the planning horizon, (h)

Variables

$P_{gt\omega}$	Power produced by unit g in period t and scenario ω, (MW)
$Q_{gt\omega}$	Heat produced by unit g in period t and scenario ω, ($\mathrm{MW_{th}}$)
$P_{fuel,gt\omega}$	Fuel consumption of unit g in period t and scenario ω, (MWh/h)
$V_{t\omega}$	Heat storage content in period t and scenario ω, (MWh/h)
$u_{gt\omega}$	Binary variable for the on/off status of unit g in period t and scenario ω
$y_{gt\omega}$	Binary variable for the start-up of unit g in period t and scenario ω
$z_{gt\omega}$	Binary variable for the shut down of unit g in period t and scenario ω

Appendix B: Case study parameters

Table 2: CHP parameters used in the case study

CHP units	Unit1/Unit2	**Heat boiler**	
Fuel	Gas	Fuel	Gas
Fuel price, (€/MWh)	10	Fuel price, (€/MWh)	10
Min. power output, (MW)	35/30	Min. heat output, ($\mathrm{MW_{th}}$)	0
Max. power output, (MW)	140/120	Max. heat output, ($\mathrm{MW_{th}}$)	100
Max. heat output, ($\mathrm{MW_{th}}$)	200/180	Efficiency	0.9
Marg. fuel consumption for power prod.	2.4/2.5		
Marg. fuel consumption for heat prod.	0.36/0.37		
Fuel consumption at min output, (MW)	40/35		
Minimum power-to-heat ratio	0.5/0.5		
Start-up cost, (€)	10000	**Heat storage tank**	
Minimum up time, (h)	1/1	Capacity, (MWh/h)	0 - 1000
Minimum down time, (h)	1/1		

PRE STUDY OF CCS FOR A BIO FUELED CHP PLANT

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ABSTRACT

The environmental performance of a potential carbon capture and storage (CCS) installation at the bio fueled combined heat and power (CHP) plant in Lugnvik, Östersund was studied with screening life cycle assessment (LCA) methodology. CCS has lately been discussed for plants using bio fuels since it is one of few possibilities to actively decrease the concentration of carbon dioxide in the atmosphere. The most common process for carbon capture, absorption in MEA, was assumed. Transportation of the captured carbon dioxide to Norway for injection in natural gas fields was the considered storage option.

The impacts from transportation of the captured carbon dioxide indicate that alternatives should be investigated, e.g. possibilities for local storage or other types of utilization of the captured carbon. The comparatively high energy use for the MEA capturing process indicates that CCS for bio fueled plants must be carefully considered. Alternative technologies for carbon capture should be further investigated - e.g. if biological methods might give better performance over chemical absorption – as should the consequences of alternative handling of the captured carbon dioxide.

INTRODUCTION/PURPOSE

Could carbon capture and storage (CCS) be of interest for plants generating district heating in bio fueled combined heat and power plants (CHP)? CCS is discussed as one possible component in a set of actions to mitigate climate change, often in terms of making it possible to continue the use of fossil fuels and especially coal power. Lately CCS has also been discussed for plants using bio fuels since it is one of few technologies giving possibilities to actively decrease the concentration of carbon dioxide in the atmosphere, in contrast to just decreasing the emission of new carbon dioxide or other green house gases.

In this pre study Jämtkraft and the Echotechnology group at Mid Sweden University has initiated investigations of the environmental performance of implementing carbon capture and storage (CCS) at the CHP plant in Lugnvik, Östersund. We have made a screening life cycle assessment (LCA) study to model consequences.

The most common process for carbon capture, absorption in MEA, was assumed. Transportation of the captured carbon dioxide to Norway for injection in natural gas fields was the considered storage option.

STATE OF THE ART

The process of carbon capture and storage is known technology and to some extent used. For example carbon dioxide is separated from methane at natural gas fields in the North Sea and injected back in geological storage. The separation praxis has in this case the economic benefit of significantly decreased gas volumes to transport to shore. Post combustion capture at power plants has been practiced, mainly with the goal of achieving carbon dioxide for different uses, but is today not common. Post combustion capture of carbon dioxide for bio fuelled power of CHP plants is presently not in large scale use, but technically post combustion capture and storage would work similarly as for fossil fuelled plants [1]-[4].

For a retrofit situation of an existing plant, post combustion capture by absorption is the most commonly discussed method. For new plants pre combustion separation or oxy fuel solutions could also be considered. The most well known absorption chemical for post combustion capture of carbon dioxide is monoethanolamine (MEA), whereas the use of methyldiethanolamine (MDEA) and chilled ammonia as absorption chemicals represents technologies under development [5].

The Lugnvik plant contains of one CHP unit and two heat only units (used at peak heat demand and at summer service shut down of the CHP plant). The plant delivers district heating to the town of Östersund and some nearby municipalities. The main fuel types are sawmill residues and forest fuels, but peat and recycled wood are also used [6], [7].

METHODS

For this study a system model was created where the Lugnvik CHP plant was assumed to be retrofitted with a post combustion carbon capture facility using MEA absorption. Electricity needed for the capturing process was assumed to be covered by increased electricity production from the plant and it was assumed that the increased heat production could be delivered to the district heating network without limitations. The captured carbon dioxide was assumed to be transported to Norway and injected in the Sleipner field. This technical model was assessed using screening LCA methodology. LCA is a methodology to study environmental impacts over whole value chains, adding such as raw material extraction to use for a specified function. The parameters assessed were Global Warming Potential (GWP) and Acidification Potential (AP).

For this screening study we considered only the CHP plant (and not the heat only units also present at the Lugnvik site), assumed that all fuel utilized (also the peat) could be considered carbon neutral (of renewable origin), and regarding environmental impacts from fuel generation we only considered transports of the bio fuels to the plant. Environmental impacts from building and eventually decommissioning of the carbon capture facility was not considered.

We have assumed a carbon capture efficiency of 90% and that a third of electricity produced in the plant will be needed to run the carbon capture process [8]. The energy need might be underestimated for a CHP plant since the figure is based on facilities with power only production, but the approximation was considered sufficient for this screening study. We have modeled a corresponding increase in fuel transports, flue gas generation and ash transports. Flue gas and ash generation were based on the environmental data for the Lugnvik CHP plant of the year 2012 [6], [7]. For the MEA use, only transportation of the necessary make up due to losses [9] was considered, not the production of the chemical itself.

A pipeline transport of the captured carbon dioxide to Norway with subsequent injection in the Sleipner field was estimated based on data from a Vattenfall study [10], including emissions from constructing the pipeline over an assumed distance of 300 km. Electricity needed for pressure boosters etc is additional to the electricity needed for the carbon capture, and was assumed to be covered from the grid according to the Vattenfall study (not from increased production in the Lugnvik plant). An additional scenario estimating truck transports instead of pipeline transport (to avoid the need for building a pipeline over the mountain range) was based on emission factors for heavy truck transports [11].

Since this is a screening study with rough estimates, we have simplified by calculating the results per produced kWh, making no difference between electricity and heat. It should be noted that the production balance is skewed toward heat through the model assumptions.

RESULTS

The results for climate impacts as GWP in carbon dioxide equivalents are shown in Figure 1. As can be seen the emissions from running the Lugnvik CHP plant contributing to GWP increases significantly by implementing the CCS compared to the present situation, due to increased fossil fuel use by the increased transportation necessary (mainly by increased bio fuel and ash transports for the plant itself, and from transporting the captured carbon dioxide to storage). These increased emissions are however dwarfed compared to the avoided carbon dioxide emissions, shown as negative emissions in Figure 1.

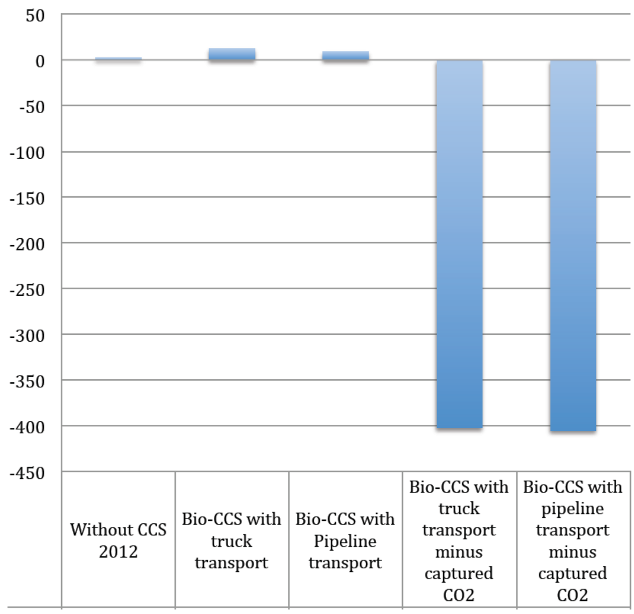

Fig. 1 The contribution to global warming for the CCS model of the Lugnvik bio fuelled CHP plant under two scenarios. Note that these results are from a screening study. The climate impact increases significantly from the present operations by introducing the CCS. The increased emissions are more than compensated for by the net withdrawal of carbon dioxide from the atmosphere through geological storage give, indicated by the large negative bars.

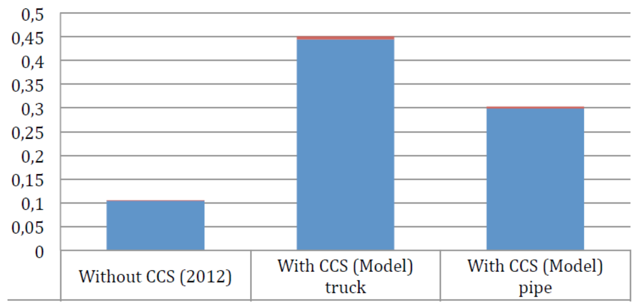

Fig. 2 The contribution to acidification, in sulphur dioxide equivalents, for the CCS model of the Lugnvik bio fuelled CHP plant under two scenarios. Note that these results are from a screening study. The acidification impact increases significantly from the present operations by introducing the CCS.

The results for acidification impacts as AP in sulphur dioxide equivalents are shown in Figure 2. For acidification the emissions and the impact only increase by the implementation of the CCS; for the parameter acidification there are no avoided impacts. Also for acidification the increased impact is to a large extent from increased transportations (and mainly to transport related NO_x emissions).

The pipeline transportation scenario would in this rough model give somewhat lower impacts compared to the truck transportation scenario.

DISCUSSION

The Lugnvik CHP plant is, compared to most coal power plants rather small, with comparatively small amounts of potentially captured bio-carbon dioxide.

This screening LCA study only gives a rough picture of the performance of the possible installation of a CCS facility in Lugnvik, but still clearly indicate that the reduction of carbon dioxide comes to a cost in form both increased use of bio fuels to deliver the same amount of benefits in form of heat and electricity, and in form of increased impacts to acidification from increased NO_x emissions The increased NO_x emissions originates from increased transports of fuels and ash due to increased incineration to cover the energy needed for the modelled absorption, and from transport of the captured carbon to the geological storage.

If the modelled technical solution should be implemented, it must be carefully studied from optimization point of view. Any increase in energy performance of the absorption process would be very beneficial. It should be investigated if alternative storage possibilities closer by could be utilized. Work must be put into further decreasing the flue gas NO_x emissions, when you implement a situation where you increase combustion of fuels without a significant increase of production.

The strongest indication from the study, however, is that for bio fuelled plants, alternative methods for both capturing and ‘storage’ of carbon should be considered. Biological absorption of carbon dioxide in flue gases by algae has been studied in small scale study by Jämtkraft and Ecotechnology in 2005 indicating a possible absorption rate of about 50% or above. If such biological processes could significantly reduce energy use in the absorption process the lower absorption rate might be acceptable for a bio fuelled plant. Alternatives to storage should also be investigated; for carbon dioxide from bio fuels perhaps secondary use as materials, bio oil, etc could be an as good option as long term geological storage, at least if the impacts from the storage / secondary use process would be significantly reduced. Other alternatives, as power to gas schemes, should also be studied and environmental and climate performances of the different alternatives carefully considered.

An issue not looked into here is risks of leakage in transportation or storage. Such considerations have been of high concern for the discussions of CCS for coal power plants in Germany.

OUTLOOK

Companies delivering district heat and other energy carriers based on bio fuels have a possibility to contribute to lowering the carbon dioxide concentration in the atmosphere. Before implementation such technologies must be further investigated regarding process optimization and how different options for both capture and storage or use of carbon will perform in environmental and energy systems perspective. Cost is also an issue which has not been looked into here.

CONCLUSIONS

The impacts from transportation of the captured carbon dioxide indicate that alternatives should be investigated, e.g. possibilities for local storage or other types of utilization of the captured carbon. The comparatively high energy use for the MEA capturing process indicates that CCS for bio fueled plants must be carefully considered. Alternative technologies for carbon capture should be further investigated - e.g. if biological methods might give better performance over chemical absorption – as should the consequences of alternative handling of the captured carbon dioxide – e.g. use for materials, bio oils, power to gas schemes etc.

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Poster Contribution

The impact on electricity generation by reducing the heat demand in the district heating system in Gävle

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Introduction/Purpose

In many areas within the EU, large amounts of fossil fuels are used to heat buildings and to produce electricity. This justifies actions from the EU and other organizations to implement energy conservation measures (ECMs) in residential buildings. However, in many Swedish areas, renewable energy and waste heat is the main source to heat buildings through the district heating systems (DHS). This contributes to low CO_2 emissions and low use of primary energy for heating. Combined with the fact that CHP plants are commonly used, a decreased heating demand also decrease the electricity production.

Billerud Korsnäs AB, a paper mill in Gävle, delivers waste heat to Gävle Energi AB. The waste heat covers more than half of the energy demand in the district heating system. Billerud Korsnäs AB and Gävle Energi AB built a new biothermal furnace in 2012 forming a joint venture; Bomhus Energi AB.

This research investigates how decreased heating demand for a building within the DHS in Gävle affects the production units for heat and electricity. A discussion regarding the importance of building regulations (BBR) as a way of sending the desired signals, when methods for ECMs are selected, is also included.

Methods/Methodology

To use as realistic values as possible, the actual model for optimizing the running order for the production units in the district heating system was used. The running order is determined by the marginal cost of each production unit. The marginal cost for some production units is highly dependent on the electricity price. Therefore, the running order is affected by the electricity spot price.

To simulate ECMs for a building, IDA-ICE was used. IDA-ICE is a dynamic multimode simulation application for accurate study of thermal indoor climate of individual zones as well as the energy consumption of the entire building. Different energy efficiency actions were simulated for one multi-dwelling building built in Sätra, Gävle, during “the million program” era. The simulations were performed on an hourly basis for the year 2013.

For the calculations and simulations, weather data from 2013 was used together with hourly data of delivered energy from the district heating system and the electricity spot price.

The impact on the use of heat and electricity of the different energy conservation measures in the multi-dwelling building were simulated. Then the marginal production unit was given according to table 1 and the change in heat and electricity production was determined.

The District Heating System in Gävle

Almost all production units in the DHS in Gävle use renewable energy, including 2 out of 3 oil boilers in the system, since they are using bio oil. The fossil fuel content in the fuel mix during 2013 was less than 0,8%.

The running order of the production systems are influenced by the electricity spot price. Electricity production units obtain a higher priority order with higher electricity price and units which use electricity receives a lower priority; see the example in table 1.

Table 1: Running order for the different production units depending on the electricity spot price

	Production units - order of priority						
electricity price	Waste heat	FGK	Evaporation	Johannes	HWC	DC	HWB
A → B	1	2	3	4	5	6	7
B → C	1	2	3	5	4	6	7
C → D	1	2	3	4	5	6	7
D → E	1	2	4	3	5	6	7
E → F	1	3	4	2	5	6	7
F → G	2	2	4	1	5	6	7
G → H	1	2	4	3	5	6	7
H → I	1	2	3	4	5	7	6
I → J	1	2	3	4	6	7	5

The production units and the corresponding companies in the table are:

- Waste heat – Excess heat from paper production, Billerud Korsnäs AB
- FGK – Flue Gas Condenser, Bomhus Energi AB
- Evaporation – Black liquor evaporation, Billerud Korsnäs AB
- Johannes – Combined Heat and Power production, Gävle Energi AB
- HWC – Hot Water Condenser – Various waste heat, Billerud Korsnäs AB
- DC – Direct Condenser, decreased electricity production at Johannes, Gävle Energi AB
- Hot Water Boiler – Steam boiler, Bomhus Energi AB

Scope and limitations

The method to use real production data and to calculate the effect of ECMs with the energy company's own optimized running order combined with results from a simulation program such as IDA-ICE on hourly provides detailed reliable results and data for evaluation.

For local weather conditions, IDA-ICE needs input from a climate file. Metrology data measured by SMHI was used to create the climate file and global solar irradiation and diffuse solar irradiation was produced by STRÅNG (reference http://strang.smhi.se/).

Results

The method used for analyzing the impact of the district heating system when ECMs are implemented in a multi-dwelling building gives a detailed picture of benefits and drawbacks in the DHS. Table 2 displays the decreased energy use for different ECMs and how the production units for electricity are affected.

Table 2: Simulated results for the decreased energy use for different ECMs and how the production units for electricity are affected.

	Attic 400 mm insulation	Reconstruction of external wall 200 mm extra insulation	Exhaust air heat pump
Reduction use heat	7.600 kWh	35.600 kWh	68.800 kWh
Increased use electricity	0 kWh	0 kWh	25.500 kWh
Decreased production electricity	950 kWh	4.400 kWh	4.800 kWh
Increased production electricity	580 kWh	2.700 kWh	2.700 kWh

When a decrease in heat demand occurs when Johannes (CHP) is the marginal production unit, a decrease in electricity production is obtained. When the direct condenser is the marginal production unit (condenser to increase heat output from Johannes) the turbine reduces the electricity production in favor of extra heat production. If the heat demand in the DHS decreases, an increase in electricity production is gained if the marginal production unit is the direct condenser.

The simulated total use of heat for heating and domestic hot water before any ECMs was 253 MWh. When 400mm extra attic insulation was added, the simulated energy decrease was 7.600 kWh. The decreased heat usage results in a decreased electricity production of 950 kWh when Johannes is the marginal production unit and when the direct condenser is the marginal production unit there is an increase of electricity production by 580 kWh. The total production decrease of electricity is therefore 370 kWh for the simulated year.

When 200 mm extra insulation on the external wall is simulated, the decrease of electricity production is 4.400 kWh when Johannes is the marginal production unit. When the direct condenser is the marginal production unit there is an increase of 2.700 kWh. The total decrease of electricity is therefore 1.700 kWh. The total saved heat for the ECM is 35.600 kWh.

When an exhaust air heat pump is simulated for the building, the decrease of electricity production is 4.800 kWh (Johannes) and the increase is 2.700 kWh (direct condenser). The total decrease of electricity production is 2.100 kWh. The total change of electricity is both the change from production units and the increase of electricity use because of the heat pump. In total, the increased amount of electricity is 27.500 kWh. The total heat savings for the ECM is 68.800 kWh, however there is also an increase of electricity use of 25,500 kWh.

The impact of electricity production in the DHS in Gävle is significantly affected when ECMs are implemented. The multi-dwelling building used for the simulation is ordinary in size, construction and utilization of energy compared to other buildings from “the million program” era in Sweden. Therefore, the building is a good representation of similar multi-dwellings.

Discussion

It is uncertain how ECMs affect the production of electricity when implemented in buildings within the DHS. Each district heating system is unique and results differ for similar ECMs depending on local fuels and production units. This study shows that the produced electricity in Gävle decreases with lower heat demand from three different ECMs for a building. Upcoming research will investigate in more detail how the DHS in Gävle can develop with both DH supplier and residences in mind.

It is important that the building regulation (BBR) sends the right signals when the methods for ECMs are selected. Electric energy has a higher quality or value than heat of relatively low temperatures. This has to be taken into account when the ECMs are prioritized and selected. Denmark has a ratio between electricity and district heating of 2,5-1, which will be changed to 2,5-0,8 in 2015. Finland has ratios of 1,7-1,0-0,7 between electricity, fossil fuel and district heating.

We propose that Sweden should introduce similar factors. The environmental impact and the use of resources will be minimized if an energy carrier with lowest possible exergy level is used. The quality factors should provide signals which develop the energy conservation in this direction.

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CHP PROJECT IN THE LARGEST LANDFILL IN MEXICO.

I. Introduction:

In the eastern part of Mexico City, there is a 3.5 million M^2 landfill with over 70 million tones of Municipal Solid Waste (MSW) , the final closure of the landfill took place in 2010. Since then and due to the decomposition of the organic material within the MSW, an important amount of biogas mainly methane (CH_4) and leachate is formed.

Biogas and natural gas will be used to produce up to 60 MW power and leachate should be properly disposed in order to avoid pollution of nearby aquifers.

In Mexico City with 8 months rainy season, we may have some 850 mm of rain every year; this fact means the natural growth of leachate within the landfill and the higher risk to pollute aquifers.

The normal way to properly dispose leachate in a landfill is to send it into an evaporation pond in order to have an evaporation process due to the sun air and heat. This process may take a long period of time.

In order to accelerate the leachate evaporation process and reduce the risk to contaminate aquifers, we will take advantage of the exhaust gases heat from the gas turbine and internal combustion engines in order to increase temperature of leachate within the evaporation pond.

The way to do it is to design a heat interchange device used to heat a working fluid (oil) and transfer the exhaust gases heat from the engines to the evaporation pond.

According to Mexican energy and environmental laws, this process may be taken as an efficient cogeneration process and eligible to have the same benefits as renewable sources of energy.

METHODOLOGY:

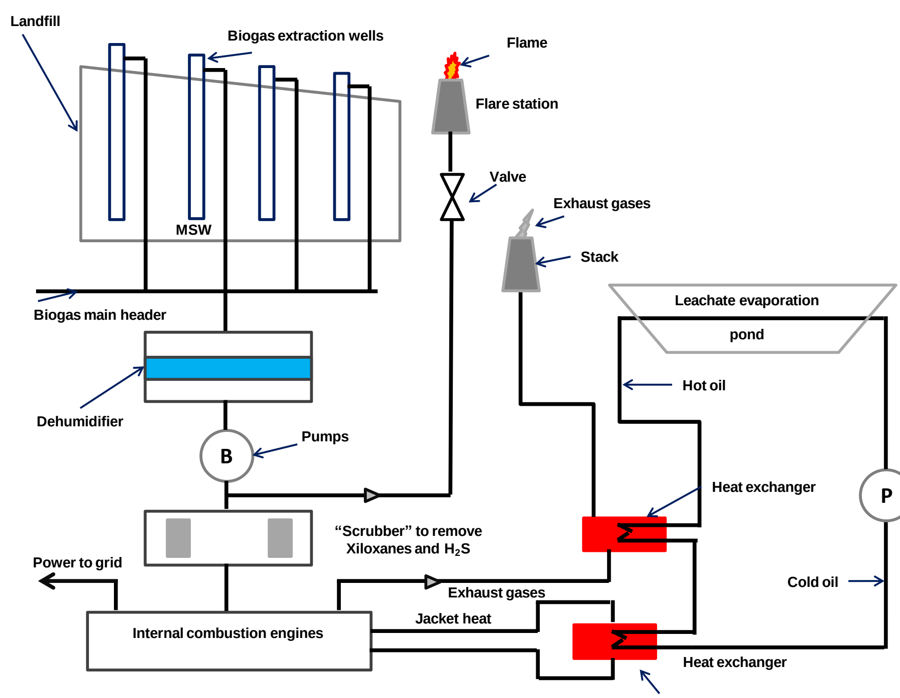
The plant runs on ten Jenbacher GE internal combustion engines of 2 MW each, which run on biogas from the landfill waste, and a 40 MW LM6000 GE natural gas turbine, for a total electrical capacity of 60 MW. Exhaust gases from the combustion engines pass through a heat exchanger, transferring heat to a working fluid (oil), which is used to evaporate leachate. The natural gas turbine runs only on natural gas See figure below for a schematic diagram of the plant. The system is designed for continuous operation, 365 days per year, but requires monthly oil changes for the combustion engines (400 hours of maintenance annually), and annual maintenance to the natural gas fired, gas turbine. Project developers estimate 95% availability, barring forced outages.

The plant's projected annual energy input is 737 TJ, of which 66% comes from natural gas and 34% comes from biogas from the landfill. The biogas contains 55% methane gas and 35% CO_2, and has a high heating value of 650 btu/ft^3.

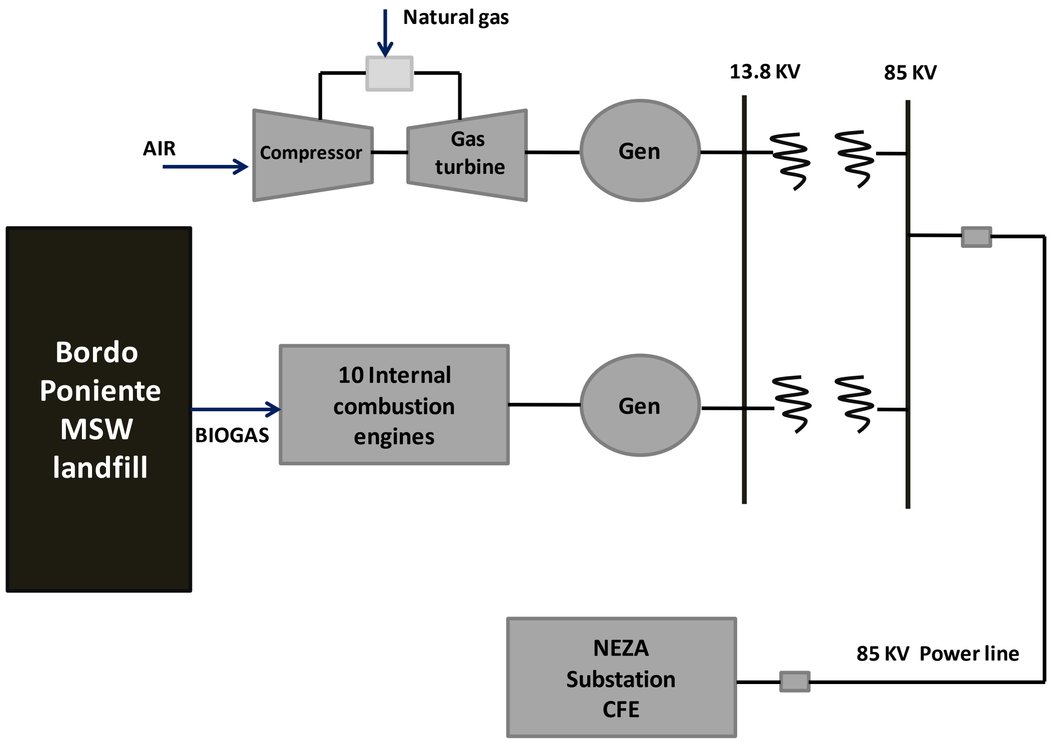
Variability in fuels

The plant has a total heating capacity of 26 MWt. On average, project developers expect annual heat generation to reach 737 TJ, and annual electricity generation to reach 473 GWH. This would give the plant an overall efficiency of over 80%.

	Electricity	Heating	Total
Capacity	60 MWe	26 MWt	86 MW
Generation	473 GWH	737 TJ	-
Efficiency	41.1%	42.9%	84%



Power generated at Bordo Poniente will feed into the grid via an 85 kV power line to the Nezahualcóyotl substation run by the state-owned utility, Comision Federal de electricidad (CFE), which ultimately wheels the electricity to final users. SEM, is not involved in transmission and distribution of power; in Mexico, CFE owns all transmission and distribution assets, which are operated by one of its departments, Centro Nacional de Control de Energía (CENACE). In the event that biogas production falls below the necessary amount for combustion, the internal combustion engines can also run on natural gas to avoid interruptions in service.



The end-user of most of the power generated at the Bordo Poniente plant will be Mexico City's street light system, owned by Direccion de Servicios Urbanos. The system has an installed capacity of 120 MW, and operates 12 hours per day. Currently, this office pays USD 0.20/kWh to CFE for its electricity. The project developers also expect to deliver electricity to the Mexico City tram and trolley system, as well as some other small electrical end-users.

The end use for heat generated at Bordo Poniente will be also, the reverse osmosis leachate disposal system. The waste heat will be captured, and passed through a heat exchanger to heat up a working fluid, which will in turn evaporate leachate from an on-site pond.

Technology justification: environmental, flexibility, economical, fuel availability, etc.

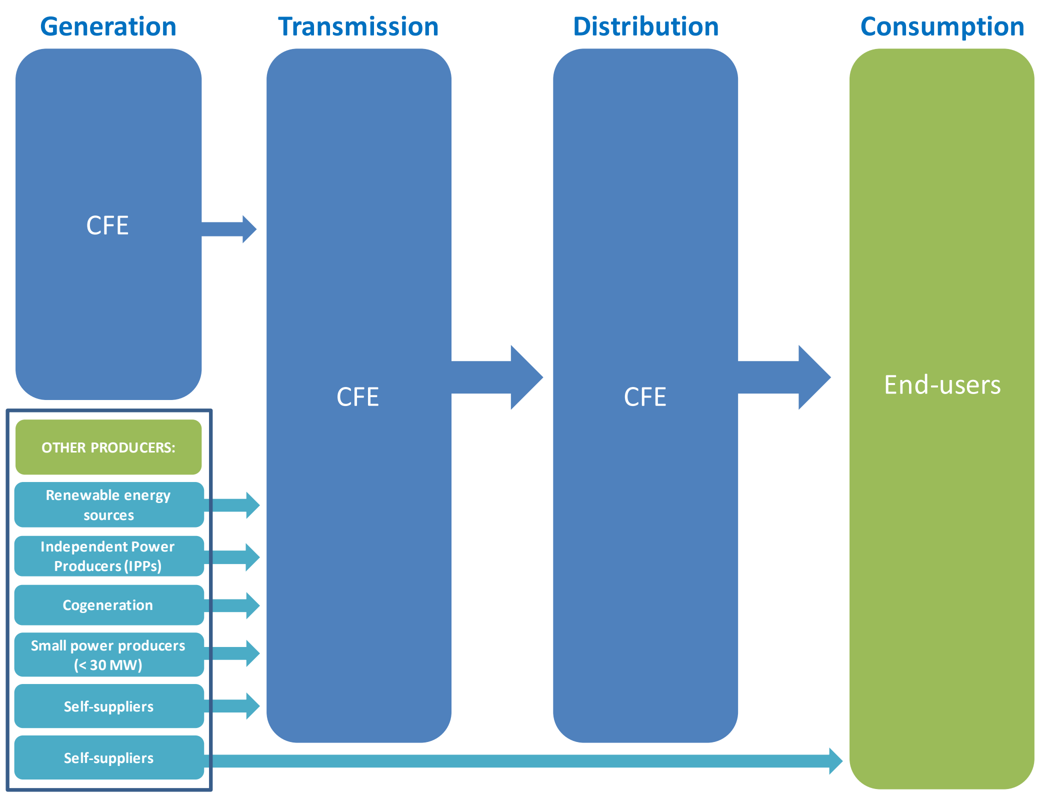
The tender offered by the government of Mexico City set a requirement for the project to generate electric power using biogas from the landfill, but did not require a specific technology. SEM considered three possible technologies:

- Using biogas in a boiler to produce steam, driving a steam turbine to generate power.
- Using biogas as a fuel to produce electricity with a gas turbine.
- Using biogas as a fuel for internal combustion engines, with waste heat recovery technology to utilise the exhaust gases.

Ultimately, internal combustion engines were selected for both economic and technical reasons. The steam turbine technology was not feasible because of the lack of water on-site. Developers determined that using biogas to fuel a gas turbine would be prohibitively expensive; compressors to bring the biogas to the appropriate pressure for the turbine would use a large percentage of power generated by the turbine. The internal combustion engine option allowed the use of exhaust gases to evaporate leachate. Conventional leachate disposal systems, such as activated carbon, are more expensive, about 5€/m^3 of leachate disposal.

National/regional regulatory context

The Mexican electricity market is largely controlled by the state-owned utility, Comisión Federal de Electricidad (CFE). CFE owns over 75% of the installed generation capacity, and it owns all transmission and distribution assets in Mexico. A 1992 amendment to the Public Electricity Service Act of 1975 partially opened the electricity sector to privately-owned electricity producers; with a permit from the Comisión Reguladora de Energía (CRE), private companies that fall into one of the following categories are allowed to produce power and connect to the grid: self-suppliers, cogeneration projects, small producers (< 30 MW), power producers who are importing electricity for self-supply or generating for export, or independent power producers with 25-year power purchase agreements (PPAs) with CFE. As of 2012, there was 12.2 GW of privately-owned installed generating capacity in Mexico, primarily using combined-cycle natural gas turbines.



Project financing: mechanisms used

SEM will build, own and operate the plant for 25 years prior to transfer back to government ownership in 2038. As a result of the project's savings from efficient cogeneration, as well as from financial incentives from the government, the developers expect the final customer to save about 25% compared to current utility prices. The expected cost of electricity from Bordo Poniente for end-users will be USD 0.15/kWh, compared to USD 0.20/kWh for electricity from CFE. These prices include transmission and distribution costs, though Bordo Poniente power will be fed into the CFE grid to be delivered to consumers. SEM expects maintenance costs of about USD 0.02/kWh generated.

The capital expenditure (CAPEX) for the final closure of landfill, biogas recovery system and leachate evaporation systems will be about USD 75 million. CAPEX for construction of the power island, switchgear, main substation, power line, and connection to CFE's grid will be about USD 90 million, bringing the total for the project to about USD 165 million. The Mexican government's development bank, Banco Nacional de Obras y Servicios Públicos S.N.C. (BANOBRAS), provided a USD 27 million grant for the closure of the landfill. Of the remaining USD 138 million, BANOBRAS provided an additional USD 96.6 million in project finance for the construction of the cogeneration plant, which required 30% (USD 41.4 million) equity. Project developers expect a 4.33 year payback period.

Financing for the project was based on the 25-year contract with the government of Mexico City.

The Bordo Poniente project falls into the cogeneration category, and is thus allowed to produce electricity for sale into the grid. Cogeneration projects are also allowed for other purposes aside from public sale of electricity, according to the Electricity Law on the Use of Renewable Energy and Energy Transition Financing.

Additionally, as an efficient cogeneration scheme, the Bordo Poniente project is also entitled to the same benefits that are provided to renewable energy projects, which include low and known wheeling values (between USD 0.020 and USD 0.030 USD/kWh), an energy banking scheme to levelise energy (kWh) output, and duty-free import of all equipment associated with the project. Additionally, under old regulations, as was the case with previous projects developed by other developers, a back-up contract with CFE would have been required, to provide electricity in the event of forced or planned outages, and back-up tariffs were expensive. Under new regulations, back-up contracts are not required, which reduces the cost for the Bordo Poniente plant.

II. Lessons learned/Conclusion

The Bordo Poniente project applied lessons learned from experience developing other biogas power plants. The Bioenergía de Nuevo León project, which began commercial operation in 2003, is a 16 MW biogas power plant near the city of Monterrey. The biogas used at Bioenergía de Nuevo León contained siloxanes, which caused silicon salt deposits in the cylinders and engine heads. The deposits resulted in vibrations higher than recommended by the manufacturer, and the engines had to be overhauled at 12 000 fired hours, rather than after 24 000 hours as recommended by the manufacturer, which doubled estimated operations and maintenance costs for the project. The Bordo Poniente plant uses equipment to remove siloxanes from the biogas prior to combustion to avoid this problem.

We are well aware this is not a “District Heating & Cooling Project”, mainly because in Mexico City average ambient temperatures does not require the use of central heating systems in winter or air conditioning systems via absorption chillers in summer, however, the use of an innovative leachate disposal system powered by waste heat from biogas power generation makes this project a unique example of an efficient cogeneration project.

Project developers in other countries and regions could apply similar technology and CHP design; however, the project relied heavily on a grant and subsidised financing from the federal government, as well as a long-term power purchase agreement with a set electricity price. The feasibility of undertaking a similar project in a different location would likely depend on the availability of incentives like these. Additionally, because the Bordo Poniente landfill is one of the largest in the world, project developers can rely on biogas for many years to come, which is not the case for every source of biogas. Nevertheless, the Bordo Poniente project provides an excellent example of an innovative use of CHP technology to improve efficiency in waste disposal and power generation, and can serve as a guide for developers of future projects integrating CHP with waste-to-energy projects.

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OPTIMIZATION METHODS OF HEAT SUPPLY SYSTEMS' SCALES.

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Abstract.

According to the Russian Law "About a Heat Supply" development of a technique of an assessment of rational scales of systems which includes area zoning by the heat supply types and definition of the rational levels of heat supply centralization is required. Mathematical models and a methodical approach focused on the current conditions are offered to solve the problem. The main idea of the study is a heat density analysis at a predesign development stage of a heat supply schemes for settlements. Optimal values of heat density and line heat density correspond to a minimum of operational costs on a heat source and networks (least cost method). The problem is solved by a set of mathematical methods, including a method of dynamic programming.

Introduction.

In previous years the heat supply development in our country was focused on creation of a large district heating systems with preferable application of the combined development of thermal and electric energy at heat power plants (CHP). District heating (DH) systems are providing about 70% of heat energy. More than 80% of the population of the country is connected to the DH systems. Typical annual loss of thermal energy in networks is around 12%, losses in the old heat networks are more than 30%.

According to the Russian Law "About a Heat Supply" development of a technique of an assessment of rational scales of systems which includes area zoning by the heat supply types and definition of the rational levels of heat supply centralization is required. The following questions are distinguished from a set of tasks:

1. Territory zoning - division of the territory into zones of the centralized and decentralized heat supply.

2. Justification of optimum levels of a heat supply centralization and concentration of heat sources (HS) capacities.

Territory zoning by type of heat supply in practice is seldom carried out in our country. At the same time, the need to meet this requirement is fixed legislatively and regulated by requirements to heat supply schemes. In the Scandinavian countries, this process is also legislatively approved. In the previous works [1,2] author considered in detail the question of territory zoning into areas of the centralized and decentralized heat supply.

State of the art.

From the beginning of heat supply development researchers investigated the problem of optimum scales of DH systems and of rational levels of HS capacities' concentration. It was necessary to choose structure and parameters of HS, to estimate scopes of the combined and separate schemes of energy supply. At that time the problem was solved as a problem of a choice of optimum thermal output of CHP. For its decision, as applied to small by the sizes and simple systems, the analytical dependence which allowed to determine economically reasonable service area of CHP at the specified heat density was received [3-5]. In works [5-8] analytical dependences and graphic representations are given. Use of these dependences as applied to conditions of the certain settlement allows to allocate zones of efficiency of various HS types, that are characteristic only for it. Calculations for schematic-structural optimization are carried out on the basis of a technique of "excess schemes", and also on a number of the options planned by the developer.

The techniques described in the works [9-10] are applied to a solution of the problem of determination of rational scales of DH systems in Sweden and Denmark. In this technique researchers use an indicator of linear heat density for determination of heat supply efficiency, compare the overall cost of the system with a variety of pipeline's configurations. They received standard values of criterion by carrying out alternative calculations of various systems of a heat supply.

Basing on results of the previous researches [3-8], the real work continues and develops main provisions of these investigations and takes into account features of a modern situation and new tendencies in a heat supply. Criteria of heat load density for the solution of problems are used in this work. The criterion of heat load density per area unit allows to estimate efficiency of a construction of the centralized heat source. Criterion of efficiency of existing DH system functioning within current scales or of an assessment of profitability of connection to it new consumers at a preliminary stage is the linear heat load density (the load per unit of network's length). Analytical dependences for determination of standard values of criteria are presented in this work.

Mathematical statement of tasks.

The task of territory zoning. In systems of a heat supply, the minimum of costs for their construction and service is reached if the condition for level of heat density is met. In this regard, the mathematical formulation of a problem of territory zoning can be written as:

$$Z^{HSS}(Q,x,t) = Z_S^{DHS}(Q,t) + Z_N(x,t) + Z^{DS}(Q,t) \to \min \quad (1)$$

where $Z_S^{DHS}(Q,t), Z_N(x,t), Z^{DS}(Q,t)$ – the heat generation cost in district heating system, the distribution cost in networks and the heat generation cost in decentralized heating system (rub/GJ); Q – heat load of heat sources (GJ/h), x – heat carrier flow on sections of the network of heat supply system (t/h); T – period of time, $t \in T$.

The optimization problem (1) should be minimized subject to following constraints:

1. Heat production and demand balance.

$$Q^t = \sum_i Q_i^{DHSt} + \sum_n Q_n^{DSt} = \sum_j Q_j^t, i \in I, n \in N, j \in J, t \in T \quad (2)$$

where $Q_i^{DHSt}, Q_n^{DSt}, Q_j^t$ - production of heat energy in DH system, decentralized system and heat energy demand, respectively (GJ/h).

2. Capacity limits of CHP units and individual units.

$$0 \le Q_i^{DHSt} \le Q_i^{DHS\max}, i \in I, t \in T \quad (3)$$

$$0 \le Q_n^{DSt} \le Q_n^{DS\max}, n \in N, t \in T \quad (4)$$

3. The equations describing the flow distribution in hydraulic circuit:

3.1. Maintaining the flow's balances in the network nodes:

$$Ax = g \quad (5)$$

3.2. Maintaining balances of pressure losses of heat carrier in the network circuits:

$$\overline{A}^T P = h - H \quad (6)$$

3.3. The equation of pressure loss in the network:

$$h = SX|x| \quad (7)$$

where A is an (m-1) x n incidence matrix for linearly independent nodes, which is obtained on the basis of complete matrix $\overline{A}$ by deleting any of its rows; $\overline{A}^T$ is a transposed complete matrix of node and branch connections; P is a vector of nodal pressures (mwc); x is a vector of flow rates in the network sections (t/h); g is a vector of flow rates at nodes (t/h); h, H are vectors of losses and operating heads (mwc); S is a diagonal matrix of hydraulic resistance coefficients s_i, (mh^2/t^2), $|x|$ is the module of vector of flow rates in the network sections, (t/h).

4. Ratio for the criterion of heat density for area:

$$HD_n^A = \frac{\sum_1^J Q_j}{\sum_1^N S_n}, j \in J, n \in N \quad (8)$$

where HD_n^A – heat density for area (GJ/h m^2), S_n– the total land area of n-th district (m^2).

5. Constraint for the heat load density

$$HD_n^A \ge q_s, n \in N \quad (9)$$

where q_s – standard value of heat density criterion for the connection to the DH system.

Standard value of heat density criterion q_s depends on: building density, number of storeys of buildings, sort and cost of used fuel, characteristics of pipelines (roughness coefficient, local resistance, etc.). Standard value of q_s corresponds to value of heat density at equality of functions of the given expenses in DH and decentralized systems. For connection of consumers to DH system, the necessary condition is equality or decrease in costs in heat supply system in comparison with the decentralized heat source. The following dependence for determination of standard value of heat density was received after carrying out the optimizing researches:

$$q_s = \frac{m(p+a)}{0.001hP_F b_{nat} - \frac{C_i}{Q_i} - D_i} \quad (10)$$

where m – approximation coefficient of numerical values of the specific cost of pipe laying with various values of heat density; a is the annuity, from the chosen interest rate and the investment lifetime; p – pipeline operation costs and depreciation charges in shares from capital investments; h – the number of hours of load use; P_F – the cost of ton of natural fuel for individual sources (rub/ton); b_{nat} - specific consumption of natural fuel for heat energy production in decentralized sector (kg.nat.f/GJ); Q_i – the heat load of centralized HS (GJ/h); C_i, D_i – coefficients of constants and variable costs for production of heat energy.

The task of justification of optimum levels of heat supply centralization and concentration of HS capacities. Standard value of linear heat density criterion they correspond to the minimum of construction and maintenance costs in the DH systems. In this regard, the mathematical formulation of a problem of territory zoning can be written as:

$$Z(Q,x,t) = Z_S(Q,t) + Z_N(x,t) \to \min, \quad (11)$$

где $Z_S(Q,t), Z_N(x,t)$ – the heat generation cost and the distribution cost in networks in district heating system.

The optimization problem (11) should be minimized subject to following constraints:

1. Heat demand and production balance:

$$Q^t = \sum_j Q_j^t = \sum_i Q_i^t = \sum_m Q_m^t, j \in J, i \in I, m \in M, t \in T \quad (12)$$

where Q_j^t – heat load of j-th consumer in the time period t (GJ/h) , Q_i^t – heat output of the i-th heat source (GJ/h), Q_m^t – heat load of the m-th main pipeline (GJ/h).

2. Capacity limits of heat units:

$$0 \le Q_i^t \le Q_i^{\max}, i \in I \quad (13)$$

3. 3. The equations describing the flow distribution in hydraulic circuit:
3.1. Maintaining the flow's balances in the network nodes:

$$Ax = g \quad (14)$$

3.2. Maintaining balances of pressure losses of heat carrier in the network circuits:

$$\overline{A}^T P = h - H \quad (15)$$

3.3. The equation of pressure loss in the network:

$$h = SX\,|x| \quad (16)$$

4. Ratio for the criterion of linear heat density:

$$LHD = \frac{Q_m}{\sum_k L_k}, k \in K \quad (17)$$

where LHD – linear heat density, (GJ/h m), L_k– the trench length of k-th section of DH pipe system, m.
5. Constraint for the linear heat density

$$LHD \ge q_L \quad (18)$$

Standard value of linear heat density criterion q_L depends on: sort and cost of used fuel, characteristics of pipelines (roughness coefficient, local resistance, etc.).

Taking into account operational cost for HS the mathematical dependence of specific operational cost in DH system is used for determination of q_L. For the accounting of operational cost for HS the multiple calculations for different types of fuel and equipment capacities were carried out. We made differentiation of the dependence of specific operational cost load by heat and found expression for LHD definition at a minimum of cost and the optimum power of a source:

$$q_L = \left(\frac{2{,}757 \cdot c_e \tau \psi}{\Delta t \eta} + \frac{0{,}042\, fb}{\psi^{0.27} \Delta t^{0.551} Q_i^{0.449}} \right) \cdot \frac{Q_i^2}{C_i}$$

(19)

where f – depreciation charges, charges for maintenance and repairs of networks in shares from capital investments; Q_i – optimal heat output of the i-th heat source (GJ/h); b – coefficient in the equation of cost of an single pipeline; τ– number of hours of unit operation; $c_э$– electric power cost (rub/kWh); η – efficiency coefficient of pump; Δt – the difference between supply and return temperatures of a network; ψ– the specific pressure drop in a network (mwc/m); C_i – the coefficient of constant cost for heat energy production in a heat source.

Technique.

Both tasks can be presented by a single technique, which allows to solve a problem of optimum scales of heat supply systems. The technique is developed. It includes the following stages:

1. Gathering of primary information (the total land area, the building type, the connected loads of consumers, information about existing heat networks and HS).
2. Calculation of area heat density (HD^A) for all districts of the city.
3. Calculation of the standard values q_A.
4. Evaluation of the received HD^A values relative to the standard q_A values.
5. If the received values of HD^A are higher than the standard values q_A, the consumers can be connected to DH system. If the HD^A level is lower than its standard values, consumers are supplied with heat energy from individual HS.
6. For consumers in DH zone the place of connection to a HS and the total trench length of heating network to it is defined. If necessary, the total trench length of heating network for redundancy is considered.
7. Calculation of linear heat density (LHD) for main networks from HS in the received scheme of system.
8. Evaluation of the received LHD values relative to the standard q_L values.
9. If the received values of LHD are higher than the standard values q_L, the consumers can be connected to the considered HS.
10. If the LHD value is lower than its standard values, the calculation of linear heat density with sequential disconnection of the most removed consumers is made. Then you make a disaggregation of the system and choice of a new HS (return to item 6).

Results.

For an assessment of the received results we will consider the heat supply system of Shelekhov city as an example. Based on offered algorithm the analysis of city heat supply system is carried out. The standard value of area heat density is equal 84 (GJ/h)/km^2. According to the technique of territory zoning by heat supply type we determined zones of the centralized and decentralized heat supply, in fig.1 decentralized zone is shaded.

On the basis of expected levels of heat consumption the dotted line allocated perspective DH zones. The Shelekhov department of Novo-Irkutsk Thermal Power Station supplies with heat of consumers in the DH sector by three main pipelines. Maximum heat load of consumers reaches 695 GJ/h and heat losses equal to 10%. The standard value of linear heat density is equal 50 (GJ/h)/km. The length of main pipelines is 16 km. We carried out calculation and the analysis of an indicator of LHD for this system.

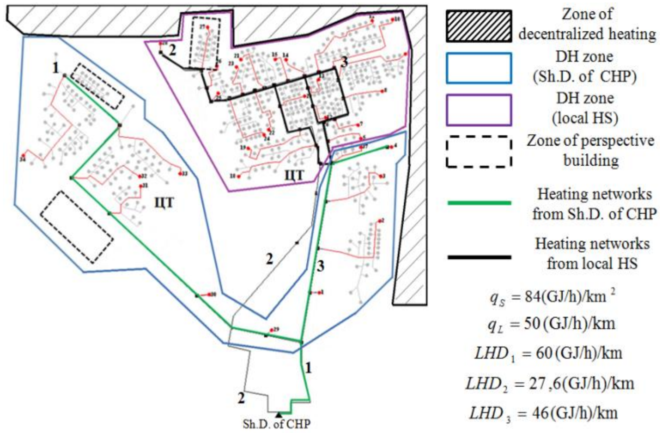

Fig. 1. The heat supply system of Shelekhov city

In areas where the condition of the linear heat density isn't satisfied, we made disaggregation of heat supply system. Calculation of LHD with step-by-step reduction of CHP plant's service zone was made for this purpose. The heat supply of consumers, who are not in the CHP plant's service zone, should be organized by the local source located in the center of heat loads. In figure 1 blue color shows the CHP plant's service zone, heating networks in this zone are marked by green color. Purple color shows the local heat source's service zone (DH system), heating networks in this zone are marked by black color. Redistribution of consumers' loads between sources will allow to cut down specific costs on production and transport of heat energy in system by 10-15%.

Conclusions.

1. Relevance of the solution of territory zoning problem and the problem of determination of optimum scales of DH systems and levels of capacities concentration was shown.
2. The technique of determination of rational scales of heat supply systems was developed. The presented technique and model were approved. Positive results were received.
3. Authors offered dependences for determination of standard values of heat density indicators for carrying out the predesign analysis of heat supply systems.
4. The carried out analysis showed that a heat supply of part of consumers is inefficient if the value of heat density indicators less than standard value. The less are heat density indicators in system, the more are specific costs for production and transport of heat energy.
5. Authors evaluated expected heat loads and carried out optimization of centralization levels of a heat supply for Shelekhov.

Acknowledgment.

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SOLAR THERMAL INTEGRATION INTO A DISTRICT HEATED SMALL HOUSE

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ABSTRACT

According to the EU's objective, all newly constructed buildings should be nearly zero-energy houses since the beginning of 2021. The requirements for zero-energy solutions implicate an on-site renewable energy generation and storage, often including solar. A new model of district heating (DH) substation including solar heating panels and a storage tank was developed using IDA-ICE energy simulation software toolkits. The domestic hot water (DHW) and space heating were heated by solar panels connected to the storage tank and the whole process was simulated throughout the year in Finnish climate. Simulations showed that solar collectors may help to save approximately half of the energy for DHW heating needs whereas the effect on the space heating was marginal. Saving is approximately 200-400 kWh per square meter of the collector area and decreases with increasing of the total collector area. The variation of the storage tank volume does not show to have significant influence on the annual energy gains as long as the required temperatures for DHW are maintained. Solar thermal integration will affect also the return temperature of the primary side which is most visible during the summer time.

INTRODUCTION

A common method for calculation of thermal solar systems for space heating and domestic hot water (DHW) heating is the European standard EN 15316-4-3 [1], normally applied on monthly basis. There are also dedicated calculation tools for more detailed analysis of solar heating components and systems [2]. These methods do not take the properties of district heating system into account. Therefore the building energy simulation software IDA-ICE [3] was used in this study to combine the detailed building simulation model with a detailed district heating substation model, including solar heating.

METHODS

Figure 1 shows one of the two single family houses used in this study in IDA-ICE program, which is used mainly for studying building indoor climate and energy consumption. Table 1 shows the energy use of the two buildings, house 2 having higher energy consumption. The buildings have a water based floor heating system, with maximum supply water temperature of 38 °C.

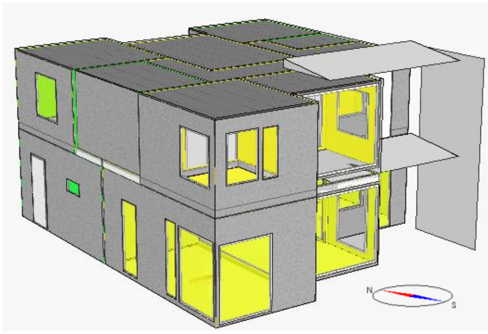

Fig. 1 House 2 in thermal simulation model IDA-ICE.

Table 1. Energy consumption of the two houses in this study.

	House 1	House 2
Space heating, kWh	6 401	17 982
DHW use, litres per day	133	220
DHW heating, kWh	2 820	4 675
DHW circulation, kWh	2 190	2 190
Total heating, kWh	11 410	24 845

Normally in IDA-ICE program the heating water and DHW are heated in a boiler, which ensures fast and robust simulation. Instead of a boiler, a district heating substation model (Figure 2) was constructed utilizing heat exchangers and control components already available in IDA-ICE.

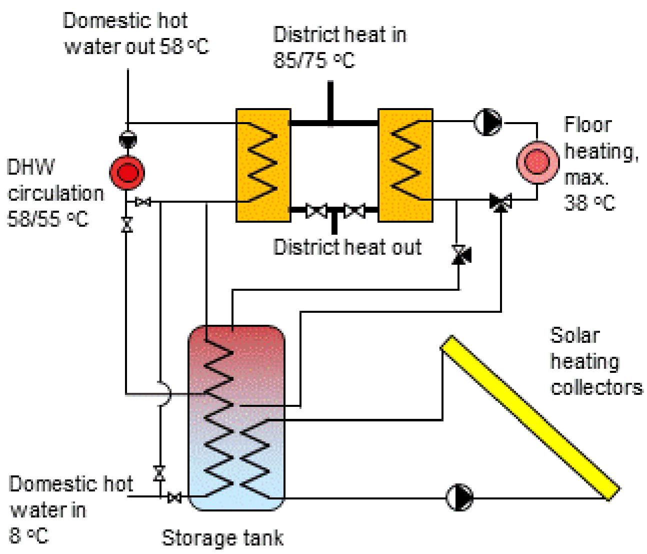

Fig. 2 Solar heating system incorporated into the district heating substation.

A solar collector model and a stratifying water heat storage model were also added, along with necessary control systems. The south facing collector has a tilt of 45° and its efficiency is shown in Figure 3. The water heat storage is 1.6 meters high and is insulated with 50 mm of polyurethane.

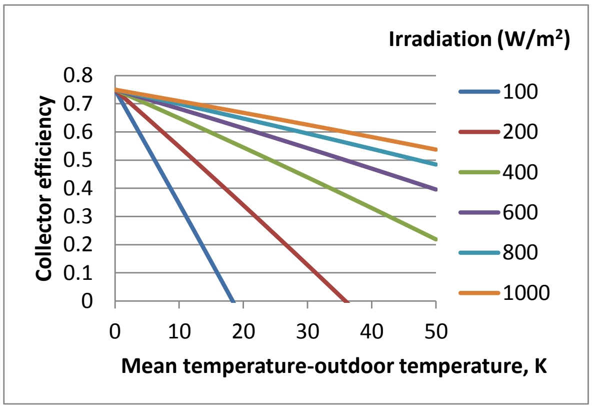

Fig. 3 Efficiency of the solar collector, depending on solar irradiance and collector temperature difference.

Domestic hot water consumption schedule was prepared using a stochastic model which puts more weight on evenings and mornings, as well as on weekends [4]. The weather file is the one represented in the Finnish building code, to be used in southern Finland simulations (Helsinki-Vantaa reference year 2012).

By combining the building and system models it is possible to simulate the performance of the combined solar and district heating system, taking into account the heating load in each room and domestic hot water consumption at each time instant. The variation of district heating water temperature and pressure could be also taken into account, by using data exchange with a DH network model, but this was not realized in present simulations. Instead, the DH water temperature was defined to be 75 °C in summer and 85 °C in winter.

RESULTS

The heating power (Figure 4) is small in both houses from late April to late September. On the other hand the heat supply from the solar collector to the storage tank concentrates to the same period, as shown in Figure 5. This means that solar energy can cover only a small part of the heating energy load of the building. This situation can be slightly improved by increasing the solar collector area and the tank volume, as can be seen in Table 2.

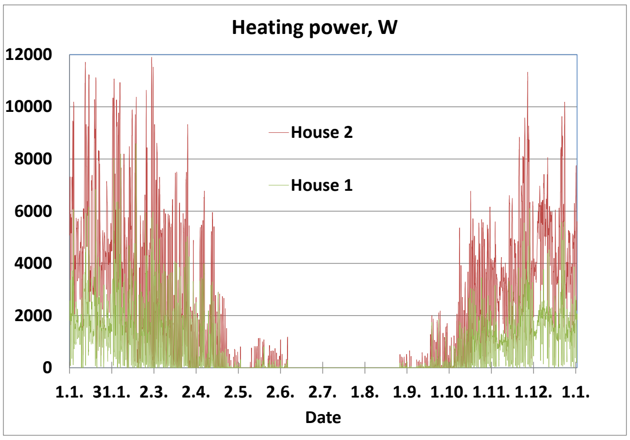

Fig. 4 Heating power of the two houses throughout the year, hourly averages.

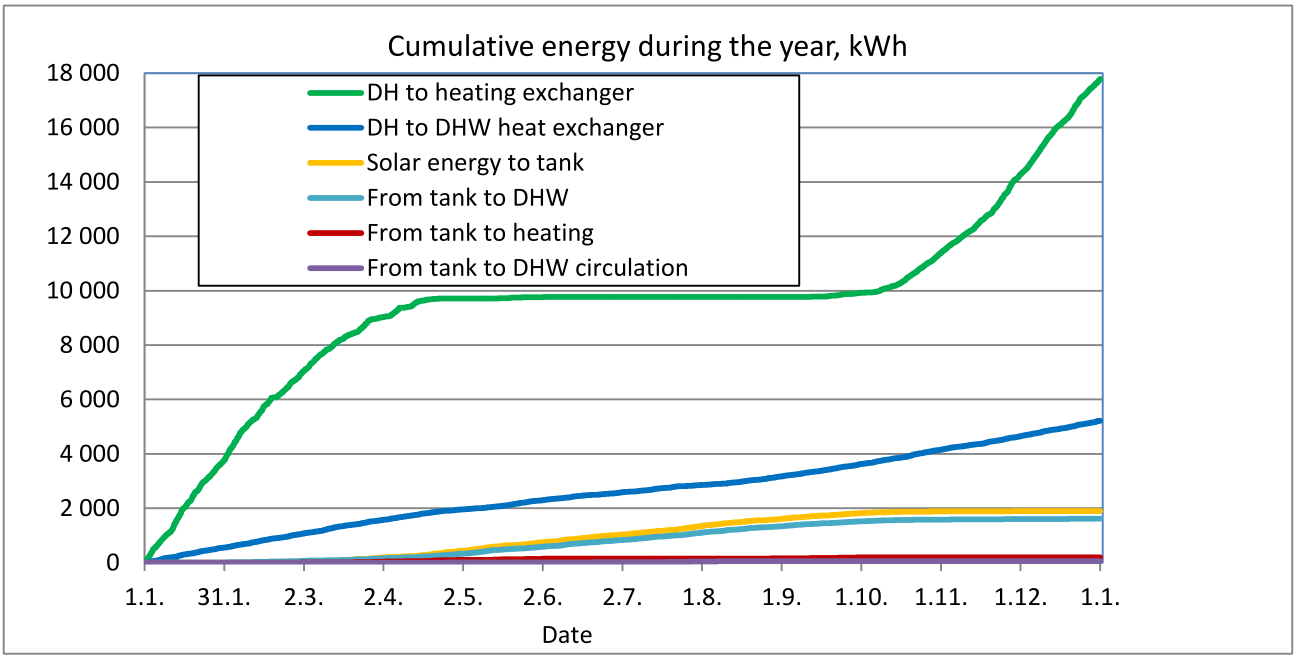

Fig. 5 Cumulative energy intake from solar collectors, solar tank and district heating in house 2. Solar collector area 6 m^2 and solar tank volume 400 litres.

Table 2. Yearly energy intake from solar tank, from district heating and energy savings. Different solar collector and tank sizings in house 2.

Solar collector area	Storage tank volume	From tank to heating	From tank to DHW	From tank to DHW circulation	District heat to DHW heat exchanger	District heat to heating exchanger	District heat saving	Saving per collector area
m^2	litres	kWh	kWh	kWh	kWh	kWh	kWh	kWh/m^2
3	200	68	1166	18	5681	17914	1259	420
6	400	193	1616	58	5220	17790	1843	307
6	800	241	1610	19	5267	17741	1845	307
12	800	389	2010	149	4764	17593	2496	208
12	1200	425	2027	109	4791	17558	2504	209
0	0	-	-	-	6871	17982	-	-

Table 3. Yearly energy intake from solar tank, from district heating and energy savings. Different solar collector and tank sizings in house 1.

Solar collector area	Storage tank volume	From tank to heating	From tank to DHW	From tank to DHW circulation	District heat to DHW heat exchanger	District heat to heating exchanger	District heat saving	Saving per collector area
m^2	litres	kWh	kWh	kWh	kWh	kWh	kWh	kWh/m^2
3	200	42	999	67	3988	6335	1090	363
4	300	64	1143	108	3838	6294	1281	320
6	400	138	1319	161	3608	6241	1564	261
6	800	80	1326	188	3662	6213	1537	256
12	800	304	1550	280	3240	6121	2051	171
-	-				5011	6401		

Increase of the tank volume does not however bring additional district heat savings because the solar heat supply for DHW decreases at the same time. Savings per collector area decreases along with installed collector area, ranging from 170 to 420 kWh per square meter, when the results for the less energy consuming house 1 (Table 3) are also taken into account.

Figure 6 shows the solar collector heating power and Figure 7 shows the temperatures in the storage tank in a week in June. Tank temperatures rise during the first days but decrease during the last two days because of less sunshine. On three days the tank temperature exceeds 58 °C, i.e. is high enough to heat the DHW circulation as well as the consumed hot water up to 58 °C. This situation is quite rare and therefore the energy gain from the tank to DHW circulation is quite low, see Tables 2 and 3.

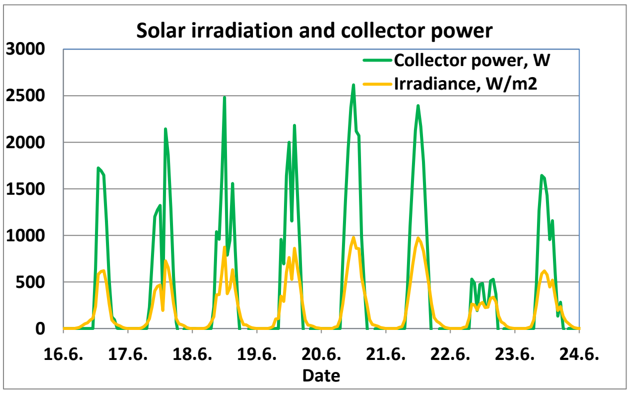

Fig. 6 Solar radiation and solar collector power during a summer week. House 2, solar collector area 6 m^2 and solar tank volume 400 litres.

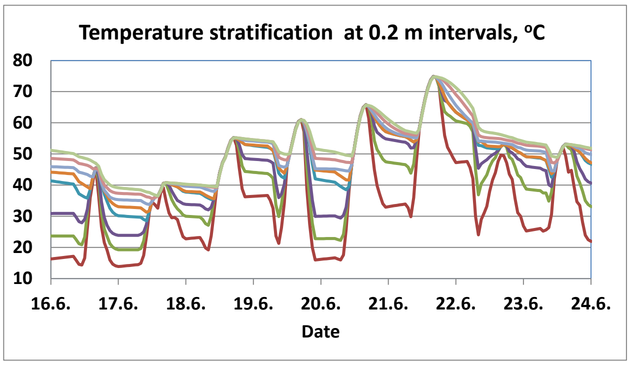

Fig. 7 Temperatures in the storage tank at 0.2 m intervals in summer week, temperature increases from bottom to top. House 2, solar collector area 6 m^2 and solar tank volume 400 litres.

DHW heating up from 8 °C is a very favourable task for the solar system due to the low temperature level. Most of the solar energy is used for this purpose. The energy saving due to solar system is approx. 55% of consumed DHW heating need when a 6 m^2 collector is used in house 1 and a 12 m^2 collector is used in house 1. Economically it may be appropriate to exclude the space heating and DHW circulation heating altogether from the solar system.

Integration of solar heat into district heating has also an impact on district heating return temperatures, from April to September (Figure 8). In summer the return temperature is approx. 3 degrees higher in a combined solar and district heat system.

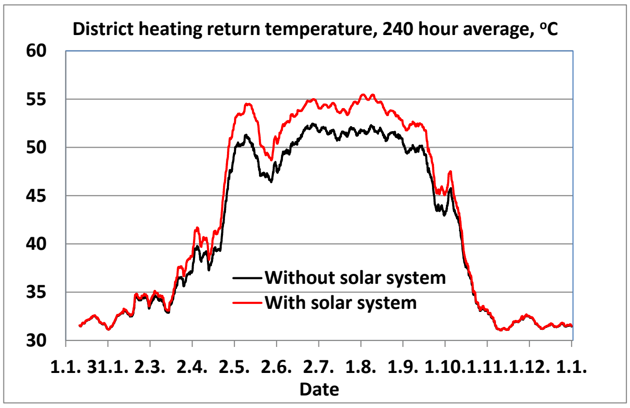

Fig. 8 District heating primary side return temperature with and without solar system, 240 hour sliding average. House 2, solar collector area 6 m^2 and solar tank volume 400 litres.

CONCLUSIONS

A new model of district heating substation including solar heating panels and a storage tank was developed using IDA-ICE energy simulation software toolkits. Simulations showed that solar collectors may help to save approximately half of the energy for DHW heating needs in Finnish climate, whereas the impact on the space heating energy was marginal. Solar thermal integration with district heating will affect also the return temperature of the primary side which is most visible during the summer time.

ACKNOWLEDGEMENT

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SEASONAL DEPENDENT ASSESSMENT OF ENERGY CONSERVATION WITHIN DISTRICT HEATING AREAS

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Abstract

When housing companies plan for energy conserving renovations, costs and amount of saved energy are usually estimated with yearly mean values. Yet the fuel mix varies widely depending on heat demand of district heating system, often with higher cost and CO_2 emission rates during winter than summer.

Instead of comparing different energy conserving measures' potentials with yearly mean values, it would be beneficial to examine them in a higher resolution, e.g. on daily or monthly basis, to identify real effectiveness of different measures in reducing CO_2-emissions and primary energy consumption.

In this study, three energy conserving measures are put into a building simulation model to obtain results of hourly energy consumption reduction, which is then fitted into a district heating optimization model to analyze the impact on district heating system.

This study also discuss the correlation between energy cost for the customer and different measures' environmental impact under new circumstances: seasonal energy price models of district heating, a price model which introduce price fluctuation throughout a year. This new factor provides a more comprehensive incitement to the property owners to encourage them to make environmental friendly decisions when planning for energy conserving renovations.

1. Introduction

In 2011, the energy consumption in the residential and service sector was accounted for 38% of Sweden's total final energy use, 90% of which was used in residential buildings and non-residential premises [1]. In order to achieve the EU 2020 targets, efforts from both energy companies' and energy consumers' side are required, and it will be much more economical and efficient if these efforts could amplify each other's efficacy. Thus thorough researches should be carried out before these efforts taking place.

After been put into use for about 50 years, many buildings built during the ambitious Million Homes Programme (*Miljonprogrammet* in Swedish, 1960~1975) are due for major renovations. Considering these buildings have high specific energy consumption, the demand for energy conserving measures would remain on a relatively high level in the near future.

We focus on three energy conserving measures and aim to analyze not only saved energy, but also the quality of saved energy, as well as the environmental impact of this saved energy. These energy conserving measures were selected by assumption of different profiles of outcomes and to represent relevant and typical measures taken by housing companies.

Selected energy conserving measures are put into a building simulation model to obtain results of hourly energy consumption reduction. Then energy consumption reduction is fitted into an optimization model of district heating system to analyze the impact on the system. Furthermore, environmental evaluations are carried out and energy cost calculations on these measures to show how energy companies could use their price models to favor environmental friendly energy conserving measures.

Impact from heat demand reduction on the district heating marginal production have been studied before [2–4]. What this study adds is modelling of a low CO_2-emitting district heating system with a relatively high share of cogenerated electricity and how the price model can reflect the environmental impact of different energy conserving measures.

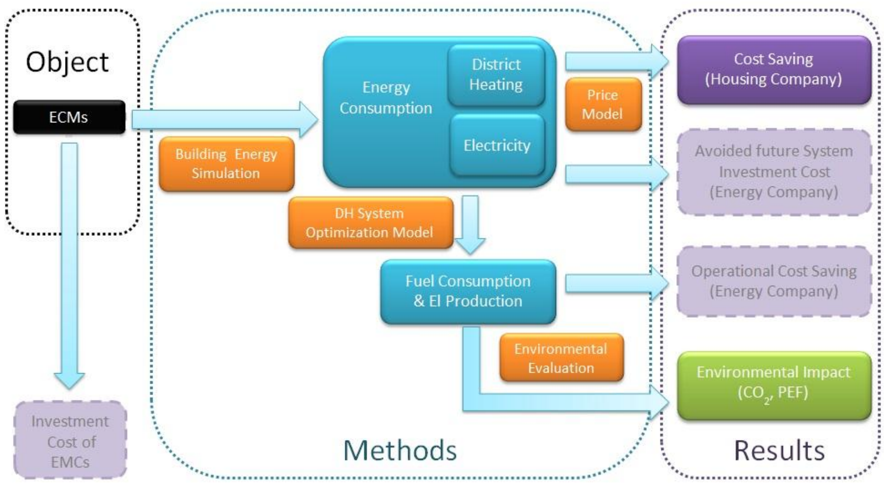


Fig. 1. Workflow framework

2. Methods

2.1. District heating optimization model

The optimization model was based on the work of Magnus Åberg [5], who generously shared his Matlab based model. Instead of the linear programming approach used by Åberg, we used the Matlab constrained nonlinear multivariable optimization function: *fmincon*.

$$y = \sum_{i}^{n} \left(x_i \times Cost_i + x_i \times alfa(\alpha_i, x_i, ub_i) \times (Cost_i - Income_i) \right) \quad (1)$$

$y = total\ cost\ of\ delevired\ heat\ [SEK]$

$x_i = delivered\ heat\ for\ unit\ i\ [MWh]$

$Cost_i = operational\ cost\ of\ unit\ i\ [SEK/MWh]$

$alfa(\alpha_i, x_i\ \&\ ub_i) = actual\ \alpha\ value\ of\ unit\ i\ as\ a\ fuction\ of\ \alpha_i, x_i\ \&\ ub_i$

$\alpha_i = nominal\ \alpha\ value, electricity\ to\ heat\ output\ ratio$

$ub_i = upper\ bound\ (capacity)\ of\ unit\ i\ [MW]$

$Income_i = income\ from\ selling\ electricity\ and\ electricity\ certificates\ [SEK/MWh]$

The objective function to minimize total cost is described in (1) and was passed as a function to *fmincon*, linear constrains in (2) were passed as matrices and vectors and constrains in (3) were passed as functions.

$$\sum_{i}^{n} x_i = HD, \qquad \boldsymbol{x} \in [\boldsymbol{0}, \boldsymbol{ub}] \quad (2)$$

$$\frac{x_2}{x_1} \leq \frac{ub_2}{ub_1}, \qquad \frac{x_3}{x_1} \leq alfa(\alpha_1, x_1 - x_3, ub_1) \quad (3)$$

$HD = Heat\ demand\ [MWh]$

$\boldsymbol{ub} = vector\ of\ upper\ bounds\ (capacities)\ [MW]$

Bypassing of the turbine was modelled in the same way as the CHP-plant except with an α-value of -1, which simulate that for every unit of produced extra heat there will be one unit less of electricity production.

Real heat demand and electricity price of year 2012 were used. Electricity certificates were valued to 200 SEK/MWh throughout the year. The optimization was done with daily average values, 365 separate optimizations. The heat storage tank was not modelled; the use of daily averages values is anticipated to compensate for that, as the main purpose of heat storage tank is to level diurnal variations in heat demand. Table 1 shows numeric values used and the components the model consists of.

Table 1. Components of the Eskilstuna district heating system optimization model

Description	Capacity heat [MW]	α-value	Operational cost [SEK/MWh]
Biomass CHP[1]	72	0.53	245
CHP FGC[2]	24	0	0
Bypass turbine[3]	38	-1	245
Biomass HO[4]	70	0	236
Bio-oil HO[5]	20	0	693
Fossil-oil HO[5]	Infinite	0	946

[1] a biomass combined heat and power (CHP) plant serving as base load. [2] flue gas condensing (FGC) at the CHP-plant, can be bypassed. [3] The CHP-plants turbine can be bypassed. [4] a heat only fluidized bed boiler, FGC is embedded into the capacity. [5] heat only boilers.

2.2. Building energy simulation

The software IDA ICE was used for building energy simulations. The building model was based on existing buildings in Lagersberg, Eskilstuna, which has been recently renovated with a goal of halving total energy consumption. These two buildings are 4 floors high, totally 6890 m^2, light concrete buildings, connected to the same district heating substation, typical of the earlier Million Homes Programme era.

2.3. Heat demand

The real produced heat in district heating system (including heat storage tank) for year 2012 was used as baseline for total heat demand. Energy conserving measures were simulated with historical weather data of 2012 as well. The heat demand after energy conserving measures was then simply calculated by subtracting contributions of energy conserving measures from the baseline hour-by-hour. In order to make it easier to compare the measures, we assumed same energy conserving measures to be applied on multiple buildings so that saved energy (heat & electricity) were scaled to 1 % of the district heating system's total heat demand.

2.4. Environmental evaluation

CO_2-emissions for electricity were accounted for by assuming future marginal electricity produced by natural gas combine cycle power plants, with a CO_2-emission factor of 400 g/kWh [6]. The Nordic electricity market average CO_2-emissions factor of 100 g/kWh were used when making average (in contrast to marginal) assessment on the district heating system.

Table 2. Used CO_2-emissions factors [6,7]

Fuel	Biomass	Bio-oil	Oil	Electricity
CO_2 [kg/MWh]	16	9	300	400

2.5. Energy conservation measures

Additional insulation (AI) was simulated as 5 cm additional insulation on external walls, lowering the total UA-value from 6.44 to 5.21 kW/K.

Domestic hot water (DHW) was simulated with a diurnal variation but with no variation over the year. Reduced domestic hot water was simulated by lowering the total hot water consumption by 20 %.

Exhaust air heat pump (EAHP) was modelled as taking 1/3 of the total exhaust air, simulating that one of the three existing air handling unit is located near the shared substation for the real buildings (a typical situation for these kinds of buildings). The simulated exhaust air heat pump lowers temperature of exhaust air to a minimum of 3 °C, serves both on domestic hot water and space heating and was modelled connected in a three-way arrangement where the heat pump serves in the middle load and district heating works as preheating and top-up heating source. This is an expensive way of connecting exhaust air heat pump yet gives good performance condition without affecting return temperature in district heating system. The yearly average COP of the modelled heat pump is 3.1.

2.6. Price models

District heating:

The simulated buildings are located in Eskilstuna, thereby price model of district heating from the local energy company (Eskilstuna Energy & Environment) were used in this study.

The price model (PM) is described in eq. (4 and consists of three parts: fixed fee, peak power fee and energy fee.

$$\mathrm{PM} = F(P) + Cp(P) \times P + Ep \times E \qquad (4)$$

$\mathrm{PM} = Yearly\ cost\ for\ district\ heating$

$F(P) = fixed\ fee, according\ to\ P\ [SEK/year]$

$P = peak\ power, calculated\ as\ mean\ power\ for\ the\ 3\ days\ with\ highest\ consumption\ [kW]$

$Cp(P) = Peak\ power\ price\ [SEK/kW]$

$Ep = Energy\ price\ [SEK/kWh]$

$E = Energy\ consumption\ [kWh]$

The energy price in PM is constant through the whole year, which is not consistent with the fuel mix fluctuation. Therefore we introduced seasonal energy price and created a mild mutation (PM') of the ordinary price model (PM).

$$\mathrm{PM}' = F(P) + Cp(P) \times P + \sum_{j=1}^{12} Cj \times Ej \qquad (5)$$

$Cj = energy\ price\ in\ a\ particular\ month [SEK/kWh]$

$Ej = monthly\ energy\ consumption\ [kWh]$

Seasonal energy price was modelled in three levels: winter (Dec, Jan, and Feb) price: 0.57 SEK/kWh, spring/autumn (Mar, Apr, Oct, and Nov) price: 0.27 SEK/kWh and summer (Maj, Jun, Jul, Aug, and Sep) price: 0.13 SEK/kWh. Setting of different price levels were based on the principal that total yearly district heating cost of baseline case under the mutation model PM' should be the same with total district heating cost under original model PM.

Electricity:

For electricity, we used an average energy price at 0.85 SEK/kWh (excluding VAT).

3. Results

The simulation result of the optimization model was consistent with real production of 2012 in Eskilstuna district heating system except that the share of fossil fuels were somewhat lower and electricity production was a bit higher in the simulation model. This is most likely because the model doesn't take downtime (about 2 % for the CHP-plant) into account and using daily average values doesn't catch all peak heat demand situations.

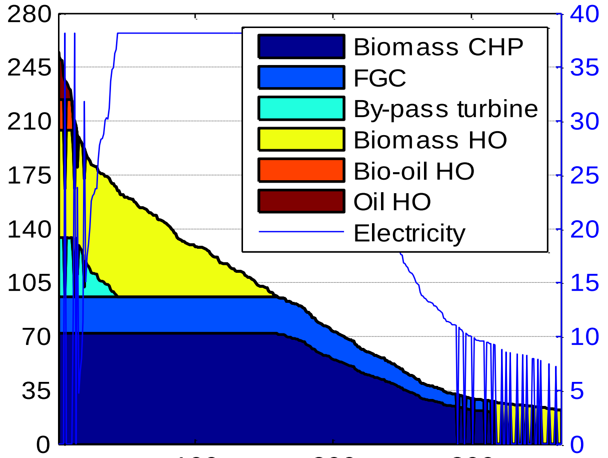


Fig. 2. Duration diagram of modelled district heating system of Eskilstuna. Left y-axis shows mean heat production [MW/day], right y-axis shows the mean cogenerated electricity [MW/day].

As can be seen in Fig. 3. Monthly saved energy for three studied energy conserving measures is scaled so that the energy saved per year matches 1% of the total district heat production., additional insulation (AI) saved much more energy during winter season than other energy conserving measures, while domestic hot water (DHW) and exhaust air heat pump (EAHP) had quite comparable impact on heat demand.

Exhaust air heat pump (EAHP) had a tendency to save more energy during the warmer season. Because of more energy (warmer and more humid indoor air) in the exhaust air leading to higher evaporation temperature, at the same time, condensing temperature was lower as the supply temperature of space heating was modelled to be lower than for domestic hot water. For July, saved energy dropped again as there was no need for space heating leading to higher condensing temperatures, hence worse performance by the heat pump.

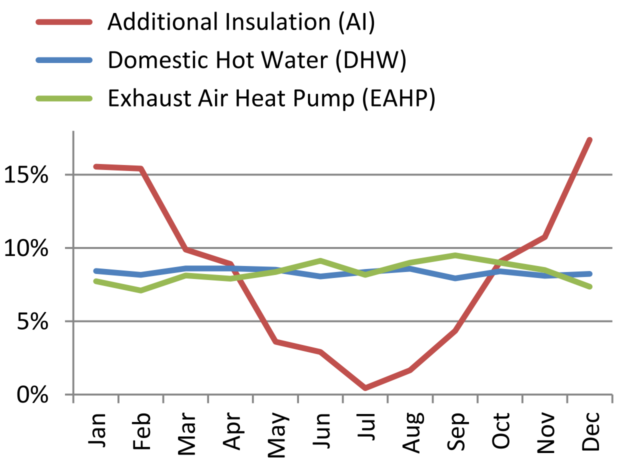


Fig. 3. Monthly saved energy for three studied energy conserving measures is scaled so that the energy saved per year matches 1% of the total district heat production.

Additional insulation (AI) resulted in more cogenerated electricity which is due to decreased bypassing of turbine (see Fig. 3. Monthly saved energy for three studied energy conserving measures is scaled so that the energy saved per year matches 1% of the total district heat production.).

For all three energy conserving measures, most of the saved energy were produced in the biomass boiler (Bio HO in Fig.4). Heat produced in the oil boilers decreases significantly in relative terms, between 3 to 11 %, to be compared with the 1 % for the total saved energy.

The impact on district heating system from exhaust air heat pump (EAHP) was larger as the scaling was done so that the total saved energy (both electricity and heat) was the same for all three measures. Which leads to decreased total heat production by an extra 47 % compared to the other two measures.

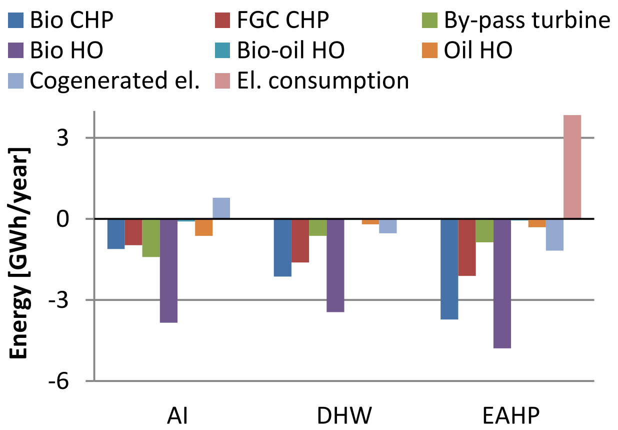
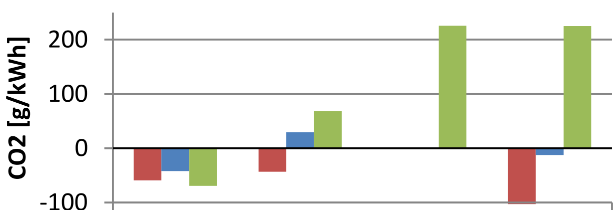


Fig. 4. The impact of three energy conserving measures under constrain of modelled district heating system.

Additional insulation (AI) gave a significant decrease in CO_2-emissions because of its favorable impact on the operation of the district heating system. The domestic hot water (DHW) showed a decrease in CO_2-emessions even though the cogeneration of electricity also decreased. Meanwhile exhaust air heat pump (EAHP) increased CO_2-emissions, mainly due to higher electricity consumption, but also because of its less favorable impact on the operation of the district heating system.

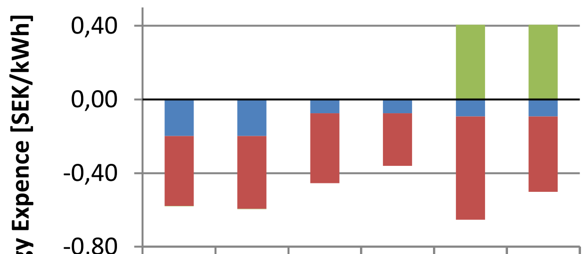


	Fuels	Displaced el.	Consumed el.	Sum
AI	-59	-43	-1	-103
DHW	-42	29	0	-13
EAHP	-69	69	226	225

Fig. 5. Impact on CO_2-emissions from studied energy conserving measures. Emissions caused by energy conserving measures divided by saved energy (heat & electricity). Operational electricity included in “Fuels”.

For average district heating production (in contrast of the marginal approach used in this study) the consumed fuels released 28 g CO_2/kWh while the displaced electricity decreased the CO_2-emissions by about the same amount, 28/kWh, leaving the total CO_2-emissions release on about 0 g of CO_2 per kWh delivered district heating. Note that the operational & displaced electricity were donated with an emission factor of 100 g CO_2/kWh instead of the 400 used for the marginal production approach.

Total specific energy cost reduction with additional insulation (AI) was the highest, reaching 0.60 SEK/kWh, one third of which was reduced on district heating peak power fee (DH PP in Fig. 6); domestic hot water (DHW) reduced energy cost by 0.45~0.36 SEK/kWh, saving almost same amount on district heating energy fee as additional insulation (AI) calculated under PM, while reducing far less on district heating peak power (DH PP) fee; the exhaust air heat pump (EAHP) reduced largest amount of district heating energy fee yet increased electricity cost leaving total energy cost reduction on the lowest level. Note that costs are given in SEK per kWh saved energy (electricity & district heating) at the building level.



	AI		DHW		EAHP	
	PM	PM'	PM	PM'	PM	PM'
Sum	-0,58	-0,60	-0,45	-0,36	-0,25	-0,10
Electricity	0,00	0,00	0,00	0,00	0,41	0,41
DH Energy	-0,38	-0,40	-0,38	-0,29	-0,56	-0,41
DH PP	-0,20	-0,20	-0,07	-0,07	-0,09	-0,09

Fig. 6. Specific energy cost reduction, grouped by components of price models. Cost calculated without VAT, per unit saved energy.

4. Discussion

The result of the environmental assessment is very much affected by how the electricity is assessed. Table 3 shows how the assessment would look like using other commonly used emission factors for electricity. Additional insulation still is the most favorable energy conserving measures even if assuming very low CO_2-emission factor on electricity.

Table 3. CO_2-emissons factors for total saved energy at the building level.

El.	930	400	100	10
AI	-180	-103	-60	-47
DHW	4	-13	-22	-25
EAHP	579	225	24	-36

Emission factors for displaced/consumed electricity (El.), from left to right in the first row: coal condensing, natural gas combine cycle, Nordic mix and Swedish mix. [g CO_2/kWh].

Both price model PM and PM' give highest benefit to additional insulation (AI) with highest CO_2-emssion reduction and lowest reward to exhaust air heat pump (EAHP) which also leads to higher CO_2-emission rate (see Fig. 7). Compared to PM, PM' gives a wider gap on cost reduction between different measures, which could send a stronger signal to property owners when making decisions on energy conserving renovations.

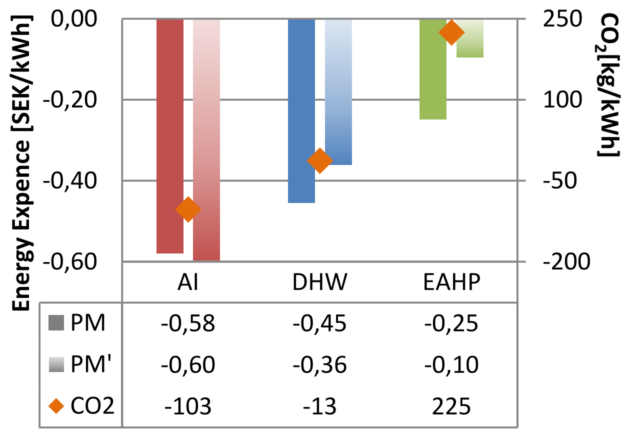


Fig. 7. Correlation energy cost reduction and CO_2-emission reduction.

In this study the measured heat demand of 2012 is used as a baseline. It would be preferable if the heat demand was to be artificially made so that it would present a more typical year from a meteorological point of view, the energy conserving measures could also be simulated with weather profile of a typical year, which would give more representative results. This kind of tool could be used for district heating companies to make prognosis of future heat demand and the characteristics of heat demand.

Simulations were made with real weather data of 2012 for Eskilstuna, which gives 9 % higher energy consumption and 4 % higher effect cost compared to simulation with typical meteorological year (IWEC2 weather file for Västerås).

5. Conclusions

When CO_2-emissions were assessed with an average production approach the result implies no CO_2-emission reductions. While when the marginal production approach were used the result shows that there are energy conserving measures that do decrease CO_2-emissions. Even the exhaust air heat pump solutions wouldn't lead to more CO_2-emission release if only looking on the effect on the district heating system (disregarding the higher electricity consumption level caused by the heat pump).

The presented results are true for the modelled district heating system (Eskilstuna district heating system of 2012). There will most likely be a new biomass CHP-plant in Eskilstuna by 2018, and then these results are not valid anymore. But within this framework a similar analysis on future district heating system or any other existing network could be made.

Both price models give rightful incitement towards energy conserving measures according to their CO_2-emission reduction levels, while the seasonal energy price could send a stronger signal to stake owners.

Acknowledgement

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NETWORK SIMULATION OF LOW HEAT DEMAND RESIDENTIAL AREA

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ABSTRACT

Energy consumption and heat demand in district heating systems will decrease in the future as low energy houses become more common and energy efficiency measures are implemented. The solutions for district heating to meet the challenges due to this trend are being studied.

Simulation of three variations of a residential area with realistic load profiles for both heating and domestic hot water consumption was carried out. A low connection rate system and a low supply temperature variant were compared to a traditional design. Dedicated models were used in both building and network simulation.

Results showed relative heat losses of 19.1 % for the low connection rate case. Low supply temperature variant resulted in 10 % lower heat losses than the reference case having relative heat losses of 10.6 %.

All studied cases required a by-pass arrangement to maintain adequate temperature level for domestic hot water service outside heating season. This resulted in increased heat losses and in peaks in pressure drop.

As in the future the operational environment is becoming more challenging for district heating, a need for comprehensive planning of whole systems taking into account all production, distribution and consumers will be more important than ever.

INTRODUCTION

Much of the district heating related research effort in recent years has focused on integration of renewable energy sources into the systems, options for distributed generation and on the effects of increasing energy efficiency in buildings. In countries with long tradition and high market share in district heating such as Finland, Sweden and Denmark, special attention has been paid on low heat density systems. [1], [2]

All the listed developments above have an influence on the distribution network and as the life time of a pipe line is counted in decades, understanding both the direct effects and long term consequences of these developments from the distribution system point of view is important in order to preserve the efficiency of district heating systems.

In this paper, a detailed analysis of a low heat demand residential area connected to district heating was carried out with focus being on the distribution network. The main points of interest were on

1) observing operation of the system based on temperatures and pressures within the network
2) evaluating the efficiency of the distribution system, mainly focusing on heat losses
3) analysing the effects of lower connection rate on overall efficiency and reliability

The objective for the paper is to deepen the understanding of interactions between decreasing demand, network design and operation.

METHODS

The main method used in the study was simulation by a district heating network model, developed by VTT. The model runs in Matlab environment and is a typical node-and-branch type of network model with dynamic temperature simulation. [3]

Simulation period of one year was used in order to provide results for a full operational cycle of a district heating system. Time step for both input and output time series was 6 minutes.

The area of interest was the Hyvinkää house fair neighbourhood in Finland, a residential area with 40 consumers in total, and the local district heating system. A total of three case studies were carried out with different connection rates, supply temperatures – defined separately for heating season and for the rest of the year, and consumer composition. These assumptions have been compiled into Table 1 below.

Table 1. Assumption for cases studied.

	Case A	**Case B**	**Case C**
Connection rate	47 %	100 %	100 %
Supply temperature	85/75 °C	85/75 °C	60/60 °C
Consumers	16 detached, 3 row houses	32 detached, 8 row houses	32 detached, 8 row houses

Two different network structures corresponding to systems of different connection rates are illustrated in Fig. 1 below. Entry point into the area is on the left top corner of the network. Thicker dots represent consumers. Dimensions of pipes in the area are based on existing design except for Case C where the increased flow due to lower temperature level made it necessary to use larger connection pipes. The distribution pipe sizes are, however, identical.

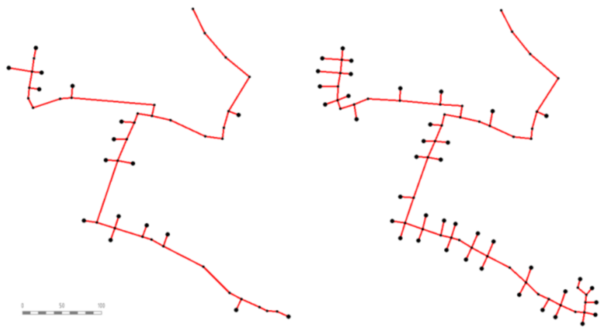

Fig. 1. The two network structures studied, Case A (left) and Cases B and C (right).

All studied cases have a by-pass arrangement at the last consumers of the two branches, letting supply water past the substation, creating extra flow and maintaining the temperature level for domestic hot water during periods of minimal consumption. This is often necessary in areas of low heat demand. [4]

The consumers were modelled as heat exchangers with conductance (W/K), secondary side temperatures and demand given as input explicitly. The inaccuracy of this approach was considered to be a minor issue as the feed temperature variations were relatively small. The entry point into the area, i.e. the producer node, was modelled only by defining the supply temperature.

All consumers were equipped with a floor heating with design temperatures of 35/20 °C. Domestic hot water design temperatures were 58/10 °C. In low temperature variant (Case C), temperatures were 3 °C lower.

To provide realistic load profiles both heating and domestic hot water usage, additional two models were utilised; IDA ICE, versatile building simulation model [5] and Apros, an advanced modelling platform [6].

The first was used in calculating the demand and secondary side temperatures for heating based on weather data, building structure and materials used.

The Apros modelling platform was used to model the random nature of domestic hot water consumption for each consumer, based on the assumed number of inhabitants per dwelling and hourly time series of consumption probability for weekdays, Fridays, Saturdays and Sundays. The curves used for probability of consumption are illustrated in Fig. 2.

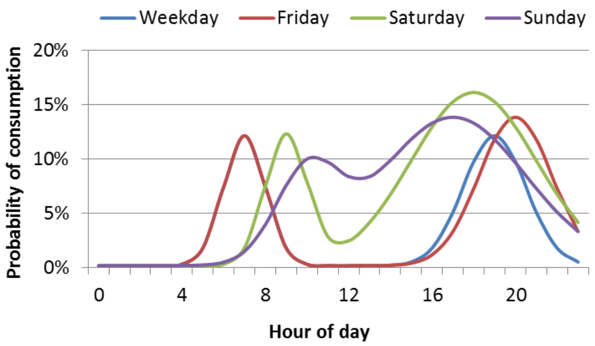

Fig. 2. Probability of consumption for different weekdays.

A sample of the time series generated by the model is presented in Fig. 3 below, illustrating the domestic hot water load for the whole area for a period of one week. The base load consists of consumption due to the domestic hot water circulation pipe within the dwelling, defined as a 250 W constant load.

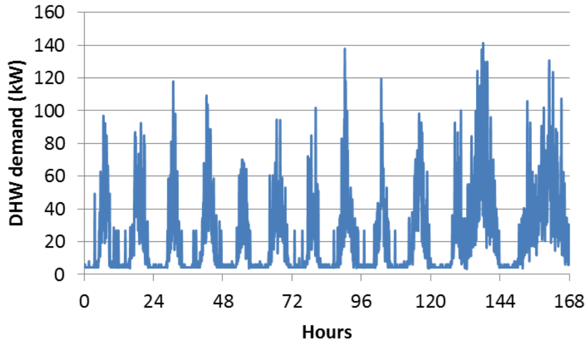

Fig. 3. Domestic hot water load for a period of one week.

RESULTS

Simulation results presented include the heat demand time series and monthly consumption, relative heat losses, return temperatures from the area, temperature variations in the network outside heating season, pressure drop and pumping power consumption. Comparisons between different simulation cases (A, B and C) are made when reasonable.

Heat demand time series for cases B and C is presented in Fig. 4. The comparison between 6 minute values and 6 hour averages is used to illustrate the variations in demand during a day. Heat demand for case A is practically identical in shape, but with peak demand of 320 kW.

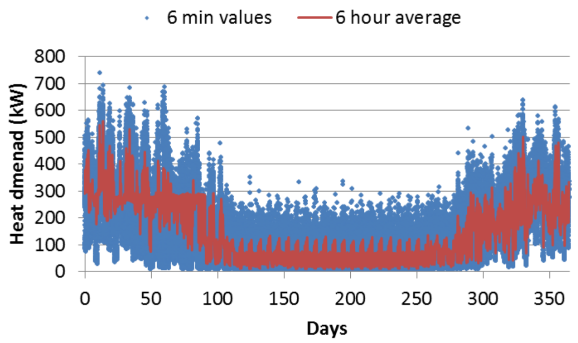

Fig. 4. Heat demand time series with 6 minute time step and 6 hour averages for Cases B and C.

In Fig. 5 the monthly consumptions for the two connection rates 47 % (Case A) and 100 % (Cases B and C) are presented. Share of domestic hot water consumption of the total consumption was 38 % for all cases. In terms of energy, this translates to 16 MWh per month for the lower connection rate and 39 MWh per month for 100 % connection rate cases.

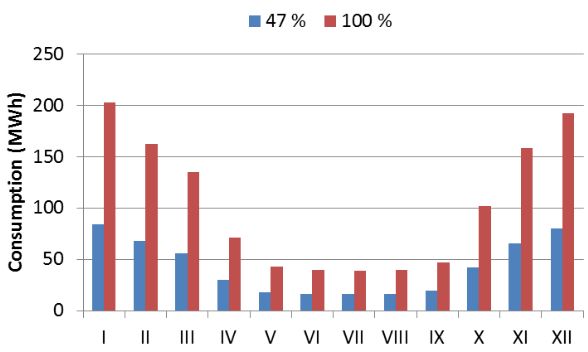

Fig. 5. Monthly consumptions for two connection rates.

Relative heat losses for each month are presented in Fig. 6 for all studied cases. As yearly values, the losses were 121 MWh (19.1 %), 146 MWh (10.6 %) and 132 MWh (9.7 %) for cases A, B and C, respectively.

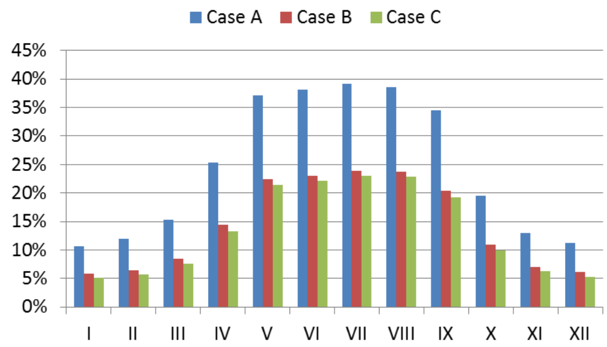

Fig. 6. Monthly relative heat losses for studied cases.

Supply side temperatures especially outside the heating season are an interesting result for a low heat demand system. These feed temperatures are presented in Fig. 7 below for different points in the network for a sample period of 48 hours. Feed temperature at the entry point of the area was 75 °C.

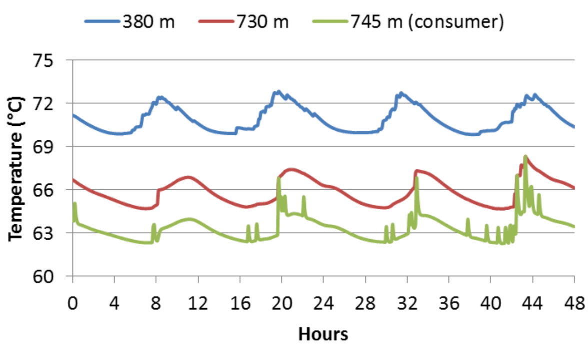

Fig. 7. Feed temperature at different points within the network outside the heating season.

An average temperature for the selected nodes in the network was calculated using the simulation results on feed temperature during the summer time. The results were combined with the distance of the nodes from the entry point into the area. The outcome is presented in Fig. 8.

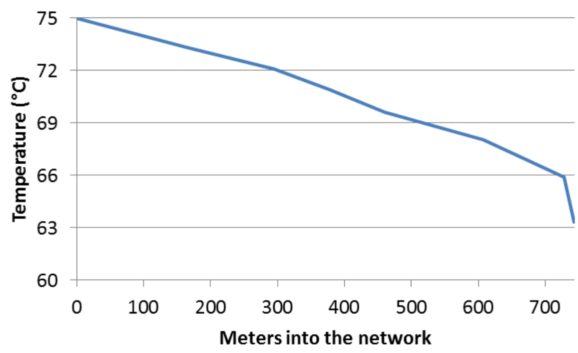

Fig. 8. Average feed temperature profile on a single branch (see Fig. 1) of the network.

Return temperature from the area for different cases as 6 hour averages are presented below in Fig. 9.

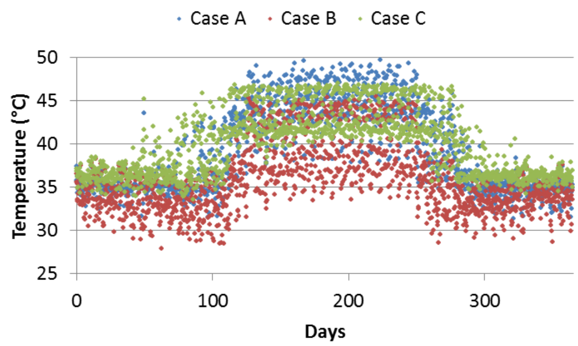

Fig. 9. Return temperatures for studied cases.

Pressure drop in the network depends on the flow rate, i.e. demand and supply temperature level. On normal operation, pressure drop is around 1-2 bar with occasional peaks rising up to 4 bar or even around 8 bar for a few hours in a year. Minimum pressure difference is 0.6 bar and was defined within the network model. The pressure drop time series for Cases B and C are presented in Fig. 10.

In all cases, pumping power consumption is negligible compared to heat losses being 5 MWh for Case A, 11 MWh and 25 MWh for Cases B and C.

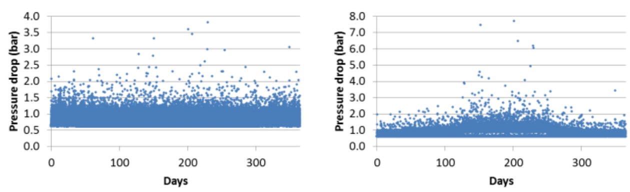

Fig. 10. Pressure drop time series for Cases B and C.

DISCUSSION

Heat demand time series represent a typical load curve for a residential area. The reasonably high share of domestic hot water (38 %) results in higher fluctuation in demand than in older residential areas. An average consumption per dwelling, including domestic hot water, was around 15 MWh for a detached house. This is in line with current building regulations.

Relative heat losses, the most important indicator on the efficiency of a district heating system, clearly show the effect of a lower connection rate. The low temperature variant experiences a modest 10 % cut in heat losses which is a bit misleading result as the temperature level (85/75 °C) is already lower than normal in Finnish systems (110/80 °C). When district heating is already facing tough competition in the heating market by e.g. heat pumps, long term investment in low heat demand district heating systems does not seem reasonable.

Temperature fluctuations and difficulties in maintaining the temperature level outside heating season is common as expected for a low heat demand area. The temperature drop in the network is significant but recovers quickly when nearing the point of consumption in both distance and time. Furthermore, it was noted that the drop is the sharpest in the connection pipe. When calculating the temperature drop per meter, distribution network got values between 0.01-0.02 °C/m and connection pipes around 0.22 °C/m. Attention should be paid in dimensioning the connection pipes, an accumulator and a small diameter pipe with steady flow could be a viable option.

Return temperatures are all in the same region, but differences do exist, especially during the summer time as can be seen in Fig. 9. In general all cases are reasonably close to each other during the heating season with Case B having the lowest values and during summer time, Case A, i.e. low connection rate, having the highest return temperature. For Case C, there is visibly less variation in temperature throughout the year.

Pressure drop and pumping power consumption are less significant in evaluation of the efficiency of the system. The most interesting observation is the steadiness of the pressure drop throughout the year with Case C, the low temperature variant. This is due to the increased flow resulting in lower drop in temperature. The reason for the higher peaks in flow and pressure drop in Cases A and B during summer time is related to the same issue, although it is also partly a result of a modelling decision of not limiting the flow past a consumer substation. If temperature difference between the incoming flow on the primary side and the set point for the outgoing flow on the secondary side is small, flow is increased significantly.

CONCLUSIONS

Simulation of a low heat demand area with three separate cases with alternative connection rates and temperature levels was carried out.

Results indicated a strong correlation between connection rate, i.e. heat demand density, and efficiency in terms of relative heat losses. Low connection rate of 47 % resulted in 19.1 % yearly relative heat losses while 100 % connection rate produced 10.6 % and 9.7 % losses for normal and low feed temperature level cases, respectively.

Temperature variation and drop especially outside heating season was observed as a peculiarity for a low heat demand district heating system. By-pass arrangements were used to alleviate this problem at the cost of increased heat losses, but connection pipes still experienced significant temperature drop.

Low temperature variation resulted in lower heat losses, but higher consumption of energy in pumping. While still insignificant, more than double consumption for pumping than in normal temperature design is worth mentioning. Appropriate design for heat exchangers can help mitigating this effect to an extent.

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PRIMARY ENERGY REDUCTION IN BUILDINGS - CASE STUDY ON A RESIDENTIAL BUILDING IN FALUN, SWEDEN

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ABSTRACT

Since a large share of the total European primary energy is consumed in the building sector, buildings have to become more energy efficient in order to reach the goals of the European energy efficiency directive. In Sweden, focus has been on lowering final energy consumption, not primary energy consumption. A relevant question today is whether a general understanding of the primary energy concept is needed to encourage selection of better energy efficiency measures from an environmental perspective. There are however uncertainties of how to calculate primary energy consumption since different primary energy factors (PEF) are used by different actors, especially for district heating (DH) and electricity (EL.).

In this study total primary energy consumption was calculated for a residential building before and after several renovation measures were made. The major change after the renovation was that a large share of the DH was substituted by heat from an exhaust air heat pump and solar collectors. A range of commonly used PEFs were assessed.

The evaluation showed that the energy efficiency measures reduced the total primary energy consumption for most combinations of PEFs. The most essential was how the DH was valued. A low PEF for DH in combination with most of the PEFs for electricity could even result in higher total primary energy consumption after the renovation.

INTRODUCTION/PURPOSE

The term “primary energy” is used more and more frequently, probably because the European energy efficiency directive is formulated in terms of primary energy [2012/27/EU]. How to calculate primary energy is however debated since different actors calculate with different PEFs. Since the energy consumption in the building sector accounts for around 40 % of the total energy use in Europe [1], it is crucial to establish a common way to calculate primary energy in order to estimate which energy efficiency measures that lowers the primary energy consumption the most, and not only the final energy.

In this paper, calculation of the total primary energy consumption was done for an existing residential building. Only two different energy sources were used, district heating (DH) and electricity (EL), and thus the PEFs for these sources are the focus in this paper.

The PEFs used and/or recommended for electricity range from 0.05 [2] to 3.0 [3] depending if you calculate for wind power or marginal production. For DH the used and/or recommended PEFs range from 0.0 [4] to 1.4 [3] depending on the PEF of the local district heating net, or if you calculate it for marginal produced district heating.

METHODS/METHODOLOGY

Total primary energy use for space heating, domestic hot water, ventilation, household electricity and building electricity was calculated for a residential building before and after several renovation measures were made. Before the renovations, DH was used to cover the heat demand. After the renovations, the main heat supply is exhaust air heat pumps and solar collectors, while DH still was used as peak heat.

Annual energy consumption data by each energy carrier, DH and EL, was used as a basis for the calculations. The annual data was recalculated using degree days in order to be able to compare the different years.

The total primary energy was calculated using different PEFs for both DH and EL. The PEF for DH was varied between 0 and 1.5, and the PEF for electricity was varied between 0 and 3 in order to cover the PEFs used and/or recommended according to the introduction above.

The total primary energy consumption was calculated for the year before and after the change of primary heat supply, as well as before and after the whole renovation period (a period of 10 years, including many additional renovations measures such as change of windows, additional insulation of attic etc.).

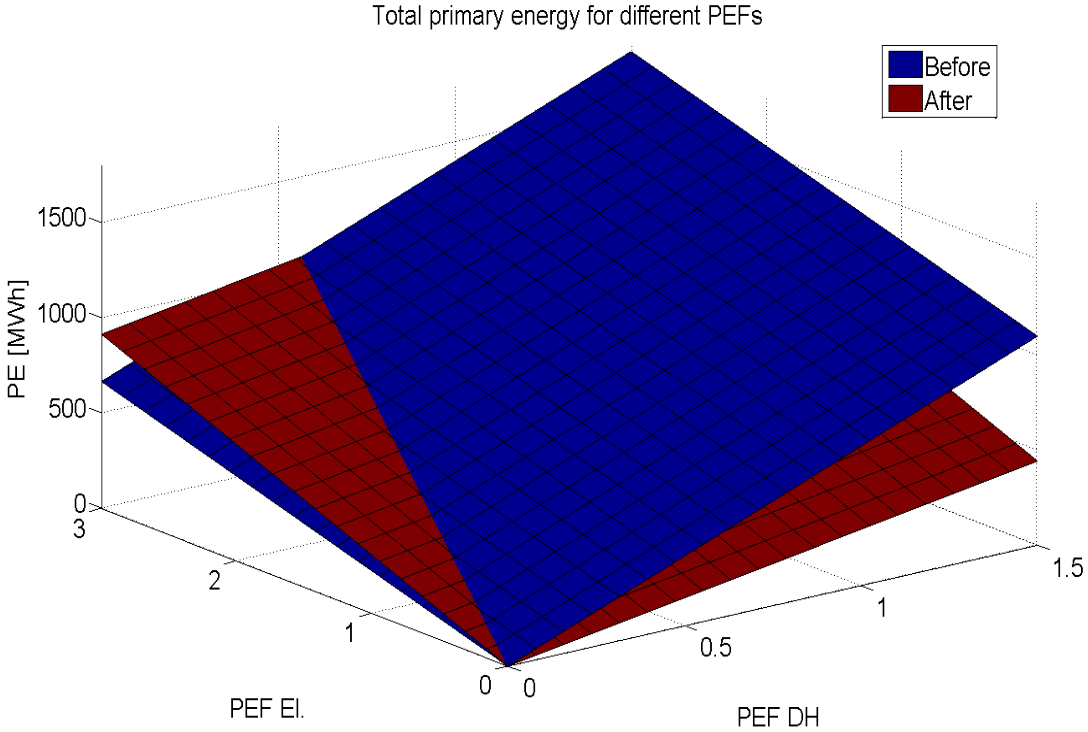

Fig. 1 Total primary energy consumption for the year before the change of heat supply, 2009, and the year after, 2011. The primary energy is calculated with PEF for DH and electricity ranging from 0 to 1.5 and 0 to 3 respectively.

RESULTS

The annual total primary energy consumption for the years just before and after the change of primary heat supply can be seen in Fig. 1. For a high PEF of DH the change of heat supply results in lower total primary energy consumption. But for a lower PEF of DH and a higher PEF of electricity the change of heat supply results in higher total primary energy consumption.

These changes in total primary energy consumption can be compared with the total final energy consumption which can be seen in Fig. 2. The total final energy consumption has decreased by almost 40 %.

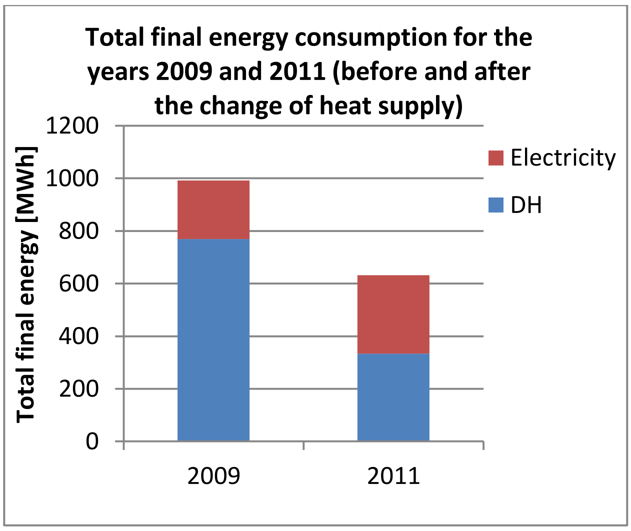

Fig. 2 Total final energy consumption for the years 2009 and 2011, before and after the change of heat supply.

Looking at the total primary energy consumption and the total final energy consumption for the year before the whole renovation period compared to the year after the whole renovation period one can see the same trend as between the year just before and after the change of heat supply.

DISCUSSION

Looking at the whole range of commonly used and/or recommended PEFs it is obvious that most ways of calculating results in a lower total primary energy consumption when changing from DH as the only heat source to DH combined with exhaust air heat pumps and solar collectors, like it was done in this case study.

However, in the case the building is located in a DH net with bio fuels or similar like in this study, a PEF of as low as around 0.1 could be used according to the Swedish District Heating Association [4]. This implies that the PEF for electricity has a high influence on if the renovation measure results in lower total primary energy consumption or not. Looking at Fig. 1 at a PEF of 0.1 for the DH, the renovation measure resulted in higher total primary energy consumption if the PEF for electricity is valued at 0.8 or above.

CONCLUSIONS

The estimation of primary energy reduction may play a vital role when choosing energy efficiency measures. However, it is important to use an appropriate PEF for the local DH net since that is a crucial factor. The actors involved in decision making should be aware of how PEFs affect the result, including how to value electricity.

ACKNOWLEDGEMENT

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RESOURCE EFFICIENT ENERGY SYSTEMS FOR BUILT ENVIRONMENT

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INTRODUCTION

The graduate school Reesbe (Resource efficient energy systems for built environment) started in Autumn 2013 with the main purpose to study the interaction between energy supply and energy efficiency measures using a long-term and system's perspective in order to achieve lower system costs, significant reduction in use of resources, substantial reduction of carbon dioxide emissions and an improved indoor climate for the renovation of the existing buildings or new constructions within the district heating systems.

The PhD projects in Reesbe focus on to find best solution for specific systems by making case studies in five middle sized district heating systems localised in Mid-Sweden. The five municipals used as case studies are Borlänge, Falun, Gävle, Eskilstuna and Västerås. Results from these cases will be presented in the conference as separate papers and this poster will serve as an overall review of the results achieved so far.

METHODOLOGY

The strength of these case studies is the close cooperation in the projects between the municipal housing company and the local energy company in each studied case. The studies focus on larger municipal projects where residential or public buildings are under retrofit. It is important to reach an understanding on a higher systems level such as the district heating or the national, Nordic or European electrical system to fully see the net result in use of primary energy resources or climatic or environmental impact.

To analyse the studied cases several methods will be employed and used in combinations, such as energy auditing, technical measurement, building energy simulation, life-cycle cost analysis, price modelling and energy system optimization.

Some of of the projects will go deeper into the site energy auditing and instantaneous and long-term measurements as well as reviewing the energy bills, building energy declaration and mandatory ventilation inspection in the studied buildings. Other projects will be more generic in the building part, using more of standard solutions for energy demand reduction and focus more on the operation of the district heating system. Also the impact of solar PV and electricity production in CHP in relation to reduced energy need due to better insulation of the buildings is addressed.

The simulation program IDA Indoor Climate and Energy (ICE) 4.0 [1] has been used to calculate the energy demand in the chosen buildings. Modelling of district heating systems can be done with a variety of approaches, using models validated against historical data or using only historical data. In the present studies both approaches were used and with a time resolution that reveals the dynamic effects in the systems caused by electricity and fuel price volatility and variation in weather conditions. For a more detailed modelling using more systems defined parameters the projects will in a next step use the energy system optimization tool MODEST [3].

The total municipal energy system was modelled with lower energy demand in the buildings, using the present energy performance as reference level. A direct estimation of local emission can be made using standard carbon emission values for the fuels [4] used in the only-heat or CHP production. For estimating the global emissions the most frequently used approach is to assume that the CHP produced electricity replaces the most costly produced electricity on the market (today coal condense power) or replaces emissions from the Swedish or Nordic mixed power production.

The Borlänge case study is conducted on a larger area of multifamily buildings (Tjärna Ängar) owned by the public housing company Stora Tunabyggen to show the impact of the measures on the district heating system for the local energy company Borlänge Energi. The Tjärna Ängar area is a neighbourhood built as part of the Swedish Million Program. One pilot building, representative for the area and has not been subject to any major renovation since built, was chosen in the building simulation.

The Falun case study has started with a single multi-family dwelling building, called Promenaden, central in Falun, and to analyse total primary energy use for space heating, heating domestic hot water, ventilation and household electricity before and after several energy conservation measures were made. Before, district heating, delivered by Falu Energi & Vatten, was used to cover the heating purposes. After the renovations were conducted a large share of the district heating demand was substituted by heat provided by exhaust heat pumps and solar collectors.

The Eskilstuna case is based on two buildings from Lagersberg, Eskilstuna, owned by the public housing company Eskilstuna Kommunfastigheter, which has been recently renovated with the goal of halving the energy consumption. The two buildings are connected to the same district-heating substation, are light concrete buildings typical of the earlier Million Program era.

The Gävle case study one multi-dwelling building built during the Million Program era in Sätra, owned by the public housing company Gavlegårdarna, was used in order to investigate how reduction in energy demand would influence the production of heat and power in the district heating system owned by Gävle Energi.

RESULTS

The over all research focus of the four cases presented above address the impact from energy conservation measures in buildings on heat and power from the company operating the district heating system to which theses buildings are connected. However, the specific research questions differ slightly between the cases. Depending on how the PhD projects relates to “real” and sharp projects to be realized in the municipalities. The results presented here reviews some highlights in the different cases. More details in each case will be found in each conference paper or poster presented by the Reesbe PhD student.

The results in the Borlänge Tjärna Ängar study gave a 53 % heat demand reduction to the residential area, which corresponds to a reduction of 3 % in the total delivered district heat from Borlänge Energi.

The result from the case Promenaden in Falun illustrates that renovation of buildings within district heating networks does not necessarily reduce primary energy use but it depends on which factors are chosen for the primary energy calculation.

Eskilstuna study shows that additional insulation gives a significant decrease in carbon dioxide emissions because of its favorable impact on the operation of the district heating system. While the exhaust air heat pump increases the carbon dioxide emissions, mainly due to higher electricity consumption, but also because of its less favorable impact on the operation of the district heating system. Using seasonal pricing with the more than double cost for district heating in December to February could then steer the housing companies to prioritize to add insulation on the buildings since this will give the highest cost-reduction for the costumers.

In the Gävle case the impact of electricity production in the district heating system is affected significantly when energy conservation measures are implemented and therefore also leads to higher total carbon dioxide emissions due to the system profile with very low use of fossil fuel all year round.

DISCUSSION AND CONCLUSIONS

The results are so far rather preliminary, but indicates that depending on the energy system set-up the reduced energy demand due to energy conservation measures in the buildings leads to lower or higher total carbon dioxide emission. The Eskilstuna system shows potential for reducing carbon dioxide emissions in the present system, the Gävle system shows the opposite. Similar results are not ready yet from the Borlänge and Falun cases, two systems that are both different to each other and to the Eskilstuna and Gävle systems. Also a case study in Västerås, in collaboration with the municipal housing company Mimer and MälarEnergi is in development.

The aim of the Reesbe projects is to develop a toolbox for modelling indoor climate, building energy demand and complex district heating systems to be used in real cases and support the strategies and plans in housing and energy companies to find joint solutions. The results so far shows that a methodology has been found for modelling the physical systems but a more difficult task is the assessment in terms of carbon dioxide emissions and primary energy factors. This is important in order to make the most efficient use of finite resource and to limit climate and environmental impact.

It is important that the building regulation code and the various environmental evaluation methods give the right signals when the methods for energy conservation are prioritized and selected. It is generally more important to save electricity than heat within a district heating system. This is even more obvious in a system with combined heat and power

ACKNOWLEDGEMENT

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RTO – RETURN TEMPERATURE OPTIMIZATION – BY USE OF SMART METERS AND HYDRAULIC CALCULATIONS

By Thomas Andreas Østergaard

COWI

ABSTRACT

Saving energy is a vital task for Danish district heating companies. FTO - **F**low **T**emperature **O**ptimization - has been used since 2005 and has led to large energy savings. However, competition with other energy systems, The Danish Energy Agency's demands for further annual energy savings, and the urge to become a greener player in the market forces Danish district heating (DH) companies in a new direction.

One of the new possibilities is **RETURN TEMPERATUR OPTIMIZATION - RTO**!

FTO can be simply defined as *"Constantly applying the lowest possible flow temperature to the network which enables all customers to receive exactly the energy and flow temperature they need at any given moment". However,* the definition of RTO is broader and more difficult to define. This paper will try to outline some of the most important aspects of RTO and some of the potential benefits and obstacles when implementing RTO.

INTRODUCTION

The question of lowering the flow and return temperatures in the district heating network is often not asked. In many countries high temperatures are used and accepted as "standards". Even in countries which are well-known for optimization of energy consumption, for example Denmark, we still find district heating networks running with high flow and return temperatures.

When operators are asked the reason for the high temperature regime the answer is often: ***"It has always been done in this manner. Why should we change it? It's been working for years!"***

Indeed it has been working perfectly and this is, of course, also one of the reasons for the great success of district heating. It does work perfectly!

In Denmark the energy crises have been driving the development of new energy solutions, and climate issues have pushed the wagon too. The Danish Energy Agency has demanded the development of new solutions by requiring all energy companies to reduce the annual consumption each year. The annual reduction is in the scale of 1.6 % for the district heating companies – each year!

In order to meet these goals the district heating companies have to turn every stone, no idea should be left untried!

FLOW TEMPERATURE OPTIMIZATION - FTO

The predecessor of RTO - FTO began in Denmark around 2004. The idea was to lower the flow temperature during periods where network demand was lower than the design load. In other words, if the capacity of the network would allow it the flow temperature was lowered.

The benefit of this behaviour is potential energy savings by minimizing the heat loss from the flow pipes.

In the beginning many people doubted that this would actually work! The fear was that there would be a lot of complaints from the customers not having enough heat or hot water. Also it was expected that the return temperature would rise and make the whole effort useless. But what really happened was *"**Nothing**".* The reason for this was of course that the temperatures used have been significantly higher than necessary. Houses have also been further insulated due to the energy crises, and there was certainly also a degree of oversizing of installation when installed, for example large radiators (due to tariffs based of consumption of M3 – not energy).

After the initial euphoria over the possibilities of lowering the flow temperature, many commercial companies launched various systems to automatically monitor and control the FTO. Seven Technologies A/S (today Schneider Electric) launched the most successful application, called the TERMIS FTO.

HOW DOES FTO WORK?

The operation of TERMIS FTO is as follows: Using data from 4 daily local weather reports a load forecast for the network to be optimized is calculated. This load forecast is fed into the TERMIS calculation module every hour, 365 days a year. The calculation engine consists of a hydraulic model calibrated and verified against the actual network, into which the network operator can input set-point temperatures for specific parts of the network.

Each hour the hydraulic calculator simulates a 24 hour operational period. This data is transported to the SCADA system as a time series of flow temperatures for each heat producer on the network. Based on this data, each producer knows once every hour what the actual flow temperature leaving the production facility should be for the next 24 hours.

Easy, right?

One of the benefits of this approach is that exactly the desired temperature is delivered and every load case has been evaluated and found within the boundary conditions for the next 24 hours.

During the last 10 years the use of the FTO has been enhanced. Many things have been improved and many district heating companies worldwide have realized both the value of the real-time models and the FTO.

STATE OF THE ART – THE BACKGROUND FOR RTO

Real-time models are becoming more and more interesting for district heating companies. Today it is possible to integrate the hydraulic models and the SCADA system to such an extent that the hydraulic models actually become a part of the operation of the network.

Therefore the next step was to try to integrate more information in to the real-time world.

In Denmark and many other places the use of so called smart meters has taken off. The trend was fuelled by the power companies that somehow managed to argue for the exchange of 500 Mio. power meters in the EU. Their argument was the need for a smart grid to minimize the cost of new power lines in Europe.

The trend was also taken up by Danish DH companies, but for DH metering. The arguments for changing the DH meters were a bit different, for example wishes to introduce new tariffs, lower service costs, enhanced surveillance of meters, better metering etc.

Most of the new meter installations were equipped with remote reading systems. So by pushing one button the DH Company could have maybe 10,000 meters read within one day. Smart!

The latest figures from 2013 show that about 100 Danish DH companies have remote metering.

METHODS/METHODOLOGY

The introduction of smart meters in district heating has increased but what has really happened? Nothing much to be honest. In spite of all the possibilities, smart meters are used mostly for the same purpose as traditional meters, namely billing.

Whose fault is it?

It is hard to tell. One could maybe have expected some more action from those who buy or sell the equipment but on the other hand…

We in COWI started to think about the use of the smart meters, could we use them for something? The idea of combining smart meters and TERMIS FTO came up.

Could we use the data from the smart meters directly in our calculations?

Data handling from many sources is one of our specialities since we are integrating different SCADA and GIS systems in order to build our FTO models. So why not integrate the meter data into the databases, extract what we need from meters and use them in FTO. This could have been a fine idea, but FTO was actually already running pretty well for us. So why bother?

It could have stayed there if it wasn't for the idea of RTO was so stumbling near.

RTO – FTO, see?

WHY RETURN TEMPERATURE OPTIMIZATION?

"*Return temperature optimization (RTO)? You can't do that*" was the first thing COWI was told. Why?

"*Because it is the installations at the customers that decide the return temperature and you can't do anything about the customer's installation. Period. Are you now finished?*"

So we thought about it. Then we decided this: "***Let's change the mind-set, we can do it if we want!***"

For decades it has been the good Latin of most DH companies that we can't interfere with the customer installations. We can hardly do anything when we have crossed the line of the main valves.

But that is history now, because the mind-set has been changed.

Lowering the temperature 1 degree in the return pipe is just as valuable as lowering the flow temperature 1 degree in the flow pipe. From the FTO we understood that it was actually rather large savings we were looking at.

How to get on with it?

EUDP

The Danish Energy Agency supports various programmes in order to support and promote saving of energy. COWI applied on behalf of a group of partners for support from the EUDP programme. EUDP supports development of new energy technologies that create growth and jobs, increase security of supply and help to make Denmark independent of fossil fuels by 2050. EUDP funds Danish participation in international cooperation and knowledge sharing on energy technologies.

The partners in this EUDP project are:

- Skanderborg-Hørning Fjernvarme A.m.b.A.
- Middelfart Fjernvarme A.m.b.A.
- Grøn Energi
- MeterWare, Luxembourg
- HSO Schneider Electric
- COWI A/S

The project was awarded support from EUDP. The objective of the project is *"Development of a unique software solution for return temperature optimization (RTO) in DH systems, using Big Data from smart meters and real-time models connected to SCADA. Development will take place in 2 full-scale tests in large DH networks, and aims to generate huge energy savings and better opportunities for renewable energy integration*"

RESULTS

The project is under way and will be completed at the end of 2014. However we have some preliminary results that give and idea of what the effect will be.

- First of all, it is possible to use data from smart meters directly in the hydraulic software and thus make better calculations. **Actually real Smart Grid**
- The use of real-time data from meters opens up new possibilities for new types of calculations.
- Combining data from metering and SCADA systems give new possibilities for cross-referencing
- We will be able to calculate the energy saved in the network by improving the customer installations
- Bringing data from metering databases into the TERMIS environment makes it much easier to detect errors in customer installations
- Focus on the RTO makes new tariffs important
- It is easy to track the customers with the worst return temperatures
- It is valuable tool to have all metering presented directly in the network model, clickable for every customer

But what is RTO in comparison to FTO?

FTO is an easy applicable tool which basically lowers the flow temperature. Simple.

RTO is somehow different.

It is not a "Push button" project one can buy off the shelf.

RTO is a multidisciplinary project set out to lower the return temperature. It involves many, many aspects of the business of the district heating company

MORE RESULTS

Just integrating smart meters into hydraulic calculations is of course not what we are aiming at. This would be too little.

So what are the real objectives?

If we compare FTO with RTO with respect to hydraulics the benefits are plain to see:

FTO	RTO
•Higher flow in pipes	•Lower flow in pipes
•Higher velocities in pipes	•Lower velocities in pipes
•Higher gradients	•Lower gradients
•More resistance	•Less resistance
•Higher costs for pumps	•Lower costs for pumps
•Large savings on energy	•Large savings on energy

Fig. 1 FTO compared to RTO

Knowing than "*lower and less*" is better than "*higher and more*" it is easy to see that RTO actually is providing additional value than FTO.

But there is more to it, the gains are actually more valuable.

If we list the full potential we will end up with one-liners such as:

- **Minimized heat loss from DH network**
- **Less cost for pumping in the DH network**
- **Increased capacity in the DH network**
- **Improved production of heat and electricity**

And here we really have some heavy advantages. The increased capacity of the DH network can really mean a lot.

An example of the benefits:

One of our clients has the possibility to achieve about 30-40 percent new customers within the next 10 years in his current area of DH supply. This amounts to an increase of approximately 30 MW peak load. The current network is well maintained and has an expected lifespan of an average of 25 years.

However, due to various historical reasons the return temperature is very high in a Danish context. The annual average return temperature is more than 50 degree C. A "normal" Danish return temperature would more likely be 40 degree C.

So what would happen if all of his customers reduced their annual average return temperature to the "normal" 40 degree C?

In this network, all other things even, the annual circulated flow will be reduced with approximately 1.3 Mio. m^3 per year!

This would of course have an effect both on heat loss and cost for pumping.

Therefore, in this specific case it would be a real win/win situation. The increase in capacity would minimize the need for reinvestments in DH network. The existing network would, in many cases, prove to be big enough to carry the extra load from the new potential customers.

Finally, as a part of the build out of the network new production capacity will be needed. This capacity is foreseen to be established by erection of a new biomass plant. This is a part of the Danish national strategy for 2050 to reduce the use of fossil fuels. In fact the plan is to be fossil free in 2050.

The lower return temperature will result in a better production of heat, since the low return temperature can be used for condensing the flue gasses.

For this client reduction of return temperature will therefore prove to be very valuable.

The client has realized these facts and started a modernization of his complete DH business. Why?

Because RTO is not a single thing, it is a change of mind-set. When you have realized this you will see that many things that might have worked for years will have to change.

DISCUSSION

Our work with RTO has taken its beginning with our knowledge from FTO. We are engineers with district heating as our daily work. We therefore know quite a lot, but we might also be limited by the way we see the possibilities.

One of the things that cross our minds first is that district heating with RTO is moving into a new phase. The old school of DH was that "***we provide the heat – and you (the customer!) do the rest."***

This is simply not true anymore. We see more and more DH companies that do more. They provide assistance to the customer, they look after the installation, they sell or lease out units. In other words, they provide services in a form and in a range that have moved them away from being the old school "provider" of heat.

This is, in fact, the biggest change that also comes with RTO. We think that it is time for the district heating companies to move the boundaries closer to the customer.

For example, seen in this light the district heating company should take over the total responsibility for the heating system.

Many would argue that new smart apps and information to the customers will enable them to do the work themselves. But we don't think is true. Customers do not want to spend the time to look after their return temperature. In fact most customers do not know what the return temperature is! Or where the heat comes from (except from the radiator…). And frankly, they don't care.

So if district heating shall be effective and competitive the DH companies must take over. Expecting the customers will play ball in this game is hardly true, the drive has to come from the DH companies. They should approach RTO and the rest of the business from a systemic point of view.

So how about it? Should the DH business go for this? Absolutely!

OUTLOOK

The outlook for RTO in DH networks is quite promising. In Denmark we have spent 10 years lowering the flow temperatures and we are still not there.

Taking into account that RTO is a much bigger task we would imagine there will be enough work to do the next 10 years also.

Looking internationally on RTO there are an enormous potential. Taking the viewpoint from our knowledge about flow and return temperatures in the other European countries there should be enough to do for many years.

Just get started!

CONCLUSIONS

RTO is a part of a package to improve the profit and efficiency of DH Company. RTO is not a single task, but a whole set of measures that have to be implemented in order to harvest all the fruits of the combined effort.

RTO could end up transforming the DH company into a modern business with full and intense focus on the customers and the bottom-line…

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EUDP
Energiteknologisk udvikling og demonstration