13th international symposium on district heating and cooling

3rd of September -4th of September

Copenhagen, Denmark

ISBN: 978-87-995917-0-1

District Energy Development Center

PREFACE

The 13th International Symposium on District Heating and Cooling is now held for the second time in Copenhagen, Denmark.

District heating systems are the dominant way to heat buildings in Denmark. Danish district heating systems varies from small systems with less than 2 GWh pr year to larger systems with up to 4500 GWh pr year. The largest district heating network is situated in Copenhagen, supplying both the capital and a large number of suburbs around it.

The Danish district heating companies are mostly owned by consumers. Thus the boards of the companies are elected from among the customers, who often work at a volunteer basis. In the larger cities the companies are owned by municipalities. A few are privately owned. Whether private, consumer owned or owned by municipalities, all district energy companies in Denmark are non-profit organizations.

Guidelines for energy policy are laid out by the Danish government, and the development is guided partly by taxes on specific fuel types and partly by government funding for selected research projects. But research and development of district energy is primarily implemented by the individual district heating companies. As the Danish district energy companies are non-profit, the development of the Danish district heating sector is largely dependent on the individual companies' grass root spirit.

The Danish district energy sector has large amounts of combined heat and power, solar, heat storage and an extensive use of heat from waste incineration and biomass. Furthermore the Danish district heating sectors focuses on a constant development of more efficient units, low temperature district heating, geothermal heat and heat pumps utilizing electricity produced by wind turbines.

The 13th international symposium for district heating and cooling is organized by the District Energy Development Center in cooperation with the Scientific Committee. On behalf of the organizers we want to express our sincere thanks to the members of the Scientific Committee, the Local Organizing Committee, the members of the Advisory Committee and our sponsors who gave us valuable support. We would like to thank the individual authors for their submitted papers and the reviewers for their time and help.

Bringing research results to development and demonstration projects is one of the activities of District Energy Development Center and we hope to further the practical application of the research results presented at the symposium.

We hope that you will experience an enjoyable stay in Copenhagen and also that this conference will improve further cooperation in the field of district heating and cooling research and development.

Morten Hofmeister, Director DEDC

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INTEGRATED MODELS TO EVALUATE DISTRICT HEATING NETWORKS

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Keywords: Optimization, Simulation, Evaluation, Strategic management

ABSTRACT

With growing environmental concern along with increasing urban population and energy needs, district heating networks are considered as a promising sustainable energy solution for cities. They enable to combine several energy sources in order to bring cost-effective and environmentally friendly solutions. As initial investment costs are expensive, it is essential to choose the most suitable solution regarding costs, environmental impacts and response to customer needs. So the design stage requires a precise evaluation of alternative scenarios (heating sources, network topology, demand structure, etc.). Besides, at operating stage it is also important to monitor and to assess a posteriori actual performances of a DH network, in order to check and to improve it. Most of existing models are optimization models, specialized for ex-ante evaluation at design level and for specific purposes. This paper presents a more general and flexible model with the aim to simulate very diverse scenarios of DH networks both at design (ex-ante) or operating (ex-post) stages, so as to be used as a strategic management tool. An energy model, adapted to various networks architecture, is coupled with economical and environmental models. A DH network is represented by an oriented graph and its energy behavior at each time step is simulated using the linear programming formalism. Principles of the model are described, including its adaptation to various energy sources, conversion technologies, demand profiles and network topologies. A practical example illustrates how the model works and the type of conclusions it can bring at the design stage.

INTRODUCTION

In Europe, DH networks supply 10% of heating needs, but this rate can be very different according to the local policies of each country (e.g. in 2007, 50% in Denmark, 5% in France)[1]. DH networks have the main advantages to improve energy efficiency (compared to private heating units) and facilitate the use of renewable and local energy resources such as waste heat, geothermal or biomass energies. In all countries where heating is needed, DH networks are considered as a promising sustainable energy solution which could allow the reduction targets of greenhouse gases emissions to be met, at a reasonable cost. However making DH networks an effective powerful leverage for local energy policy requires looking at combining many different parameters in a complex process. So local planners and decision makers need tools both for decision making (which is the best path for the network? the best combination of energy sources ?) and for strategic management (how can the DH network be adapted to the evolution of customers' needs ? How to evaluate long-term monitoring ?). Indeed, it is essential to evaluate different scenarios of DH networks (concerning different energy mixes or network topologies) at the design stage (ex-ante), to select the best adapted one, all the more so as a DH network constitute a long-term investment. In the same way, the assessment of a DH network, at operating stage (ex-post) is necessary in order to check and improve its performance from an energy, environmental and economical point of view.
A literature review shows that existing DH network models are generally specialized optimization models with very specific objectives. Two main categories of models can be identified.

These models are designed to answer two different types of objectives : firstly help decision tools which allow an evaluation of scenarios at the design stage can target the network topology optimization [6], the network design optimization [7], or the energy-mix optimization [8]. Secondly the objective of real time management tools, mid-term and long-term tools, is to optimize the DH network operating [9, 10].

Regarding heat production systems, some models consider several production systems (heat pumps, combined heat and power (CHP), boilers, etc.) [11], while other only use a CHP unit [12]. It can be noted that a CHP unit is present in all the models analyzed, since this technology enables simultaneous production of heat and electricity, the latter being sold to the grid. The total simulation period vary from hours to one year depending on the aims of the model and the type of users considered, but in general, it is split into smaller periods when the fuel's price or the demand intensity is changing [10].

Depending on model objectives, different levels of details may be adopted for elementary model equations and for input parameters. For instance the PipeLab model [4] which aim is to optimize the design of pipes of a geothermal DH network takes into account many pipes' variables (material, pressure losses, etc.), whereas the Persson's model [3] which aim is to evaluate a DH competitiveness rather considers economical parameters, particularly to make a detailed analysis of the different types of costs. Verda [5] mainly uses thermo-hydraulic parameters and fluid dynamic parameters to propose a model to optimize the functioning of a multi-scale storage.

Existing models generally use linear programming [6], mixed integer programming algorithms [7], and more occasionally non-linear programming algorithms [14]. In their optimization routines, the objective function to be minimized is always a cost function. It can either be the total cost of the DH network, which includes the investment costs and the operating costs [3] or only the cost of the energy supplied to customers [11]. When the DH network has a CHP unit or can be supplied by another network, electricity purchase can also be considered [13]. Eventually, profit from the electricity sale is deducted from the total costs.

Literature review shows that existing models generally lack of flexibility, both concerning the typologies of networks which can be modeled and regarding the questions which can be answered, since they have very precise targets.

This paper deals with the development of a more general strategic management tool suitable for ex-ante and ex-post multi-criteria evaluation of DH networks. The energy model proposed here simulates a DH network running on a given period (typically one year), based on heat load data adapted to the type of evaluation expected (real data or simulated data resulting from another model of energy demand simulation). This energy DH model is designed to be coupled with an economical model and an environmental model, to form a global strategic management tool. This tool can be used as a basis of discussion by both the local authority and the network operator, at different stages of the DH network life cycle, in order to take decisions about the creation/extension of networks (Which energy sources should be chosen to satisfy specific energy needs ? How many more customers can be connected to an existing network ?) or to assess the performances of the network and compare them to the forecasting (Why are the operating costs higher than expected ? Does the carbon emissions of the DH network respect the commitments of the city ?). After a description of the DH model's principles and structure, a simple example illustrates how it can be used and what kind of conclusions come with it, to define a strategy of management.

DESCRIPTION OF THE MODEL

Overview

The model presented in this paper is basically a simulation tool which reproduces the DH network functioning over a given time period. The objective is not to optimize a set of parameters, but to evaluate energy performances of a DH network, through the long term simulation of its functioning both at design stage (a priori evaluation of different scenarios) or at operating stage (evaluation of operating performances). Although optimization routines are used to emulate short term management and control of the network for each time step, it is not an optimization approach.

This tool is general and flexible, it enables to model a large range of scenarios which vary in terms of network architectures, energy technologies, and demand structure. This tool is particularly adapted to model big sized multi-sources networks (especially when there are several fatal heat sources), and smaller networks in a complicated situation in which some parameters, such as prices or available power, are varying over the simulated time period. The model could assist decision makers by simulating the effects of different scenarios (which can be used at the design stage, but also at the operating stage in addition to the evaluation of performances), such as the introduction of a new plant, a rising or a decreasing heating demand, costs variations due to new taxes, etc.

Structure of the model

The energy model represents a DH network by an oriented graph and simulates its energy behavior at each time step, using the linear programming formalism, to optimize resources allocation. An hourly time step is chosen, which allows simulating scenarios with parameters that vary hourly, such as the available power of domestic waste incineration plants or fuel prices. The energy results can then be coupled with other external data, through environmental and economic analyses [16].

In the proposed model, a DH network is composed of *n* nodes which can be either substations or heating plants, and *m* branches which stand for pipes. Heat flow is directed from one node to another and the graph is oriented.

The network topology is provided to the model via a *simple graph format* (sgf) matrix which describes the number of nodes and branches of the graph and how they are linked together. All the matrices describing the network topology (successor matrix, predecessor matrix, connectivity matrix, etc.), which are needed to implement the optimization problem, are calculated from this sgf matrix.

The following notations are used : *S* is the set of heat sources, Pm_j is the heat flow transferred in branch *j*, $Su(i)$ is the set of outlet branches of node *i* (successors) and $Pr(i)$ is the set of inlet branches of node *i* (predecessors).

At each time step, a node *i* is characterized by :

- its maximal power P_i^{max} (with $P_i^{max} = P_{Srce_i}^{max}$ power of the source if *i* is a heat plant and 0 if not),
- its operating costs C_i (accounting for plant efficiencies) (0 if it is not a heat source); cost used here are variable costs in order to represent priorities between heat sources for short term decision making ; they do not take into account investment cost,

- its heat demand P_i^{dem}(0 if it is a heat source),
- the entering heat flow : $P_i^+ = \sum_{j\in Pr(i)} Pm_j$
- the leaving heat flow : $P_i^- = \sum_{j\in Su(i)} Pm_j + L_j$

In the same way, at each time step, a branch *j* has :

- a maximal handled heat power Pm_j^{max}
- heat losses L_j assumed to be affine function of handled power.

There are $(m+n)$ unknown variables to be determined at each time step : heat flows transferred in each branches of the network Pm_j (m variables) and the power production of each heat source $PSrce_i$ (n variables). To compute the values of these state variables, the model is based on the minimization of the heat production cost of the whole network at each time step over the all simulated period, under thermal pipes capacity constraints (1), heat sources capacity constraints (2) and energy balance constraints (3) at each node.
The objective function to minimize is the global heating cost in the whole network is $\sum_{i\in S} C_i \times P_i^-$

The optimal solution is found under three types of constraints :

$0 \leq Pm_j \leq Pm_j^{max}$ (1) for each branch *j*

$0 \leq P_i^- \leq P_{Srce_i}^{max}$ (2) for each heat source *i*

$P_i^+ = P_i^- + P_i^{dem}$ (3) for each consumer node *i*

To solve this optimization problem, in which all the equations and the objective function are linear, the linear programming (LP) formalism is obviously chosen for being the simplest way to tackle this kind of problems. Besides LP can handle a great number of variables, which is not necessarily the case for the non-linear formalism [14]. In addition, LP allows finding a global minimum of the objective function and not only a local minimum [15].

The optimization problem is solved by using a variant of Mehrotra's predictor-corrector algorithm [2], a primal-dual interior-point method. The optimization problem is stated using an LP standard matrix format as follow :

The objective function is $min_X f^T X$ such as

$$\begin{cases} A.X \leq b & (4) \\ Aeq.X = beq & (5) \\ lb \leq X \leq ub & (6) \end{cases}$$

with $f^T X = f(1)X(1) + f(2)X(2) + \cdots + f(m+n)X(m+n)$. The vector X is $(m+n)$ long as there are $(m+n)$ unknown state variables (*n* node powers and *m* branch powers).

In our model, the inequality (4) is not needed. The energy balance constraints are transformed in the form required by the equality (5) and the capacity constraints have directly the form of inequality (6).

To simulate the DH network in operating conditions, the LP optimization solver is run at each time step to return the best combination of heating sources and power flows in pipes. For that kind of modeling tool, simulations are usually made with an hourly time step, over a one-year running period, which enables to simulate some hourly variations of input parameters (demand, available power plants, and energy price). Actually any time period and time steps may be used if simplifications are made on input data (like assumptions about constant parameters), longer time steps can be simulate, leading to faster results.

Flexibility of the model

The model presented in this work is the core model of a more general management tool. Its particularity is due to its flexibility of modeling and to the way in which its energy results can be exploited through environmental and economic analyses. Some examples are given to illustrate how the model can be adapted to simulate various network architectures, heat demand, energy sources and conversion technologies.

The model is suitable for any network topology, hierarchical or looped network structure can be easily addressed. The model considers fixed supply and return temperatures and variable flow rate, but it can be extended for fixed flow rate and variable temperatures. Interruption or limitation of supply or other temporary problems in the network due to maintenance or failures can be modeled by modifying the maximal heat flow transported through pipes. Interconnections with other DH networks may also be tackled by inserting additional source nodes. Regarding the production costs, the model may consider specific costs, such as pumping costs or environmental taxes by giving a cost to heat transferred into branches where pumps are located, or by giving an additional cost to the concerned heat sources.

In terms of heating demand, the model can tackle very different demand profiles (simplified demand profiles aggregated on large periods, or detailed hourly profiles), it only depends on the accuracy of available data and on the objective of the simulation. The model offers the possibility to simulate “virtual sources” associated to consumer nodes. It means that some customers can temporarily use a personal heat source as an independent heat producer, for its own supply, at a specific partial disconnection cost.

Lastly, the model is also flexible concerning energy sources. Indeed, a large panel of heat production plants can be considered, from fossil fuel plants to renewable energy sources, provided that their maximal capacity, efficiency and energy cost are known at each time step. The model always gives the priority to the cheapest energy source. Heat proceeding from domestic waste incineration plants, can be modeled as a free energy source with an hourly variable available maximum power. Time varying features of energy sources (costs, available power) are tackled through input parameters.

RESULTS

The model presented above is applied to a district heating system case study composed of 2 heat production sources, a geothermal plant and a conventional gas boiler and 4 delivery points. Each source can supply each substation and domestic hot water is also taken into account. Total energy needs for the network are approximately 124GWh per year. The model simulates the running of the network for each time step. For this example, it is assumed that pipe capacities are always adapted to the power flows and that 5% heat losses take place in the distribution network. Figure 1 illustrates the network.

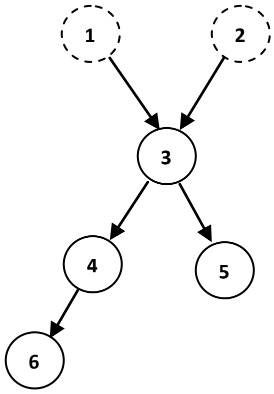

Fig. 1 : Schema of the network studied.

The geothermal plant is a heat source at constant temperature and constant flow-rate, with very low variable production cost. Its maximum heat power depends on the network return temperature and heat-exchanger effectiveness and it is computed at each time step using the Equation 7 :

$$Pmax = \dot{m}c_p\varepsilon\,(T_G - T_R) \qquad (7)$$

where $\dot{m}$ is the geothermal water flow rate, c_p the specific heat capacity of water, ε the heat exchanger effectiveness, T_G the temperature of the geothermal source and T_R the return temperature in the network. In this equation, only T_R is variable, it is calculated at each time step using Equation 8, all the other parameters are supposed to be constant.

$$T_R = T_D - \frac{P_{sup}}{\dot{M}c_p} \qquad (8)$$

With T_D the depart temperature in the network after the heat exchanger, P_{sup} the supplied power, $\dot{M}$ the DH water flow rate.

Two scenarios are implemented and analyzed. The differences between them are the variation ranges of depart temperatures in the network and the temperature of geothermal source. The characteristics of the heat production sources and the different scenarios are described in Table 1 and Table 2. Some of the results are illustrated by Figure 2 and Figure 3.

Table 1 : Characteristics of heat production sources.

	Geothermal plant	Gas boiler
Cost	0.01€/kWh	0.04€/kWh
Maximal power	Calculated at each time step	60MW

Table 2 : Description of the two scenarios analyzed.

	Scenario 1	Scenario 2
T_D variation range	60-110°C	80-100°C
Geothermal source temperature	90°C	90°C

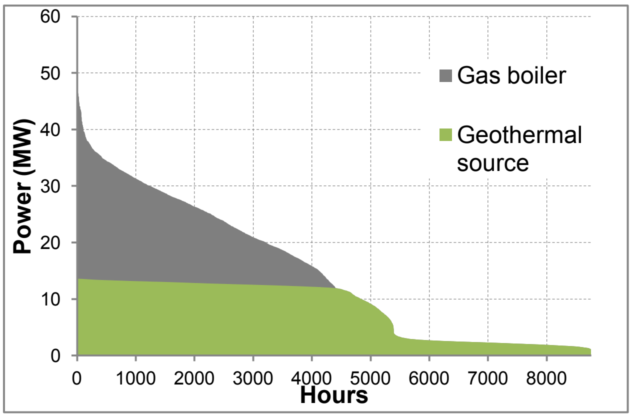

Fig. 2 : Load curve for scenario 1.

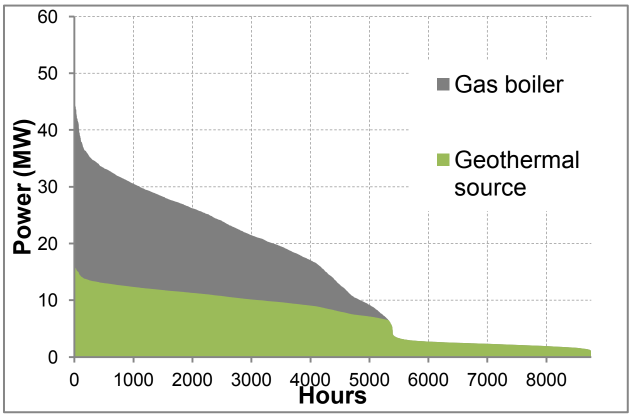

Fig. 3 : Load curve for scenario 2.

The load curves indicate the proportion of heat production for each heating plant during the year related to the power needed to satisfy the customers' needs. Using these load curves allows planning the production schedule of the DH plants. Table 3 presents the optimal heat production dispatching and Table 4 shows the energy balance and the production costs associated to each case.

Table 3 : Optimal heat production dispatching at the lowest possible cost for each scenario.

	Heat load range	Starting heating point	Covering ratio
Scenario 1	<12MW >12MW	Geothermal source Gas boiler	56.7% 43.3%
Scenario 2	<6MW >6MW	Geothermal source Gas boiler	49.2% 50.8%

Table 4 : Comparison of the energy and costs balance for each scenario.

	Total losses	Energy distributed	Average cost	Total cost
Scenario 1	5 526 MWh	126 622MWh	24.0€/MWh	2 976 k€
Scenario 2	5 524MWh	126 622MWh	26.4€/MWh	3 267 k€

The main conclusions from the analysis are the following. In Scenario 1 the energy base source production is the geothermal source which satisfies the most important part of the heating needs (56.7% of the distributed energy), the gas boiler is used as soon as the needed power exceeds 12MW (for 43.3% of the distributed energy). Most of the year, the geothermal source is sufficient. On the contrary, in Scenario 2 the geothermal source used as the base energy source is not sufficient to cover 50.8% of the energy supplied to the network, so that the gas boiler must be operational as soon as the heating needs exceed 6MW. Regarding the costs, the DH network proposed by Scenario 1 is around 290 800€ under the costs in Scenario 2, which can be explained by the difference in the costs of energy production sources (the production of a geothermal kWh is four times cheaper than the production of a kWh from the gas boiler) and by the difference in the covering ratios. This difference in costs can also be seen in the MWh average cost. Considering the total year period, in Scenario 1 a MWh costs on average two euros less than a MWh in Scenario 2. It can be noted that the total losses are approximately the same in both scenarios, because the energy distributed and the pipes' performances are the same in the two cases. Scenario 2 is not really adapted to the example of DH network proposed here, partly because the geothermal source has too high temperature relatively to the heating needs of the network consumers.

This example illustrates how important it is to compare different possibilities in order to choose the best scenario. Here the variation range of the depart temperature in the network as well as the temperature of the geothermal source are critical parameters to take into account. These temperature values determine the production schedule, and consequently they influence the production costs and the network competitiveness.

CONCLUSION

The objective of the DH model proposed in this paper is to simulate the operating of a DH network, by choosing the cheapest heat sources by merit order at each time step, taking network constraints into account. This model, which considers many features, is relevant for most of the DH networks.

From a strategic point of view, local authorities could take decisions from scenario analysis, particularly concerning network characteristics to use in relation to heating needs and production costs. For instance, thanks to this model, decision makers could estimate the amount of energy required to satisfy actual demand and design the geothermal plant or, using demand forecast, they could assess if the Scenario 2 is adapted to a growing heat demand.

This model is part of a more extended strategic management tool which is being implemented. In the meantime, additional components (such as particular energy production sources: solar panels, heat pumps, etc.) are still to be incorporated to the model.

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MODEL-BASED ANALYSIS OF INNOVATIVE DISTRICT HEATING SOLUTIONS FOR DISTRICT ENERGY SYSTEMS

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ABSTRACT

This analysis aims for a model-based approach to determine possible heat supply options for a selected neighbourhood. First the heat demand for the area and existing heat supply technologies are analysed using a high spatial resolution. Possible supply technologies are evaluated and included into the energy system model TIMES Local. The modelling approach considers grid based supply technologies which are used to determine the spatial connection between the different sub-regions of the analysed neighbourhood. Based on this modelling approach the development of the heat supply and the integration of district heating and solar heating is shown.

INTRODUCTION

Energy efficiency and sustainable use of energy is one of the main issues today. Especially in local energy plans the need for efficiency is often combined with smart energy systems and energy autarky. To fulfil these demands the design of the heat energy supply of districts and neighbourhoods requires new innovative technologies to increase the appeal of the district but also to meet ecological targets. This being said district heating as part of the local heat supply system needs new concepts and supply technologies. To evaluate these innovative concepts a model based approach can be used.

This approach is taken in the EnEff:Stadt Ludwigsburg project, which task is to develop an energy concept for a neighbourhoods with the aid of an energy system model. For the neighbourhood Grünbühl in Ludwigsburg, Germany, the model TIMES Local is used. The energy concept which has to be developed shall also include the possibility of the build-up of an innovative district heating system which might partially substitute the existing natural gas supply.

The comparison and evaluation of the different innovative district heating solutions with other options of the heat supply is carried out by the energy system model TIMES Local. The energy system model TIMES Local optimizes the supply system of the study case using a cost minimizing approach. To display the district heating system within TIMES Local a high spatial resolution is used to divide the district into several segments. These segments are displayed within TIMES Local as independent model regions. Between the regions different routing solutions for the district heating grid are represented as import or export processes in the TIMES Local model.

NEIGHBOURHOOD GRÜNBÜHL

The neighbourhood Grünbühl which was review in this study is located in the Ludwigsburg, Germany. Within the scope of the project Eneff:Stadt [1] an urban planning and an energy plan have to be developed for the neighbourhood Grünbühl as well as for the bordering neighbourhood Sonnenberg. While this has already been preceded for Sonnenberg, those steps are still to be done for the neighbourhood Grünbühl.

The building structure in the neighbourhood Grünbühl mainly consists out of buildings erected in the 1950s and 1960s and therefore shows high need for redevelopment. The buildings are mostly big apartment blocks in parallel construction. Due to the demographic trend and needs for redevelopment those buildings have to be rebuilt or even demolished [2]. Within this redevelopment measures the opportunity arises to increase the energy efficiency as well as the urban living conditions.

Fig. 1 Map of the neighbourhood Grünbühl

The fragmented structure of different building owners in the neighbourhood presents an obstacle in this process. Therefor it is not known for sure when and whether measured planned by the local authorities can be implemented. According to this reason the analysis of the heat supply is based on the existing building and residential structure as the implementation of possible redevelopment measures highly depends on the building owners whose actions can't be foreseen at the moment.

Current heat supply

At the present stage the heat supply for space heating and domestic hot water is carried out by decentralized heat generators. Therefor the energy carrier natural gas is used. In the northwest corner of the neighbourhood exists a stub to the district heating net of the bordering neighbourhood Sonnenberg. This stub can be used in case the erection of a district heating net in Grünbühl shall be carried out.

In order to analyse the different heat supply options the existing heat demand was determined. To determine the heat demand the analysed neighbourhood was divided in twenty regions. The regions are used for the modelling with TIMES Local to achieve a spatial resolution of the neighbourhood.

Fig. 2 Heat demand in Grünbühl

The determination of the heat demand is based upon the consumption data which was provided by the public utilities of the city Ludwigsburg. Based on the provided data the specific consumption depending on the size and age of the buildings was calculated. The specific consumption data was used in case no data was provided for a building. Using this methodology the heat demand could be determined down to the building level. The aggregated heat demand for the regions in which the neighbourhood was divided is shown in figure 2. The total heat demand of the neighbourhood Grünbühl is 12.5 GWh per anno.

HEAT SUPPLY OPTIONS

Different heat generation options have been considered in the analyses of the possible supply options for the neighbourhood Grünbühl. First of all the existing supply be decentralized natural gas boilers is possible. The existing natural gas net can as well be used for block heating stations. The block heating stations can be used for the decentralized supply of big facilities but also with the option to feed into a district heating net which might be erected. Possible locations for a block heating station are region 10 which includes a school and region 12 where a residential complex with five to eight floors is located.

The possibility of the erection of a district heating net is considered as well. The heat supply for the net can result either from the existing heat plant in Sonnenberg or be carried out be decentralized heat feeder. Possible decentralized feeders are block heating stations or solar heating.

Solar heating can either be used for the domestic hot water supply or even as an additional feeder for the district heating net. The technical potential for solar heating is determined be the available roof area in the neighbourhood as well as by the solar load curve which was used to represent solar heating in the TIMES Local model.

TIMES LOCAL

The energy system model, TIMES (The Integrated Markal Efom System), is a further development of the two model generators, MARKAL and EFOM-ENV, written in GAMS. TIMES was developed in recent years within the „Energy Technology Systems Analysis Programme (ETSAP) from the IEA with contribution from the IER. It is classified in one category with the models MARKAL, EFOM or MESSAGE. The model generator, TIMES, was developed in the general modeling language of GAMS due to reasons of being better transferable. TIMES is a multi-periodic linear optimization model based on a technical approach at which single plants are aggregated. The purpose is the evaluation of the economically optimal energy supply structure at a given need of end use energy and energy services and also at given energy and climate policy requirements. For this, the discounted system costs are minimized, whereas the single players (industry, supply, households) could have different economic considerations. The main objective of the model development of TIMES is the flexible structure to ensure a simple mathematical adjustment to the respective problem [3].

The TIMES Local model [4], [5] is an application of the TIMES model under particular consideration of the requirements of the local energy planning, which is taken into account in the topological structure of the reference energy system (RES). The TIMES Local model concentrates on the heat supply system of the analysed area. The objective function of the model is minimization of the total discounted costs over the time horizon from 2010 to 2050. Each model year is divided into 576 time slices in order to be able to display a high resolution for the solar load curve as well as the demand curve.

In order to achieve a high spatial resolution the analysed are has been divided into so called regions. In the TIMES Local model an aggregation for each of those regions is carried out. Each region possesses its own set of technology definitions to represent the supply of the region. The technology definition includes different building sizes as well as corresponding heat generation and heat supply technologies. The demand curve is assigned for each region as well according to the given 576 times slices of the TIMES Local model.

To include the spatial position of the model regions is determined by grid-based supply systems. In this case the reference energy system (RES) includes apart from the regions, which represent the space heating demand of the buildings, additional model regions to represent grid-based supply systems like e.g. district heating. Different supply technologies for space heating and domestic hot water are implemented in each demand region. In case of district heating the heat supply is carried out by customer stations which are connected to a district heating grid which is represented by the additional model regions. The possible district heating grid is divided into several parts. For each part there is determined which demand regions can be supplied by this part of the district heating grid as well as the conjunction with are parts of the district heating grid. Each part of the district heating grid is represented as an independent region in TIMES Local. The connection between the different parts of the district heating grid and between the grid and the demand regions are represented by trade processes.

As block heating stations also are considered there is the option to include such decentralized heat generators. The heat produced by those technologies can either be used within the demand region where the decentralized heat generator is locator or can be exported to the part of the district heating grid which is connected to the corresponding demand region. This way the heat generated in a demand region can be supplied to other demand regions in case the district heating grid is available (Fig. 3).

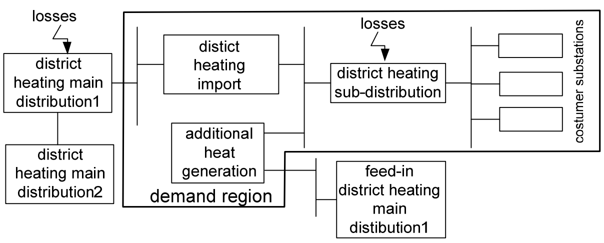

Fig. 3 Part of the reference energy system (RES)

To implement the analyzed neighbourhood Grünbühl into the TIMES Local model the area has been divided into twenty demand regions. Each region was represented in the model. The space heating and domestic hot water demand were determined based on existing supply data (Fig. 2). The spatial connection between the demand regions is carried out by the district heating grid which is divided into 13 parts which are connected to each other and to corresponding demand regions (Fig. 4).

Fig. 4 Possible district heating grid

The available technologies for space heating and domestic hot water in this analysis are natural gas boilers, natural gas block heating stations with an optional feed-in into the district heating grid, district heating customer substations and solar heating. Solar heating can be used either for the domestic hot water supply or as an additional feeder for the district heating grid. For the base-year 2010 a supply based entire on natural gas boilers is assumed.

HEAT SUPPLY DEVELOPMENT

The modelling approach has been used to evaluate the development of the heat supply in the neighbourhood Grünbühl. Based on the determined heat demand for space heating and domestic hot water (Fig. 2) the demand has been defined in TIMES Local. Based on the demand a cost optimal solution has been determined by the model considering the different sub-regions and the grid based supply systems.

In figure 5 the space heating demand and the distribution between the technologies for the neighbourhood from 2010 until 2050 is displayed. Regarding the base-year 2010 the space heating demand of 36 TJ/a is covered entirely by natural gas boilers.

In 2015 the share of natural gas boilers drops to 65% as the district heating grid is erected. The erection of the district heating grid contains all possible traces so all sub-regions are connected to the grid. As there are still natural gas boilers in stock the share of district heating in space heating supply rises until 2030 when the vintage natural gas boilers are substituted. Although a complete supply can't be achieved as natural gas boilers are still used. The space heating supply from natural gas boilers is from 2030 on around 12 TJ/a while district heating contributes 36 TJ/a to the space heating supply.

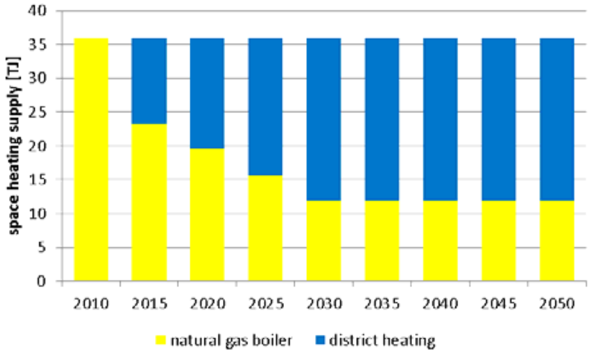

Fig. 5 Space heating supply

Regarding the deomestic hot water supply (fig. 6) similar results as for space heating can be achieved. After the base-year 2010 where all 9 TJ/a of demostic hot water demand are provided by natural gas boilers their share decreases as the district heating grid is erected. In addition to the district heating grid solar heating is installed as well. In 2015 0.6 TJ are supply by solar heating while by 2030 the solar heating supply is doubled and reaches 1.2 TJ/a. Similar to the space heating supply the supply by natural gas boilers decreases as vintage units are replaced by district heating. As district heating doesn't reach a full supply of the analysed neighbourhood natural gas boilers are still in use until 2030 which leads to a domestic hot water supply of 0.8 TJ/a from 2030 on.

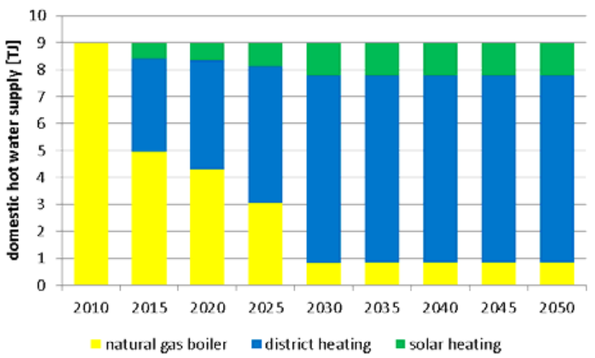

Fig. 6 Domestic hot water supply

The shares of the used technologies for the low temperature heat supply of the analysed neighborhood Grünbühl are shown in figure 7. As already shown in the separate view of the space heating and domeastic hot water supply the initial share of natural gas boilers of 100 % in base-year 2010 decreases as the district heating grid is erected. The share of district heating increases until 2030 when the maximum share of 69 % is reached. Solar heating which is only used for demestiv hot water supply reaches 3 % of the total heat supply whereas the rest is covered by natural gas boilers.

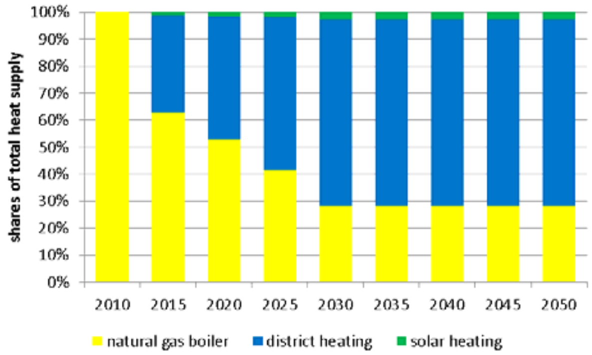

Fig. 7 Shares of total heat supply

CONCLUSON

This analysis shows the application of a model based approach to identify heat supply options. The used modelling approach includes a high spatial resolution to display grid based supply systems as well as different characteristics of sub-regions of the analysed area. This way the heat demand can be disaggregated and supply options can be considered for each sub-region.

The results show that the erection of a district heating grid along with solar heating for domestic hot water leads to a cost optimal solution for the analysed neighbourhood.

The results which are generated by TIMES Local can be used in local planning to evaluate possible heat supply options and to have a model based approach which can be used by local government as well as by energy suppliers.

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DEVELOPMENT OF DISTRICT HEATING SYSTEMS - COGENERATION VERSUS ENERGY EFFICIENCY OF END USER

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Keywords: Cogeneration, District heating, Energy efficiency, Energy end-use

ABSTRACT

Development consumption of district heating systems turns to energy efficiency phase in Baltic States. It means that owners of DH system have to make decision how to operate in conditions with reduced energy consumption year by year.

The experience of energy efficiency measures which consist from demand side management integrated in renovation of buildings shows potential of reduction of thermal energy in building in range of 30 to 60 %.

Paper presents methodology for analysis of DH systems situation in energy efficiency improvement conditions and results of analysis.

The methodology is tested for case study of Riga DH system development in next 10 years. DH system in right bank side of river Daugavas connected with 3 large CHPs (100 – 400 MWe) fuelled by natural gas and different small energy sources. The load of cogeneration plants is decreasing because of reduction of heat consumption of end users. The energy efficiency measures in buildings can cause decrease of energy efficiency of electricity production in cogeneration units.

INTRODUCTION

EU energy efficiency and renewable energy targets are set by the EU Climate and energy package 2020. Each EU country works out national action plans which show activities for reaching both targets and forecasted results. Both targets can be met only if a development of energy sector is viewed as the sustainable development of integral system. Effective use of energy sources in production units is tightly related to end consumption in long term. Sustainable solutions for reduction of fossil fuel consumption in production sources oblige to accurate defining of future tendencies and setting of benchmarks for energy efficiency measures.

Since, energy efficiency measures lead to reduction of energy sources at the production sites reorganization of operation of the production units is required by considering load distribution and choice of renewable energy sources. It is especially critical in cases when heat is delivered to households and service sector from the district heating systems since increase of energy efficiency reduces the heat consumption. Reduction of heat consumption makes existing installed heat capacities excessive and leads to partial load operation with lower efficiency. In case of cogeneration, a reduction of heat consumption leads to shorter periods of operation in the cogeneration-mode, and increases duration of the partial or full condensing mode operation. Decrease of cogeneration-mode operation results in loss of efficiency of a plant.

Several technological solutions of energy generation could be implemented in a district heating system in case of heat load changes during a year. Assessment of integration of different biomass gasification alternatives as well as absorption cooling as a district heating system strategy presents advantages and shortages of improvement energy efficiency of all system together [1], [2].

The aim of the study is to find the optimum solution in cases when heat load in district heating system decreases due to energy efficiency measures and loss of customers who decided to disconnect from the system. The paper shows a method for assessment of alternatives for operation of cogeneration plants in situations when load of the plants diminish. The method is tested on part of district heating system in capital of Latvia – Riga.

MODEL FOR EFFICIENT DISTRICT HEATING SYSTEM DEVELOPMENT

Sustainable development of heat supply system depends on load development. It is important to analyse a situation which results when energy consumers carry out energy efficiency activities and the heat consumption is radically reduced. Building standards minimizing heat losses in the newly constructed buildings make these new buildings as very marginal heat consumer in the heat supply development models. Thus, it is necessary to assess not only an existing situation but to create a hypothesis for development of the heat supply system (see Fig. 1) which accounts for substantial decrease of the heat consumption, i.e. in extent of 40 to 60%.

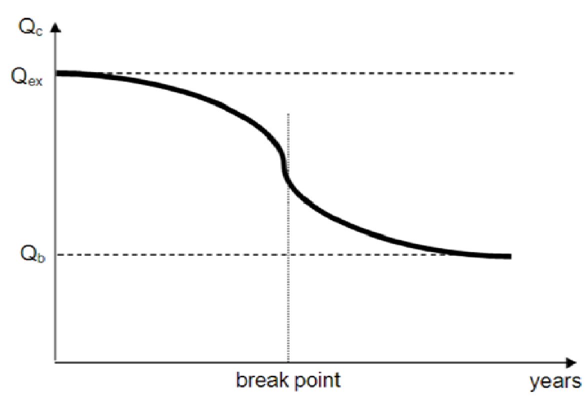

Fig.1 Hypothesis for development of heat consumption over time

In order to construct heat consumption duration curve, the benchmark Q_b, which sets the lowest value of the heat consumption, has to be determined. Human factor introduced delay in realisation of energy efficiency measures determines that the heat consumption is reduced rather slowly up to the break point which marks more intensive period of building improvements. The existing level of consumption Q_{ex}, the value of benchmark Q_b and “break point” period differs in each EU country, region and city. Change of consumption over time may be different as well. The hypothesis for development of heat consumers is important to assess technological solutions for development of heat production sources and to justify these both economically and ecologically.

The model includes characterisation of the existing situation which shows the present energy consumption which depends on ambient air temperature leading to variable load through a year. Assumptions have to be made for forecasting of possible heat consumption in the future, and the forecast for development of heat consumers is included in one of the model blocks. Heat duration curve corresponding to the existing and the forecasted heat consumption is constructed. Heat load in the new situation is covered by mutually competing plants, and operation of these plants is established by three technical parameters, i.e. power-to-heat ratio of cogeneration plants, efficiency and share of renewable energy in the energy balance. All three parameters have to be maximised for the whole year period, i.e.:

$$\alpha \rightarrow \max$$
$$\eta \rightarrow \max$$
$$k \rightarrow \max$$

where

α – power-to-heat ratio;
η – energy efficiency for the whole year;
k – share of renewable energy sources in the balance.

Therefore, an algorithm for forecasts of operation of the existing plants considers adaptation of the plants to the new conditions. The technically possible operation alternatives include time dimension, meaning consideration of the development of the plants. All alternatives which are chosen are justified from economic, environmental and climate change aspect and correspond to the base requirement, i.e. operation in the cogeneration-mode. Operation of the plant in the cogeneration-mode through a year is possible in cases when heat consumption is basically constant. It means that two options with a constant heat load can be identified:

- installed capacity of cogeneration plant corresponds to the load of hot tap water supply;
- heat produced in the cogeneration plant is equal to annual heat demand of the heat supply system.

Algorithm of the model is illustrated in Fig. 2.

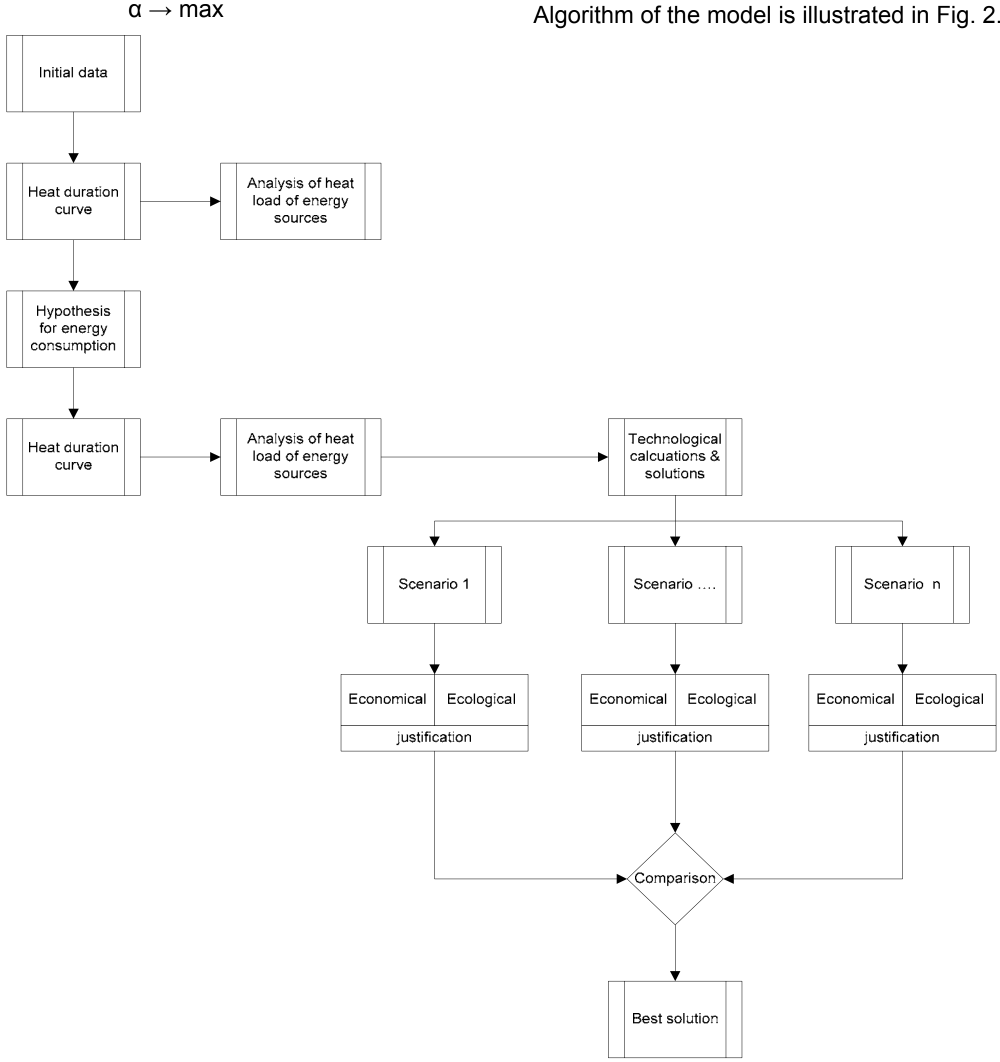

Fig. 2 Algorithm of development model of energy supply plants of district heating system

The last condition can be satisfied if heat storage systems are used which allow even-out heat consumption variation and establishing a stable operation of the cogeneration plant. Surplus heat, produced by the cogeneration plant during periods of low demand can be stored in heat storage system, and the stored heat can be taken from the heat storage to cover required peak loads at periods of the high demand when the capacity of the cogeneration plant is not sufficient.

In both cases, heat capacity of cogeneration plants required by the heat supply system is determined by equation (1):

$$Q = Q_{ann} / \tau, \qquad (1)$$

where

Q – heat capacity of cogeneration plant, MW_{th};
Q_{ann} – heat produced by cogeneration plant operating in cogeneration-mode during a year, MWh_{th}/year
τ – hours of operation per year.

Electrical capacity of cogeneration plant is determined by using power-to-heat ratio from the equation (2):

$$\alpha = N/Q, \qquad (2)$$

where

α – power-to-heat ration of cogeneration plant (depends on technology);
N – electrical capacity of cogeneration plant, MW_e.

MODEL TESTING. RIGA CITY RIGHT BANK DH SYSTEM

Existing situation

Riga city right bank DH system for meeting the district heating supply needs is connected to three main energy sources fuelled by natural gas:

- cogeneration plant RTEC-1;
- cogeneration plant RTEC-2 which consists of:
  - o old cogeneration block RTEC-2/0;
  - o first cogeneration unit RTEC-2/1;
  - o second cogeneration unit RTEC-2/2;
- cogeneration plant “Juglasjauda”.

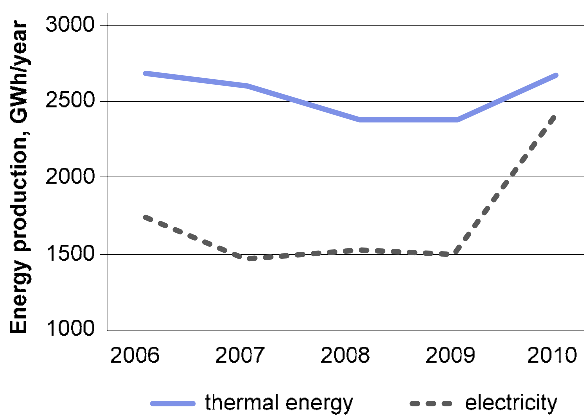

Fig. 3 Heat and electricity generation in Riga’s cogeneration plants (TECs) [3], [4]

Data from the utility “Latvenergo” [3], [4] indicates that the heat generated by Riga’s combined heat and power stations (TEC-1 and TEC-2) in the time period from 2006 and 2010 was in the range of 2400 - 2600 GWh/year which changes in accordance with the climate conditions (see Fig. 3).

The Riga TEC 1 was reconstructed in 2005. The power station has two gas turbines, one steam turbine and two water boilers. The installed electrical capacity is 144 MWe, but the cogeneration thermal capacity is 150 MWth and the total thermal capacity is 377 MWth. In 2010 a new water boiler was installed with a heating capacity of 116 MWth.

The Riga TEC 2 is currently comprised of two parts: the old (Riga TEC-2/0) and new block (Riga -TEC2/1) which have installed capacities of 662 MWe and 1347 MWth. The station is powered by 3 energy steam boilers, two steam turbines and one combined cycle gas turbine block. The installed electrical capacity of the new block is 407 MWe, the heat capacity– 264 MWth.

Both power stations use only fossil fuels: natural gas as the basic fuel, and heavy fuel oil (RTEC-2/0 and RTEC-2/1) and diesel (RTEC-1) as the reserve fuels. The data of the thermal energy and electricity generated at the Riga TEC1 and Riga TEC2 (Riga TEC2/1) in period 2006 - 2010 are summarised in Figure 4. The volume of electricity generated at Riga TEC-2 has increased significantly in 2010 due to addition of gas turbine combined cycle unit.

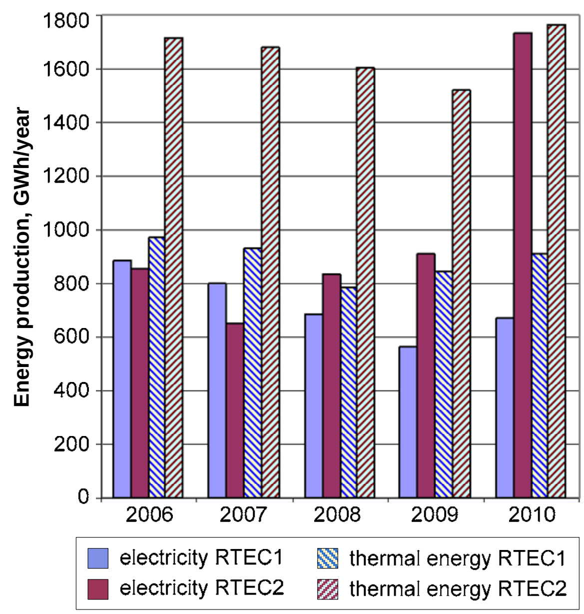

Fig.4 Thermal energy and electricity generation at Riga TEC1 and Riga TEC2

An analytical example of the considered Riga TECs operational efficiency can be derived by calculating heat demand coverage by the plants. The Riga TEC 1 does not operate at full capacity and part of heat demand is covered by heat-only boilers since operation in cogeneration regime would generate the following amount of thermal energy:

$$Q_{cp} = Q_{hw} * \tau + (Q_{chp} - Q_{hw}) * \tau_1 \text{ ,GWh/year} \qquad (3)$$

where

Q_{cp} – thermal energy which can be covered with the existing equipment, GWh/year

Q_{chp} – installed heat capacity for cogeneration plant, MW
Q_{hw} – hot water load and DH heat loss capacity, MW
τ – operational length of the hot water system, h/year
τ_1 – length of the heating season, h/year

Potential of heat energy generation of RTEC-1 share 40% of total energy consumed by Riga city right bank DH system.

Q_{cp} = 100 *8700 + 50*5000 = 1120 GWh/year

As this operational efficiency analysis example for the Riga TEC shows, it is possible to reach a production volume in the cogeneration regimes of 1120 GWh/year instead of 909 GWh/year (see Figure 4). It is important to note that 909 GWh/year is generated by using also the water heating boilers which mean that, with the most optimistic estimate; the share of cogeneration production is only 60 – 70%.

The operational aspects of the heat supply system of the right bank of the Riga city and the loads of Riga's TEC1 and TEC2 were analysed [5]. In order to achieve the efficient use of the capacity of heat supply and flexible regulation, the central heating supply systems of large cities are usually planned by envisaging the use of highly effective cogeneration stations for the base-load regime, and to use them at their maximum capacity for as long a period as possible. However, for operations at the peak regime and close to that, large cities usually use water heating boiler units that are either installed in the cogeneration station itself or are distributed along the perimeter of the heat network in order to increase the security of the system (see the thermal load coverage planning for Riga's DH supply system at Riga's TEC-1 and TEC-2 in the heat supply zone in Fig. 5).

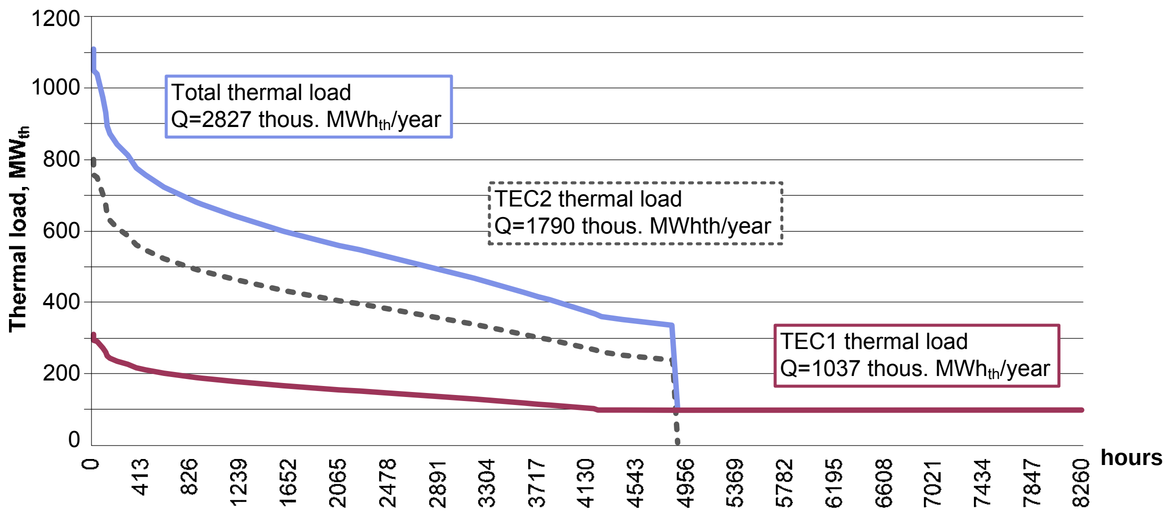

Fig.5 Heat duration curve in Riga's TEC-1 andTEC-2 supply zone [5]

The heat consumption of the DH system of the right bank of the city of Riga currently is covered by the Riga TEC 1 and Riga TEC 2 first unit (RTEC-2/1).

The cogeneration equipment of the Riga TEC 2 old block (RTEC-2/0) at partial cogeneration regime (more at the condensation regime with a lower efficiency rate) could operate at less than 3000 h/year to cover peak loads. Such an inefficient approach is not practised by any power station since water boilers are installed for the purpose of covering maximum loads.

Table 1.Heat base-load and demand

Parameter	Symbol	Dimensions	Values
Total thermal load	Q	MW_{th}	500
Hot water load	Q_{hw}	MW_{th}	100
Total thermal energy consumption	Q_c	GWh_{th}/year	2827
Heating season heat demand	$Q_{g\_hseason}$	GWh_{th}/year	2447
Summer heat demand	Q_{summer}	GWh_{th}/year	380

Development of energy efficiency in energy end user side. Results

The two EU energy efficiency directives show a clear need to reduce energy consumption [6], [7]. Latvia's thermal energy consumption estimates that the current specific energy consumption rate of 150 - 250 kWh/m^{2}year is high and will decrease in the near future. Furthermore, energy efficiency projects conducted on buildings indicated that it is possible to reach thermal energy consumption of 70 – 80 kWh/m^{2}year. The rate of thermal energy consumption of the Riga DH supply system will decrease considerable because currently energy efficiency measures have been introduced in only 21 apartment buildings in Riga, which is less than 1% of the total number of apartment buildings in the city. Thus, the consumption of thermal energy in the current buildings in the next 5- 10 years may decrease by 20 – 50%.

The consumption of thermal energy in the Riga DH supply systems could increase by the newly connected buildings. However, the increase in this proportion over the next 10-20 years will not compensate for the decrease in energy consumption which will be gained through the introduction of energy efficiency measures. This can be assumed due to the fact that, in accordance with the requirements of EU directives, new buildings must conform to low energy consumption buildings and their owners are increasingly often choosing independent energy sources [7].

Alternative solutions of energy generation

At least five to six alternative solutions of operation of energy efficient cogeneration plant in Riga city exist today. Some of them are analysed below.

Sustainable development of heat load for Riga city right bank district heating system can be hypothetically characterised by three scenarios:

- The existing natural gas-fired cogeneration plants operating 3000 hours per year each. During the remaining time of the year the plants are kept idle or operate in condensing-mode.
- Only one of the natural gas-fired cogeneration plants operates during a whole year in cogeneration-mode (RTEC-2/1) by using heat storage facilities. The other plants are kept idle or operate in condensing-mode.
- Fuel switch from the fossil fuel to the wood fuel is made in one of the natural gas-fired cogeneration plants in order to operate during a whole year in cogeneration-mode by using heat storage facilities. The other natural gas-fired plants are kept idle or operate in condensing-mode.

Scenario 1. Continue to operate in regime when each plant operates for 3000 hours a year

The thermal load for the Riga TEC-1 cogeneration equipment is planned at 100 MWth throughout the year. The installed cogeneration heat capacity is 150 MWth which means that with the heat capacity of 50 MWth it would be possible to cover the heating load of 3000 to 3500 h/year, which further indicates that thus the cogeneration capacity would be used at its maximum and would operate effectively.

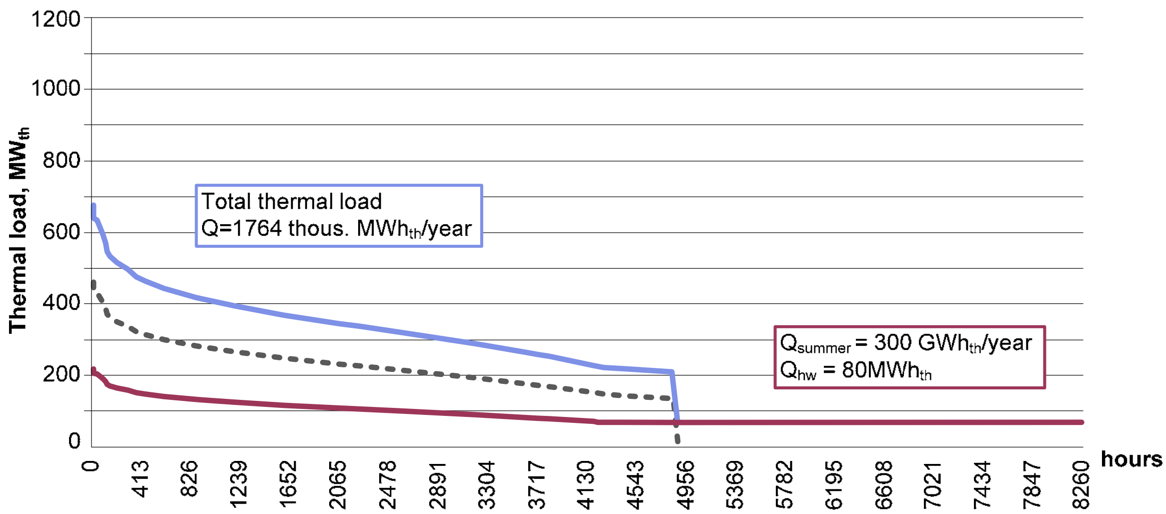

Fig. 6 Heat duration curve after energy efficiency measures in energy end user

The cogeneration equipment of the Riga TEC-2 old block (RTEC-2/0) at partial cogeneration regime (more at the condensation regime with a lower efficiency rate) could operate at less than 3000 h/year to cover peak loads. Such an inefficient approach is not practised by any power station since water boilers are installed for the purpose of covering maximum loads.

The cogeneration equipment of the Riga TEC 2 new second phase (RTEC-2/2) at partial cogeneration regime (more at the condensation regime with a lower efficiency rate) could operate at less than 3000 h/year to cover peak loads instead of boilers. Such an inefficient approach is not practised by any power station since water boilers, which operate at an efficiency rate of 93-95%, are installed for the purpose of covering maximum loads.

Table 2. Heat load and thermal energy demand. Scenario 1

Parameter	**Symbol**	**Dimensions**	**Values**
Total thermal load which could be provided by cogeneration	Q	MW_{th}	300
Hot water load	Q_{hw}	MW_{th}	80
Total thermal energy consumption	Q_c	GWh_{th}/year	1764
Heating season heat demand	$Q_{c\_hseason}$	GWh_{th}/year	1464
Summer heat demand	Q_{summer}	GWh_{th}/year	300

Scenario 2. Heat load is covered by Riga TEC2/1 by using heat storage systems

The installed thermal capacity of 264 MWth of the first unit the Riga TEC 2 (RTEC-2/1) is sufficient to cover the heating consumption and it could operate effectively at 5000 h/year.

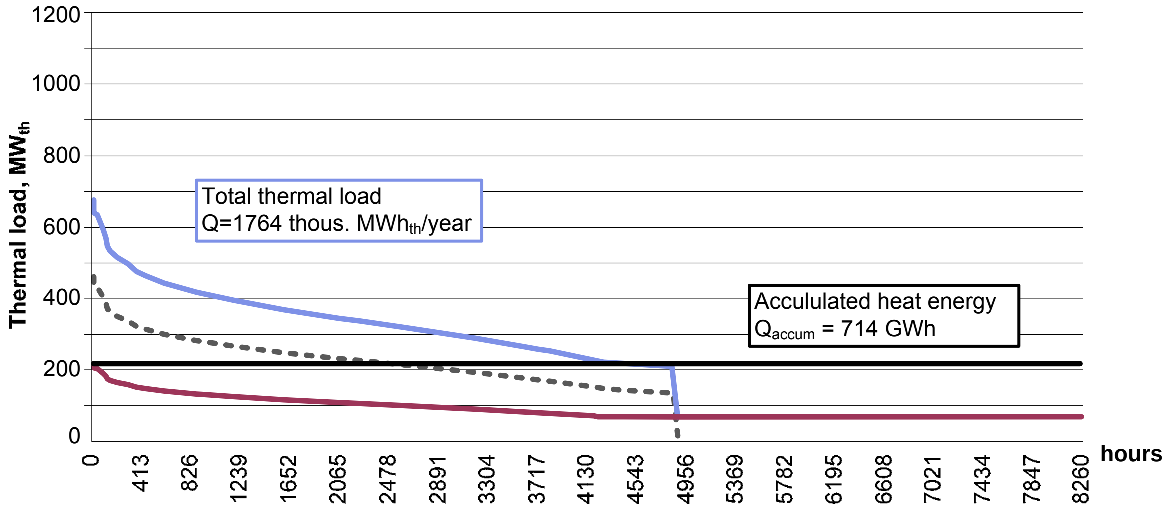

Fig. 7 Heat duration curve after energy efficiency measures are implemented in energy end-user side

Some equations and assumptions for calculation modelling of heat load and demand for thermal energy generation, consumption and accumulation for cogeneration plant work in cogeneration regime are presented below.

Heat load of cogeneration plant:

$Q = Q_c / \tau$, MW_{th} (4)

Heat energy used by consumer in summer season:

$Q_{summer} = Q_{hw} * (\tau - \tau_1)$, GWh_{th}/year (5)

Heat energy used by consumer in heating season:

$Q_{c\_hseason} = Q_c - Q_{summer}$, GWh_{th}/year (6)

Heat energy produced during heating season:

$Q_{g\_hseason} = Q * \tau_1$, GWh_{th}/year (7)

Heat energy accumulation:

$Q_{accum} = Q_c - Q_{g\_hseason} - Q_{summer} - Q_b$, GWh_{th}/year (8)

where
Q_b – heat produced by natural gas-fired boilers, GWh_{th}/year.

Results of heat loads and thermal energy demand are presented in Table 3.

Table 3. Heat load and thermal energy demand for the Scenario 2

Parameter	Symbol	Dimensions	Values
Total thermal load which could be provided by cogeneration	Q	MW_{th}	210
Hot water load	Q_{hw}	MW_{th}	80
Total thermal energy consumption	Q_c	GWh_{th}/year	1764
Heating season heat demand	$Q_{c\_hseason}$	GWh_{th}/year	1464
Summer heat demand	Q_{summer}	GWh_{th}/year	300
Heat energy produced during heating season	$Q_{g\_hseason}$	GWh_{th}/year	1050
Heat energy accumulation	Q_{accum}	GWh_{th}/year	414

Scenario 3. Natural gas is replaced by wood fuel in Riga TEC 1 and heat storage is installed

The thermal load for the Riga city right bank DH system load is planned to cover by TEC-1 biomass cogeneration equipment. Fuel switch from the fossil fuel to the wood fuel is made in one of the natural gas-fired cogeneration plants in order to operate during a whole year in cogeneration-mode by using heat storage facilities. The other natural gas-fired plants are kept idle or operate in condensing-mode.

Biomass cogeneration plant thermal capacity 200 MW_{th} is planned to operate throughout the year.

Table 4. Heat load and thermal energy demand for the Scenario 3

Parameter	Symbol	Dimensions	Values
Installed heat capacity of cogeneration	Q	MW_{th}	200
Hot water load	Q_{hw}	MW_{th}	80
Total thermal energy consumption	Q_c	GWh_{th}/year	1764
Heating season heat demand	$Q_{c\_hseason}$	GWh_{th}/year	1464
Summer heat demand	Q_{summer}	GWh_{th}/year	300
Heat energy produced during heating season by cogeneration plant	$Q_{g\_hseason}$	GWh_{th}/year	1000
Heat energy produced by natural gas-fired boilers	Q_b	GWh_{th}/year	20
Heat energy accumulation	Q_{accum}	GWh_{th}/year	414

RESULTS AND DISCUSSION

Comparison of Riga city right bank energy sources development of three scenarios in case of substantial reduction of existing heat demand is presented in Figure 8.

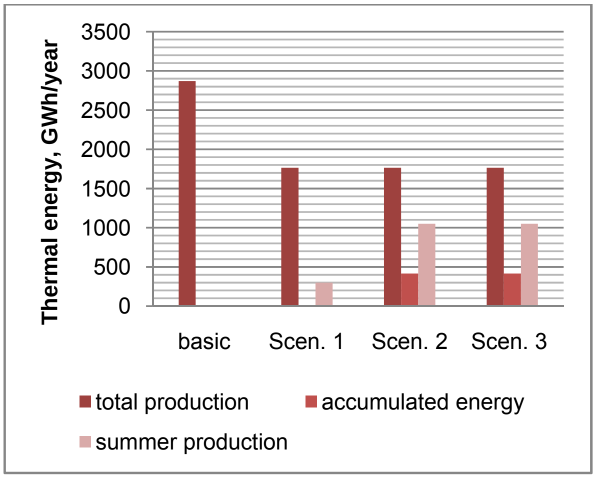

Fig. 8 Thermal energy production and accumulation

Results of analysis of technological solutions show that Scenario 3 allows to use completely installed capacity of cogeneration (see Fig. 8).

Evaluation of the optimum solution requires economic comparison of the scenarios. Results shown in the Table 5 are obtained by using the following assumptions:

- price of natural gas: 25.2 Ls/MWh$_f$;
- price of wood chips: 11 Ls/MWh$_f$;
- heat price: 32.4 Ls/MWh$_t$;
- discount rate: 12%;
- economic lifetime: 25 years.

Table 5. Economic comparison of the scenarios

	Scenarios		
	1	2	3
Heat produced, GWh$_{th}$/year	1764	1764	1764
Electricity produced, GWh$_e$/year	1757	1764	889
Natural gas consumption, GWh$_f$/year	4131	4151	25
Wood fuel consumption, GWh$_f$/year			3093
Fuel costs, MLs/year	104	105	35
Capital costs, MLs/year	76	55	52
Operation and maintenance costs, MLs/year	17	7	9
Total costs, MLs/year	197	167	96
Costs of electricity, Ls/MWh$_e$	80	62	43

An economic comparison is based on costs of produced electricity. The costs of electricity are determined by subtracting revenues of heat sales from the total costs, and then allocating the remaining costs to the produced electricity. Capital costs include recovery of investment made in the considered cogeneration plants, peak boilers and seasonal heat storage systems. The investment costs for the seasonal heat storage systems are estimated using the source [10]. The actual capital costs of the existing plants is not considered in the calculations since the goal of economic comparison is to compare the three possible solutions on equal basis in order to find the solution with the lowest costs of electricity.

The results show that due to investment in single wood-fired cogeneration plant, use of relatively cheap fuel and seasonal heat storage, the scenario 3 has the lowest costs of electricity. Less electricity is produced in the scenario 3 than in other two scenarios since the wood-fired cogeneration plant has lower power-to-heat ratio. If the difference in power production has to be covered by import it does not change the economic ranking of the scenarios since the average electricity price level in Nordpool power market is circa 32 Ls/MWh$_e$ (45 EUR/MWh$_e$).

The results indicate that due to energy efficiency measures the new Riga TEC 2 second unit (RTEC-2/2) may not have sufficient heat load in order to operate in the cogeneration-mode. Another drawback is that the technology uses imported natural gas which increases Latvia's dependence on the import currently provided by a single supplier. Thus, the construction of the second unit of the Riga TEC 2 could be contradictory to EU directives on cogeneration, energy efficiency of buildings, energy services and renewable energy sources, and on their implementation in Latvia [6]-[9]. The solution may be justified from the aspect of power security since it provides an additional capacity which can also be flexibly used in combination with wind farms in the future. However, considering the current price level in Nordic – Baltic electricity market it is doubtful that the plant will be competitive in the market when upon commissioning.

CONCLUSIONS

1. The thermal energy consumption of the Riga right bank heat supply system is such that it is possible to cover demand with the existing, recently reconstructed cogeneration station at Riga TEC 1 and the first unit of TEC 2 (RTEC-2/1). Moreover, the Riga TEC-2 first unit will operate only 3000 – 5000 hours per year. In order to cover peak loads, water boilers are installed.
2. The thermal energy consumption of the Riga heat supply system will decrease because of the expected energy efficiency measures. Currently energy efficiency measures have been introduced in 21 apartment buildings only, which constitute less than 1% of the total number of the apartment buildings in the city. Thus, the consumption of thermal energy in the existing buildings most likely will decrease by 20 – 30%.
3. The thermal energy demand of the Riga heat supply system due to the newly constructed apartments could increase, however the increase over the next 10-20 year period will not offset the reduction in consumption which will be gained through the introduction of energy efficiency measures. This is due to the fact that, in accordance with the requirements of EU directives, new buildings must conform to that of the low energy consumption buildings and the building owners are choosing individual energy sources more and more.
4. The new Riga TEC 2 second unit (RTEC-2/2) equipment may not be operated in an effective cogeneration regime because the thermal energy consumption of the right bank of the city is fully covered by the equipment of Riga TEC 1 and Riga

TEC 2 first unit (RTEC-2/1). If the equipment of the second unit of Riga TEC 2 is connected to the heat supply system of Riga, then at that same time it would be necessary to close the operation of the equipment at Riga TEC 1 or Riga TEC 2 first unit. Otherwise, to operate Riga TEC 2 second unit equipment in cogeneration mode for 3000 hours a year would require operation of the equipment of Riga TEC 1 or Riga TEC 2 first unit in the condensation mode.

5. An economic comparison of the three scenarios indicates that the lowest costs of electricity may be obtained if wood-fired cogeneration plant in combination with seasonal heat storage system is installed instead of the gas-fired gas turbine combined cycle cogeneration plants.

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TOWARDS SMARTER DISTRICT HEATING AND COOLING NETWORKS

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Keywords: District heating and cooling, optimization tools, thermal energy storage, DHC model, speed pumps control, temperature supply optimization, load prediction

ABSTRACT

Districts heating and cooling are the best way to supply consumers (city, building, industry…) with an environmentally friendly energy.

This centralized system allows mixing different sources of energy: renewable, waste and fossil, to increase share of renewable energy, and consequently, to decrease quantity of CO_2 per kWh of consumed energy, to reach last environmental rules.

District network is a solid solution identified to answer environmental challenges, but this old technology has to be optimized to make it more and more efficient.

Actually, DHC could be improved to decrease thermal losses, which is the most important disadvantage of the system.

Methods to operate a district network and consequently one or some thermal power plants, could be also changed or improved to reduce consumption of fuel and produce only energy needed by consumers.

This paper describes research done by Veolia Environment Research and Innovation (VERI) to identify solutions allowing optimization of DHC and increasing efficiency of this system.

Different tools or technologies have been or are currently being tested by VERI. The results show that some new solutions dedicated to DHC are necessary to have a better knowledge of networks; they help operators conduct their installation with more flexibility and minimal waste.

INTRODUCTION

VERI, Veolia Environment Research and Innovation, is the research centre of Veolia. The energy research department of VERI would investigate, evaluate and develop innovations to meet Dalkia's (Veolia's energy services division) operational requirements. Energy distribution on urban networks can be improved by using advanced operation tools.

Dalkia operates more than 700 district heating and cooling networks all over the world. These centralised systems are the responses for energy and environmental challenges of today and tomorrow. Indeed, they could play a major role for European countries to meet their environmental objectives for the reduction of greenhouse gases emissions, because DHC is the technology which produces the smallest emissions, and they enable a diversity of energy options, fuel flexibility for the operator thus creating also a market advantage of those systems over more conventional decentralised solutions.

Dalkia permanently aims to improve the optimization of the energy distribution, according to previous objectives, but also has to manage multi-renewable energy sources in DHC. This new energy diversity generates a more and more complex DHC configuration. To overcome these challenges, operators, who work to ensure the continuity of the service provided to clients, need to have adapted tools, to help them in the thermal power plant management, to reach and maintain a certain level of environmental, energy and economic efficiency.

Different solutions to optimize DHC were identified and/or tested by VERI. Two types of technologies could be distinguished: Hard solutions and soft solutions (last ones could be physical or statistic tools).

VERI is testing some of these tools in Dalkia Power plants. The aim of this research is to measure the gain generated by the innovation in DHN operated by Dalkia.

More precisely, solutions tested by VERI are:
- Thermal energy storage (TES);
- Variable speed pumps control;
- Real time DHC model;
- Supply temperature optimization;
- Load prediction.

THERMAL ENERGY STORAGE

Storage allows distinguishing consumption and production. The operator does not have to match energy production with consumption at all times, he can make use of TES to produce energy according to thermal power plant constraints and environmental objectives.

TES could also increase the renewable energy share and optimize energy production. Indeed, to increase share of renewable energy, it is necessary to use source of this type of energy at 100% of its capacity. But of course, it is not always possible, because production is function of consumption, which is not constant. That is why, most of the time, renewable energy are used under their maximum capacity. Whereas, when there is a peak load, these sources are not enough, and it is necessary to start a peak load boiler. TES allows storing excess renewable energy to use it later, when network consumption increases.

Thus, TES is essential in association with:
- An intermittent energy (for example solar energy).
- A renewable energy (for example: biomass, biogas…);
- A CHP ;
- A thermal energy production which needs electrical power (boilers, chillers, heat pumps…).

This combination could help to delete or reduce power peak load on production units, thus avoiding also starting units with a high Carbon content and high operational costs.

A study on TES of 8m^3, connects, in parallel, with one biomass and two gas boilers, has been done to obtain a technical and economical feedback on this equipment. The aim was to identify the interests and the energetic mix of the system, to analyse intrinsic performances of tank and calculate economic and environmental gains. For that, measurements of production units and storage tank were recorded during one heating season. The results are:

TES efficiency, defined as the amount of energy delivered to the DHC over the amount of energy stored in a tank, is 88% on average during the heating season.

12 %, i.e. 16.6 MWh per month, of consumed wood is promoted by thermal storage on average during the heating season. This system allowed reducing gas consumption by 22 %, i.e. 75.4 MWh on the same period. Consequently, 17.6 ton of CO_2 were avoided.

Stratification on the tank (figure 1) is very well set, and the thermocline is 40 cm on average (figure 2), which is a good value in comparison with height and volume of the tank.

The first figure below shows stratification during a de-storage cycle whereas the second figure describes the thermocline in the tank.

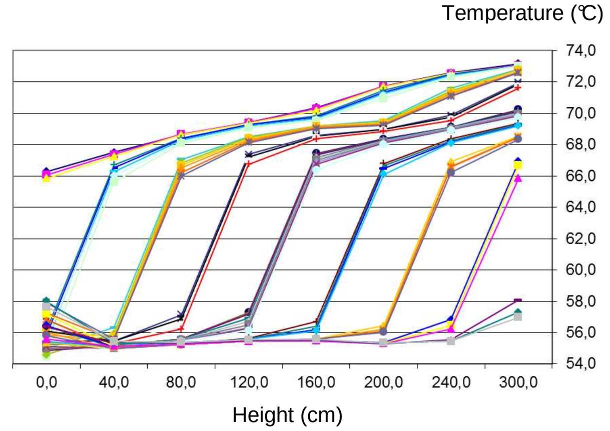

Fig. 1 Stratification in a TES

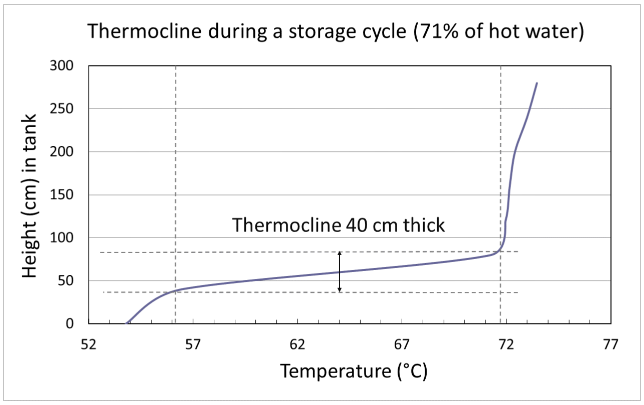

Fig. 2 Thermocline in a TES

This feedback shows that the thermal storage is a relevant solution to an economic production and utilization of renewable energy.

VARIABLE SPEED PUMPS CONTROL

Most of the time, district heating and cooling networks run at variable volumetric flows, even if pumps work with constant speed engines. According pump's characteristic, when volumetric flow decreases (Q), at same speed (N), the manometric height (ΔP) increases. To optimize the energy distribution and to decrease electric consumption of pumps, which is proportional with manometric height (ΔP), it is possible to add dimmers on pumps' engines. This system allows decreasing speed of pumps to match "real" needs of the network. Pump functioning point is consequently optimized.

In more detail (figure 3), red curves intersection represents DHN functioning point for one pump speed N1. At this point, manometric height created by pump is ΔP1. For the same heat load (the same flow Q), if speed of pump decreases to a N2 value, the pump's manometric height becomes ΔP2, which is lower than ΔP1. It is consequently possible to save up, because pump electrical consumption decreases.

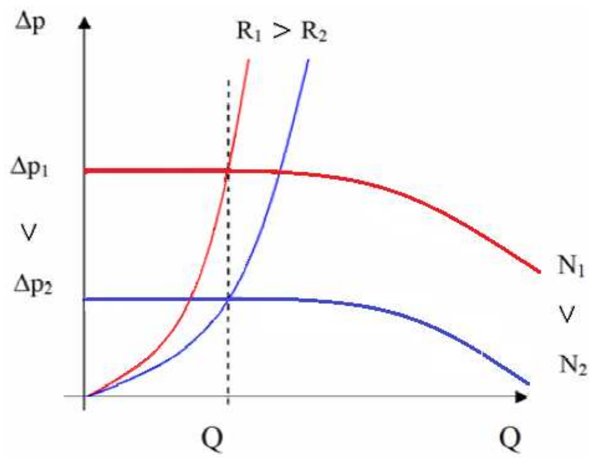

Fig. 3 Speed pump decrease

Theoretically, advantages of this solution are:
- Important saving on electric energy consumption;

- Low investment and short payback return time on it.

Only known inconvenient is the level of equipment in sub-station. It is necessary to install (or to already have) two ways valves position indicator or differential pressure sensors in sub-stations,

A study was done by Dalkia and VERI, on a pilot site, to obtain a technical and economic feedback on system of variable speed pump, implemented in DHC. Results were encouraging, because a significant decrease of the electric consumption of pumps has been noticed compared to the former control law. Saving is estimated between 20% to 40% on pumps electricity consumption.

REAL TIME DHC MODEL

Real time DHC model enables Dalkia to obtain and gather some information about the DHC, without any sensors in it. This type of tool could be extremely relevant for operators, knowing that the optimization of the supply chain can be made even more difficult to do as a result of very long heat distribution times.

A solution to do real time modelling of DHN was identified by Veolia; it is Termis Operation developed by 7 Technologies. This technology lies on two parameters: pressure and temperature, and can improve energy distribution performances. This software is a revolution which could allow different functions to operators:

First, it helps operators to know the correct state of the DHN. It helps also to have a better understanding of the energy distribution.

Moreover, it permits to identify critical points, to optimize the production and distribution process. This solution enables also operators to analyze and anticipate the network's behavior.

To finish, it is also possible to work off line, on DHC data to analyze past events, thus enabling to establish better operation methods, for later.

Termis Operation is tested by Dalkia to evaluate the benefits on a thermal power plant, more particularly as regards to operators and their acceptance of this new software.

SUPPLY TEMPERATURE OPTIMIZATION

To optimize DHC it is also possible to optimize supply temperature; i.e. adapt supply temperature in function of district heating consumption. Indeed, a supply temperature too high could generate very important thermal losses which represent a lot of money. A supply temperature not well set up is the most penalizing parameter to keep an efficient DHC. This method of optimization consists to find the best combination between temperature and flow, to decrease enough thermal losses, without too much increase pressure drop.

French literature values thermal losses decrease at 16% using optimization [2]. Termis operation, with Temperature Optimization option (figure 4), allows Dalkia to obtain a supply temperature controller tool, in order to lower thermal losses and avoid super-heating this network. VERI is, at the moment, testing this solution in a pilot DHC, to evaluate saving and impact on thermal power plant efficiency.

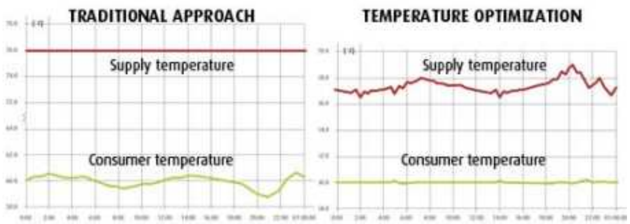

Fig. 4 Optimization of supply temperature [1]

LOAD PREDICTION

Another useful solution to optimize a DHC is a load prediction software. Most of the time, it is a statistic tool, used to forecast consumption on the DHC. This system estimates what will be the consumption on the network, using weather forecast. Consequently, it allows operators to know what will be the future production at the thermal power plant.

Combined with the other optimization solutions (storage, real time model, supply temperature optimization…) this last tool could turn a classic DHC into a smart system. Knowing the future demand allows a better management of fuel stores, easier maintenance and better start and stop of production units. Load prediction is also necessary to optimize supply temperature.

VERI is currently testing load prediction tools to evaluate new performances on DHN operated with this type of technology. VERI has not obtained any results yet, but it seems as if this solution becomes more and more necessary for operators.

CONCLUSION

Today, there are numerous possibilities to improve DHC efficiency. The main objective is to decrease thermal losses which are the most penalizing effect due to district network. To do so, it is possible to use an optimization supply temperature tool, in association with a real time model (like Termis) and a load prediction statistic tool. This combination could help operator to have a better understanding and overview of their district network, thus avoiding a too high supply temperature.

Besides temperature optimization, it is also possible to adapt pumps speed in function of consumption to decrease electric energy consumption.

To finish, thermal energy storage allows increasing renewable energy share in the mix energy of a DHC, and helps operators to produce in function of production units constraints and not consumption.

VERI is testing or has tested all these tools or technologies to select optimal solutions. These innovating systems will help Dalkia to face environmental challenges of tomorrow. Dalkia and VERI are currently reinforcing their works on these topics by setting up a dedicated research team in Warsaw (where the largest urban district heating system of the EU is operated by Dalkia), who will thus join the existing Veolia R&D network.

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SMART CITIES: CHALLENGES AND OPPORTUNITIES FOR THERMAL NETWORKS

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Keywords: Smart City; smart district heating and cooling networks; adaptive; intelligent; integrated; efficient; effective; attractive; structures; concepts; technologies; processes

ABSTRACT

To achieve climate mitigation and energy supply security targets, urban energy systems will need to substantially increase their energy efficiency and handle an increasing fraction of renewable energy resources. Within a Smart City, a holistic approach is applied to achieve these targets, considering all aspects that are relevant for energy conversion, distribution, storage and end-use.

After a brief introduction of the Smart Cities concept based on six main properties (adaptive, intelligent, integrated, efficient, effective and attractive), the respective implications for thermal networks are presented and the challenges and opportunities to enable the transition into a future-proof energy system are discussed.

1. INTRODUCTION

The Smart City approach considers urban energy systems from the point of view of the whole energy transformation chain (demand, supply, distribution and storage) and the interactions with urban planning, mobility, water, waste, the quality of life of its citizens and socio-economic conditions. The necessary changes in the urban energy system will be enabled by the development of new structures/ concepts (e.g. integrated planning and design approaches, efficiency measures), the diffusion of specific technologies (e.g. building integrated renewable energy technologies, storage technologies, ICT) and new processes (e.g. policy and planning processes).

Since almost half of the final energy use in Europe is related to heating services [1], and the construction and expansion of district heating networks is a crucial prerequisite for the large scale utilisation of renewables, such as geothermal and solar thermal energy [2], thermal networks are an important part of the urban energy system and therefore have to be included as key technology into the Smart City concept.

2. Properties of Smart Cities and their implications for thermal networks

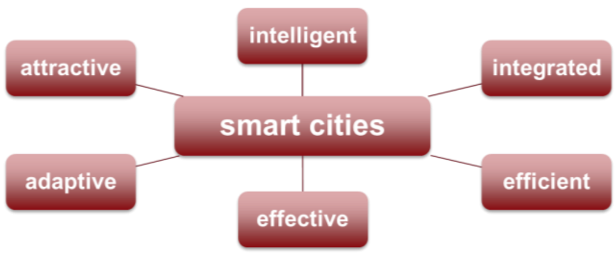

Fig. 1 properties of smart cities [3]

Based on a broad review of actual definitions for smart cities, international projects in this field and a stakeholder consultation process, Saringer et al. [3] have proposed a set of six properties that characterise smart cities, see Fig. 1.

When targeting sustainable urban development, this set of properties has concrete structural/ conceptual, technological and process implications in all the fields contributing to urban sustainability. The main strategic implications in the particular technological field of thermal urban networks are discussed in the following, pointing out the challenges thermal urban networks will be confronted to in the next decade.

2.1 Smart Cities are adaptive

> *Systems adapt themselves to new framework conditions and keep their functionalities while considering new situations [3].*

Implications for thermal networks:

In principle, thermal networks can adapt very fast (*short-term*) to the energy supply and demand situation, as they can be considered as “neutral” to the energy sink and source - when considering appropriate feed-in conditions. For the adaptation to fast fluctuating demands and resources, storages (central and distributed tanks), demand-side management (DSM) and peak-load boilers have to be integrated and managed. Therefore, advanced ICT technologies might be introduced (e.g. smart heat meters) and the hydraulic components (mainly the valves) have to be designed in a way that they can support accurate control of the operation of plants and buildings.

The main *long-term* framework conditions for thermal networks within a Smart City include: 1. decreasing heat demand of buildings due to high building standards and increasing retrofitting rates, but also an increasing need of comfort including cooling, 2. increasing fossil fuels costs, together with an increasing fraction of fluctuating renewables distributed into the network and 3. the trend for liberalised energy markets. In general, adaptations of the thermal networks topologies are relatively limited since the investments costs are high. Related *long-term* adaptations consist in adjusting the network development with urban planning processes and performing the right investments for infrastructure at the right time.

Medium-term adaptation of the temperature level in existing networks might be necessary to increase the potential of renewable energy resources and decrease distribution losses. Further conceivable (medium-term) adaptations could include the cost effective installation of new distributed micro-networks connecting a few buildings to reach a local optimum using cost effective installation techniques and materials. This could include new developments but also existing buildings and combinations of both.

2.2 Smart Cities are intelligent

Innovative approaches are developed. New information and communication technologies are used [3].

Implications for thermal networks:

First, thermal networks need to be intelligently planned or adapted. Going beyond an accurate application of planning and design standards for thermal urban networks, the challenge is to consider both the implications of long-term development scenarios and the multiple possibilities to design a network that best feat into the urban structure it deserves (optimal network topology and typology, optimal operation parameters), considering all technical possibilities that might not be foreseen in design standards. The different technological possibilities available are described in detail in the part “smart cities are integrated”.

Second, thermal urban networks need to be operated intelligently. This involves first the real-time knowledge of the operational state of each part of the network (metering) and then the possibility to modify this state (control). The practice shows that even though operation data is nearly always centrally collected (at least for the generation plants, not as frequently for all substations), it is primarily used for safety control and for ensuring that the plant operates at the conditions it has been designed for. When it comes to remote control possibilities, experience shows that few district heating systems have this feature implemented at substation level and that the possibilities to control plant operation parameters and schedules are sometimes rather limited. This issue will become crucial when considering an increased number of distributed heating and storage sources and the related necessity to integrate the different control systems (plant, network, storage, substations).

Third, the smart metering issue is not only relevant for the utility operating the thermal urban network, but also for the end-users who can access, visualise and interpret their own heating energy consumption data thanks to dedicated information software and hardware. The functionalities of such applications should not be limited to a simple visualisation of energy consumption trends, but enable the end-user to interact with the heating and cooling system, e.g. to modify set-point temperatures and heating schedules.

Last, the possible connection of new loads to a district heating network, e.g. white goods as like dishwashers within buildings is part of an intelligent thermal urban network concept.

2.3 Smart Cities are integrated

Synergies are generated through intelligent system integration and cross-links between thematic fields. Expanding system boundaries enables a better understanding of interactions between thematic fields. Intersectoral aspects are also to be understood on a spatial level (e.g. cooperations between cities and their surroundings) [3].

Implications for thermal networks:

The integration of thermal urban networks can be understood from a spatial and energy system point of view.

1. Integration from a spatial point of view:

As an important part of urban energy infrastructure, the technical-economic feasibility of thermal urban networks is closely related to urban planning parameters and processes, e.g. [4]. An optimal network integration requires not only the definition of priority areas which mainly depend on the heating energy and heating power demand density, but also a process guaranteeing that the network planning and implementation process will relate to other development processes (e.g. construction of buildings) in the areas to be deserved.

In particular, the urban structures (including existing energy infrastructure) and topologies as well as the land-use characteristics (e.g. the spatial distribution of industrial, commercial and residential sites) might orientate the planning decisions towards the development of micro networks, city-wide networks or even regional heat transport networks (as demonstrated in [5], [6]).

2. Integration from an energy system point of view

Thermal networks have to be considered as an integrated part of the entire (urban and international) energy system. As such, all interfaces between the network itself and the remaining parts of the energy system have to be considered and constraints have to be defined in order to optimise the network planning and operation. The main objectives for this optimisation consist in minimizing exergy losses and the emissions associated to energy supply.

The energy integration methodology provides the theoretical thermodynamic background for performing the optimisation. Applied at a city scale (e.g. following the example of [7], the methodology allows for characterising the infrastructure requirements (additional energy conversion and storage capacities, type, location and design parameters of energy conversion technologies etc.) based on a characterisation of heating and cooling demand and supply capacities in terms of temperature and power.

In particular, applying this methodology on a large scale provides a decision basis for selecting the most appropriate site and size for heat pumps, combined heat and power plants (both technologies being at the interface between electrical and thermal networks) and thermal networks. The same methodology can be applied to select the optimum heat distribution temperatures while considering temperature requirements on the building side and the supply side (including waste heat from industry).

The result is a complete integration of demand and supply, leading to optimal network topologies and typologies developed together with energy concepts (e.g. 3-pipes systems, low temperature networks for combined heating and cooling, CO_2 networks…).

Fig. 2 shows an example for an optimised interface between the thermal and the electricity network for the integration of fluctuating renewable energy resources.

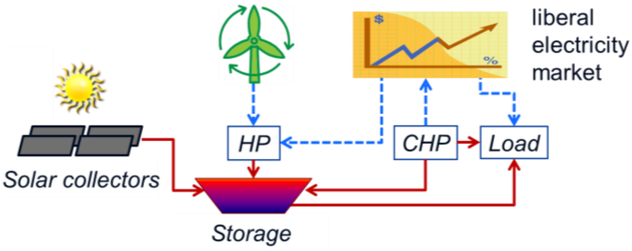

Fig. 2 interface to electricity system: integration of renewables [8] (modified)

Depending on the market price for electricity, either the heat pump (low price) or the CHP plant (high price) operates. The generated heat energy is then either delivered to the consumers (winter) or stored in the seasonal heat storage (summer). Above that, a heat only boiler is used for back up and peak loads and solar thermal collectors are used for additional charging the storage.

A further aspect of integration from an energy system point of view consists in considering the possible *interface between thermal networks and mobility services*:

- A broad diffusion of electric vehicles (including cable cars and subways) will increase the demand for electricity and therefore shift the current equilibrium between electricity and heating energy production from CHP plants. This effect might be accentuated when considering a further diffusion of renewable electricity production capacities.
- Using the battery of electric vehicles for air-conditioning of the cabin or tempering the freight reduces their operating distance significantly. This creates opportunities for using portable and compact thermal storage devices (e.g. [9], [10], [11]) that could be used in combination with thermal networks.
- The expected competition for alternative fuels like biogas and hydrogen produced from excess electricity via electrolyses will further link the production of thermal energy and the provision of mobility services: the alternative fuels can be used either in CHP processes (using the heat in DHC networks and the electricity for electric vehicles) or directly in mobility applications (driving energy).

2.4 Smart Cities are efficient

> *In comparison to non-integrated approaches, significant efficiency improvements and energy demand reduction levels (in particular from fossil energy sources) are to be obtained. A maximum end-use output is to be obtained from a minimal use of resources [3].*

Implications for thermal networks:

The optimised integration of thermal networks within the whole energy system creates a *system flexibility* enabling one to achieve the highest overall efficiency of the energy system, by choosing the optimal combination of technologies. CHP plants that allow a variable ratio between the produced electricity and heat (e.g. CCGT plants) can be operated in combination with heat pumps to allow a „virtual" extension of an existing district heating network [12], see Fig. 3. Here, the overall efficiency depends mainly on the COP of the heat pump and the thermal efficiency of the gas turbine [13].

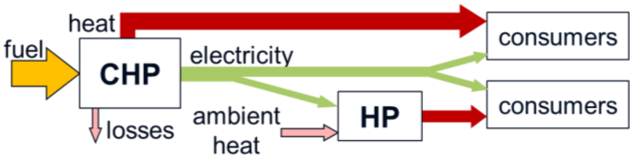

Fig. 3 coupling of CHP processes and heat pumps

Another important measure for increasing the efficient use of the available (renewable) resources is their *cascade usage*, also implying a low exergy approach[1].

This concept consists in adapting the exergy level (the temperatures) in the network to the customers for best usage of the available exergy and in doing so, achieving a maximum exploitation of the available energy resources. Some industrial customers need rather high temperatures (e.g. above 100°C in hospitals). Space heating in traditional residential buildings is generally been ensured by radiation heat transfer from radiators at about 70°C. To gain comfortable room temperatures in buildings with e.g. floor heating or concrete core activation, supply temperatures between 30-50°C are sufficient, e.g. [14], [15], [16]. The energy cascade consists in connecting low temperature applications to the return line of existing networks (as demonstrated in [17] and [18]) and at the same time decreasing the return temperature, see Fig. 4 as an example configuration.

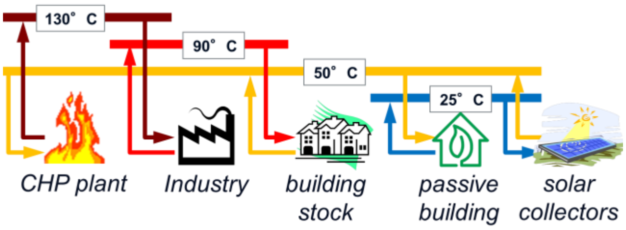

Fig. 4 example for cascade usage in thermal networks

The efficiency of many supply technologies is increased significantly by decreasing the return temperatures, e.g. solar thermal collectors and CHP processes [19]. Moreover, reduced temperatures in the network will decrease system losses and might enable one to use flexible plastic piping with the possibility of a cost effective installation.

2.5 Smart Cities are effective

> *In comparison to non-integrated approaches, significant impacts are to be obtained. The higher effectiveness is to be understood with regard to indicators characterising the future urban and post-fossil society [3].*

[1] Exergy is a measure of the actual potential of a system to do work. Whereas electrical (and mechanical) energy consists of 100% exergy, the exergy of thermal energy depends on its temperature related to a reference system

Implications for thermal networks:

The effectiveness of measures in the thermal network sector is given when a high share of heating energy demand in a city is covered by district heating: measures in this sector have a significant impact on the overall urban energy system efficiency when the broad diffusion of the technology is given, which is already the case in many cities. This is the main advantage of centralised energy generation technologies: any change towards sustainable heat production capacities brings environmental benefits to consumers connected to the urban thermal network.

2.6 Smart Cities are attractive

> *Attractiveness for citizens and investors leads to increased quality of life and secure perspectives for investors [3].*

Implications for thermal networks:

1. Attractiveness for the citizens

In principle, citizens require a comfortable and reliable heat (and cold) supply at affordable costs. Additionally, there is a demand for a renewable as well as self-sufficient energy supply among end-users.

Thermal networks are competing in an open market with other heat sources like oil, gas and heat pumps (depending on availability and legal constraints[2]). Whereas the basic requirements (comfort and reliability) are in general fulfilled, being connected to thermal networks often carries negative connotations such as: being dependent on the respective utility in long-term contracts without the possibility of withdrawing, high connection costs, a non-self-determined level of comfort and a tariff system, that is unfavourable to save energy[3]. To increase the acceptance in the population and the motivation of the customers to connect to the thermal network, following aspects need to be considered:

- Creating possibilities for the customers to control their level of comfort by intelligent control systems (e.g. smart meters)
- Introducing transparent, adaptive and flexible tariff systems, especially considering low income households
- Developing new business models allowing the customers to participate.
- Increasing the share of renewables and improving the image of thermal networks

2. Attractiveness for investors

The investment costs related to the installation and extension of thermal networks, the construction of power plants, the utilisation of waste heat in industries and the connections of buildings to the network are substantial. As a result within a competitive heat market, very long payback periods are expected, that in turn result in a decreasing attractiveness for investors.

From the perspective of the industry, the interest in investing in equipment for harvesting waste heat is often rather low, due to a) high costs of the equipment, b) the need for back-up systems that are often expected to be provided by the respective company, c) relatively low energy prices and d) a focus on product quality.

As thermal networks are and will be an important part of the urban energy infrastructure, possibilities have to be found to foster investments. This could include

- Decrease the cost of network components (especially pipes and substations) and related installation works, e.g. via innovations in the production processes and standardisation
- Increasing the connection rate to thermal networks by increasing the attractiveness for the citizens (see above)
- Creating new business models for the investment into infrastructure, e.g. lowering the interest rates or creating advantages in emission trading
- Channelling the use of public funding for the efficient integration of renewable in DHC networks
- Introduction of new cooperation structures and transparent decision processes in urban planning
- Adjusting the subsidies for all energy sources with respect to the optimisation of the whole energy system (e.g. funding of individual heating systems only outside connection areas of thermal networks)
- Creating attractive business models and legal frameworks for the industry to increase the amount of waste heat fed into thermal networks

3. How to enable the transition of thermal networks: challenges and opportunities

Considering the framework provided by [3], the main topics mentioned in the technology roadmap for district heating and cooling [20] and the implications discussed in part 2 of this article, concrete adaptations of current structures/ concepts, technologies and processes are necessary to enable thermal urban networks to support and drive a smart city development.

Structures/ concepts

a. Low temperature networks, cascade usage of resources, new network types
b. Interface to other networks (CHP and heat pumps)
c. Interface to efficiency measures
d. Energy management

Technologies

a. Energy conversion technologies and storage
b. components (pipes, substations …)
c. Domestic hot water (DHW) preparation
d. Sensors and communication technologies (Smart heat meter)
e. Household appliances with DHC connection (washing machine, dishwasher)

Processes

a. Planning processes
b. Business models
c. Implementation process (phasing, transition steps etc.)

[2] In some cities, it could be forbidden to use polluting heat sources for controlling the air quality in certain areas
[3] Some utilities have high fixed and low variable costs

The following presents a discussion on challenges and opportunities for all necessary adaptations introduced.

3.1 Structures/ concepts

a. Low temperature networks, cascade usage, new network types

Challenges: On the one hand, design activities will have to involve both demand and supply side and consider design improvements on both sides, even if there is no standard planning procedures for this at the moment. On the other hand, the complexity of feasibility studies for cascade usage of resources will be increased due to the number of actors to be involved and the limited data availability.

Beyond these planning difficulties, the interest of industries to deliver waste heat might be limited by their main priorities (quality of the industrial production process, engagements towards clients). The fact that there is no legal framework or business model that would systematically support such project types at the moment will not facilitate the development of such concepts. These issues will have to be handled in the framework of pilot projects.

Opportunities: Most of the single technologies enabling the development of low temperature networks and cascade usage of resources are already available (heat exchangers, pipes, storage technologies etc.). The optimal planning and design of such projects needs to be supported by modelling techniques considering both thermodynamic and economic effects.

b. Interface to other networks (CHP and heat pumps)

Challenges: First, heat pump technologies are often perceived as concurrence technology for district heating utilities, since the development of district heating has been closely related to the diffusion of CHP plants. Concepts integrating heat pumps either as heating plants or as demand-side technologies need to be further developed and implemented. On the other side, the decreasing heating energy demand from a long-term perspective might have an impact on the economics of CHP plants operation. This requires strategic planning activities for heating plant capacities to consider this aspect for the next decades.

A technological challenge is related to the availability and performance of high temperature heat pumps (for domestic hot water preparation or industrial applications).

Opportunities: The trend towards low-temperature networks is supported by the improvement of building energy performance standards, leading to heating energy needs at low temperature. This also should enable the exploitation of unused energy sources, in particular of low temperature waste heat. In this context, large scale heat pumps could be used as centralised heating sources for distributed micro-networks.

c. Interface to efficiency measures

Challenges: The building sector is one of the major energy consumers in cities. For increasing the energy efficiency of the urban energy system it is implicitly necessary to increase the retrofitting rates of the building stoke significantly. The resulting decrease in heat demand leads to an increase of the relative distribution losses in thermal networks and in a decrease of their cost effectiveness[4].

Opportunities: For ensuring an economic feasible development, urban planning needs to identify regions where an effective reduction of CO_2-Emissions due to retrofitting of the buildings is possible. As a result, the priority for retrofitting will be put on buildings with CO_2 intensive heat sources (like oil and gas boilers). After a transition period, new network structures and types (low temperature networks, cascade usage) will enable thermal networks to cost-effectively supply also areas with low heat density with renewable energy resources.

d. Energy management

Challenges: From a technical point of view, as mentioned in part 2., the limitations of current control systems and in particular the hydraulic limitations of old district heating infrastructure (e.g. for control of valves) limit the possibilities of energy management (supply and demand side). From a legal point of view related to demand-side activities, the possibilities related to the measures that can be concretely implemented on the building side might interfere with current contract structures (heat supply guarantee etc.). Heat delivery contracts should be revised to support demand-side management activities.

Opportunities: Progresses made in metering techniques and information technologies could definitely support the further development of real-time energy management strategies (see also section 3.2 d). On the other side, there are a number of "smart" operation concepts for district heating networks that can be implemented with simple control strategies, as the utilisation of the network as storage while considering supply temperature variations [21], [22], [23] and [24].

3.2 Technologies

f. Energy conversion technologies and storage

Challenges: Many district heating systems were installed several decades ago considering different boundary conditions. To handle an increasing share of fluctuating energy production from renewables and increasing energy prices, the systems need to be more flexible and efficient. This includes the implementation of cost effective and high efficient CHP plants (in particular biomass and biogas) with flexible operating schemes and an improved power-to-heat ratio. As the application of cooling networks is expected to increase, more efficient and more flexible cooling generation is needed.

One crucial factor for handling fluctuant resources will be the spread of thermal storages (include storages for cold) within urban energy systems. The systems need to be cost efficient, flexible and integrated into the whole energy system, especially to support electricity networks.

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[4] in some cases the heat demand decreases also due to deurbanization, e.g. some cities in the new federal states of Germany

For handling large amounts of solar energy, seasonal storages will be necessary. Pilot systems are already implemented, but there is a need for reducing the heat losses and increasing the cost effectiveness especially for large scale applications. Also, the awareness for those systems needs to be increased.

The integration of respective components into the urban energy system require more and cost efficient ICT in the networks for an integrated management between the production, storage, distribution and consumption, in this context the application of smart heat meters need to be evaluated (see 3.2. d).

Opportunities: Many technologies are already available in the market or in a test phase at small and medium scale demonstration projects. The full implementation in urban energy systems is an early stage and advanced tools for integrating thermal networks with the urban energy system are under development. The need for updating the infrastructure is recognised by many policy makers and urban planners.

For reducing peak load, in many networks short term storages are used effectively and experience in design, production, integration and operation is gained. This knowledge needs to be exploited further.

Materials with a high storage capacity are still expensive, but are currently development and implemented for different applications.

g. components (pipes, substations …)

Challenges: Within a given DH network, components such as pipes are an integral part and to a great extend not easy replaceable. Improved pipe systems could only be applied in new networks.

Usually new pipes and substations are handicraft made with a low cost efficiency. In general, they are designed for temperatures above 70°C. In order to include as many renewable energy resources as possible and to decrease the thermal losses and in turn increase the efficiency of the energy distribution, the components need to be more flexible in terms of temperatures and changing energy demand situation in short and long term.

The increasing number of (private and industrial) buildings with a surplus of thermal energy from e.g. solar thermal collectors and storage capacities for thermal energy created the need for a bidirectional interaction with the network and appropriate components.

Due to disruptive construction and maintenance works, thermal networks often have a bad image in the population. For adapting faster to new framework conditions, new installation technologies are needed with as little inconvenience as possible for the population.

Opportunities: The tendency for lower network temperatures will enable one to use new materials (e.g. flexible plastic piping) which in turn result in more cost effective installation techniques. New piping layouts are developed and marked available (multi piping systems) that allow to implement new network structures and usages (e.g. cascade usage).

Initiatives for the standardisation of pipes and substations and for the harmonisation of requirements throughout Europe are currently discussed. This could enable manufacturers to improve the production processes and to decrease the construction/ maintenance time.

New possibilities for the non-invasive construction and maintenance of thermal networks, like improving trench-less technology, narrow trenches, etc. are currently under development and will help to reduce the costs and impact of the expansion of networks.

h. Domestic hot water (DHW) preparation

Challenges: Following the trend for low temperature networks, below a certain temperature the risk of legionella propagation occurs when storing DHW[5]. For removing legionella, different options are commercial available, including ultraviolet sterilisation and reverse osmosis. Those technologies are relatively cost intensive and therefore not jet appropriate for large scale use in thermal networks. Another option could be the use of high temperature heat pumps for creating suitable temperatures at the customer side, but appropriate systems are currently not available.

Opportunities: different approaches for producing DHW in low temperature networks without storage are already available or near introduction on the market: a) Direct DHW preparation (continuous-flow water heaters). The resulting high peak loads can be handles by installing storage tanks on the network side (centralised or distributed e.g. [25]). b) Additional heating can be applied e.g. via electric heaters, a common option in office buildings with a low demand for DHW. Via thermal networks, DHW can be preheated in order to reduce the electricity demand for additional heating.

i. Sensors and communication technologies (Smart heat meter)

Challenges: Whereas smart meters are intensively discussed in smart grid applications (e.g. [26]), the added value for introducing smart meters in thermal networks on a large scale urban network has to be elaborated carefully for the DHC utility as well as for the customers: Suitable smart meters are relatively expensive and the installation costs are high (including the setup of an appropriate ICT infrastructure). Additional barriers are legal issues (e.g. data security and privacy) and a possible impact on the comfort of the customer being subject to DSM. Moreover, the effect of DSM on the network operation has to be evaluated carefully, especially considering a limited potential in the network. Additionally, the motivation for implementing DSM is rather low because the heat that is usually produced by CHP plants is not applicable to energy markets with time variable tariffs, fluctuating energy sources are in fact not significant in thermal networks and fossil fuels for peak load coverage are relatively cheap.

[5] e.g. Austrian standard ÖNORM B 5019: in public buildings, 60°C has to be exceeded permanently when storing DHW

Opportunities: Due to the continuous technological development, smart meters for the electricity grid will be available on the marked for a reasonable price soon and smart heat meters will follow this trend. The customers are more than ever used to use ICT as like computers and smart phones and the diffusion of wireless communication technologies (e.g. UMTS) will support the setup of sensor networks and enable cost effective communication. For the most relevant loads in thermal networks (e.g. industrial customers, big offices, swimming pools, hotels …) the potential for DSM is rather large and the implementation of smart meters could be very cost effective. The tendency for an increasing number of distributed heat generation systems in thermal networks (e.g. industrial waste heat, micro-CHP, solar thermal) will foster the application of smart heat meters.

j. Household appliances with DHC connection (washing machine, dishwasher)

Challenges: The substitution of high exergetic electricity that is used in white goods to produce heat by thermal energy from thermal networks is hampered because suitable household appliances are still in a demonstration phase with a limited marked availability and relatively high costs. Additionally, installation costs in the buildings could become significant if new pipes are necessary.

Opportunities: The use thermal energy directly instead of electricity increases the efficiency of the energy system as electricity production is more primary energy intensive. This possibility is especially interesting for larger consumers (hotels, laundry and dry cleaners, restaurants …). Similar options could be developed also for (pre-) cooling of appliances like refrigerators or cold storage rooms connected to a cooling network.

Using intelligent control strategies, those appliances could be considered as additional load that can be used for DSM.

3.3 Processes

a. Planning processes

Challenges: Current planning processes for district energy infrastructure projects do not always support new types of district heating and cooling networks (e.g. low-temperature district heating), mainly due to the fact that this might imply additional requirements on building-side temperature levels for heating and cooling or domestic hot water preparation systems, which might be interpreted as a further limitation of design possibilities. Low-temperature district heating networks require an integrated planning of both demand and supply systems and a supporting framework (planning tools, normative framework, technical skills, contractual framework etc.) to do so.

Another challenge is related to the number of stakeholders to be involved in the planning process, especially when it comes to exploiting waste heat potential from industrial sites or including demand-side measures in the overall concept. Increasing the number of stakeholders implies a higher complexity in the planning task, more difficulties to access data and many private economic interests to satisfy.

Opportunities: The task of developing and planning new types of district heating and cooling systems can be more easily performed in the case of new neighbourhood development projects coordinated by urban development authorities, in particular if development briefs are used to include additional building-side requirements (e.g. related to the temperature levels) during the tendering procedure.

Even if this task cannot be easily performed in existing urban structures (e.g. for district-scale refurbishment projects involving the connection to a thermal network), processes have to be developed and proposed for the specific situations, e.g. involving dedicated agreements and contracts between utilities and building owners.

b. Business models

Challenges: Even if well-defined business models are often seen as a key element for supporting the implementation of innovative urban energy infrastructure projects (in particular thermal network projects), regulatory frameworks for these models are often missing, which might slow down the implementation process or even bring business models to fail because of legal issues. This might concern for instance the involvement of tenants as shareholders or the feeding of distributed heat sources (e.g. industrial waste heat).

Opportunities: ESCO and public-private-partnership-models can be proposed in many different configurations and involve different levels of public authorities (local, regional), utilities, industries, building owners etc., depending on the project types and the main interests of the involved stakeholders. This large number of possibilities creates many opportunities for successful business models.

Even if the organisational and legal frameworks of thermal urban networks are very different from the ones of electrical networks, the business models for innovative thermal urban network projects can be inspired by the experience of distributed generation in electrical networks.

c. Implementation process

Challenges: The implementation processes (phasing, transition steps etc.) for innovative thermal urban network projects are confronted to the difficulty of adaptation in a transition environment: current district heating and cooling infrastructures (including the energy generation facilities) are planned, financed and operated in given contractual conditions which cannot easily be amended to facilitate the further development of innovative thermal urban networks concepts. This is particularly applicable for the financing (already operating plants and infrastructure need first to be completely financed before being replaced or re-powered) and the operating conditions (a network designed for operating at given conditions cannot be easily operated at other conditions).

Opportunities: There are few opportunities for managing the transition of current thermal urban networks towards new types of networks. One path to follow consists in developing small-scale networks (e.g. low-temperature district heating) while targeting a junction of these first micro-networks in future.

CONCLUSIONS

Thermal networks can play an important role in the future Smart Cities if they can ensure a reliable and affordable heat and cold supply to various customers with renewable energy carriers like waste heat, solar thermal and geothermal energy. For this purpose, following main strategic implications for thermal networks were identified:

- They have to **adapt** on a short-term to the energy supply and demand situation, in a long-term by adjusting the network development with urban planning and in a medium-term by adaptation of the temperature level in existing networks and the installation of new distributed micro-networks.
- They should be **intelligently** planned and operated as well as enable the end-user to interact with the heating and cooling system.
- They need to be **integrated** in the whole urban energy system from a spatial point of view (related to urban planning parameters and processes) and from an energy system point of view (e.g. optimizing the interfaces to electricity networks).
- They will help to achieve the highest overall **efficiency** of the energy system, by choosing the optimal combination of technologies and enable a maximum exploitation of available energy resources by cascade usage.
- They are **effective**, when the measures have a significant impact on the overall urban energy system efficiency when the broad diffusion of thermal networks is given.
- They need to be **attractive** for the citizens and investors by increasing the cost efficiency, creating possibilities for the customers to participate and developing new business models.

To reach the related transition, thermal networks have to undergo far-reaching changes on following different levels:

- **Structures/ concepts** (low temperature networks, cascade usage of resources, new network types, the optimisation of the interface to other networks and to efficiency measures as well as energy management)
- **Technologies** (Energy conversion technologies and storage, components (pipes, substations …), the preparation of domestic hot water, sensors and communication technologies and household appliances with DHC connection)
- **Processes** (planning processes, business models and implementation process)

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SMALL SCALE DISTRICT HEATING SYSTEMS. DEMAND SIDE MANAGEMENT EFFECT

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Keywords: Small district heating system, shrinking cities, demand side management, green energy planning

ABSTRACT

Energy strategies of Nordic countries and Baltic States include different green measures. They play significant role in all energy sectors especially district heating.

Baltic States has different targets. However some features are common. Small scale DH systems (up to 5000 MWh/year) are widespread in municipalities today. The range of heat supply differs a lot: the best of them have well organised efficient operation conditions, but others destroy the heating system with chimney of ovens coming out from walls of each flat.

The present paper presents an analysis of future development of the thermal energy supply systems. The model for technological, economical and environmental (including climate) analysis is created for small municipal district heating systems from different viewpoints: continuing DH system operation, complete or partly decentralisation, diversification of energy sources. Modelling presents results on the influence of energy efficiency improvement at the end user side (in range of 30 to 60 %) to operation indicators of DH systems.

Results and discussion on directions of development of small systems are proposed within the article. The implementation of a long term green energy planning will favourite the development and corrections in the DH system development in particularly in small systems.

INTRODUCTION

From statistical figures is possible to detect a rising within the last decade of the number of district heating (DH) systems. This increasing is associated to systems where combined heat and power (CHP) units are prevalent respect simply boiler house (BH) based systems.

A blooming of papers based on simulations are accomplished to this latest trend mostly in terms of DH size optimization, different types of operation modes (only heat production, only power generation or CHP system), and different degrees of decentralization and diversification of the source use [1].

Moreover many papers highlight about suggestions and analysis of different energy strategies to be implemented within the development of energy policy in relation to the DH systems. This aspect is more evident on the Nordic countries and Baltic States mostly in reference to the proposal of different green measures and strategies.

Countries as Denmark and Sweden have the most developed DH system mainly focused on use of renewable energy sources (RES). The same trend is also common to Baltic States: in fact Latvia according to the energy and climate 2020 documents and the RES Directive 2009/28/EC [2] has set a target of 40% of RES within the total gross energy final consumption.

DH using bio-based sources are subjected to tax exemption in connection to energy saving and environmental improvements. Nevertheless the possibility to convert to small-scale bioenergy DH system registers studies where the affection to the local environmental quality is a sensitive point [3].

In regard to the energy aspects of DH based of CHP different results pointed out the beneficial effects in this direction mainly due to high the conversion efficiency [4]. In the same time the same studies highlighted also the environmental impact for both energy planning and plant future strategies (new plants authorization and/or renovation of old plants). During the literature review has been pointed out other interesting matter of concerns like the importance of the geographical position in respect the point of emission of the energy source[5], the importance to take into account local and global aspects in the pollutant dispersions [3-6].

In the light of what before mentioned District Heating systems, and in particularly those implementing CHP units, represent an important milestone for the development of a sustainable energy system and decreasing of green house (GHG) gas emissions. This aspect if even more favourable when local available renewable sources are taken into account.

The more sustainable and environmentally sound solution doesn't means the most easily to be implemented. In fact the optimization and maintaining of the system is an interdisciplinary question involving several aspects:

- specific economical situation of the country where is located,
- share of the exploitable heating sources (and the consequent possibility to diversify the fuel supply),
- conditions of the distribution systems,

- the price of the fuels,
- other important factors related to society habits and behaviours and investor financial capabilities.

A sort of guideline on how find the optimum situation based in the previous mentioned multisided problems is provided in the ''Neptune Declaration'' [7] a declaration in regard to the revitalizing of the DH and CHP in the Central and Eastern Europe. This document stresses the key role that should be played by municipalities in maintaining and develop the DH system in relation to the financing question and regulation aspects.

During the symposium during which the declaration has been formed the main aspects in relation to the following financial aspect have been pointed out at different Government scales:

- favourite the third-party financing for promoting investments on the DH maintaining and development;
- set a "zero" debt situation guarantying for DH operators a favourable re-start for further investments;
- decrease the risk perception for investor (foreign and/or local) in order to encourage investments guaranteeing medium/long terns legislative measures and regulatory mechanisms;
- compensate for foregone revenues of DH/CHP companies, as a result of applying special heat tariffs for not rich people.

As mentioned a primary role should involve the municipalities that have to foster the free market of the energy price and propose long term regulatory frame based on the society need. This is important in order to make the redesign (construction, reconstruction, renovation) of the DH system a challenging option for private investors.

For small scale DH systems related to small towns the situation is related to particularly conditions complicating but making very actual the question on renovation and redesign of the DH system. In the Baltic States within the last period has been detected a decline of the number of final consumers [8]. This means that redesigning, renovation and reconstruction of small district heating system is a challenging opportunity.

The contraction of people living in small community is only one of a wider big problem happening in the nowadays industrialized society and where in Europe is mostly evident in post-soviet country. This problem is called "shrinking", it also involving medium and big size city and the causes of the phenomenon are resulting from different processes (e.g. out-migration due to economic crises and decline, demographic ageing, process of deindustrialization [8-10]. This aspect specifically related to the renovation of energy sector infrastructure (like DH it is) will be better explain within this paper.

Maintenance and renovation of the DH system are in the agenda of the Latvian National Energy Action Plan but in the future planning the problem of the shrinking seems not enough investigated. In the light of that possible green energy strategy for small DH system are proposed within the paper.

In the light of what before described the main aims of the present paper are addressed to proposing possible schemes and methods on how fostering energy efficiency investment through the effect of a demand side management, and to propose green energy strategies and algorithms in order to favourite medium-long term regulation frame for small scale DH system in small municipalities.

Therefore the paper covers the following issues:

- a brief Latvian district heating system description;
- the problem of shrinking cities in relation to energy infrastructure;
- an algorithm for a demand side management programme model;
- implementation of green energy planning for small scale district heating system;
- Latvian case study (Beverina).

BRIEF LATVIAN DISTRICT HEATING SYSTEM DESCRIPTION

In the Latvian district heating sector, heat is produced in boiler houses and cogeneration plants. Heat produced from boiler house has decreased from 62.2% in 2000 to 47.4% in 2009 [11].

An increasing share of district heat produced in CHP plants is in the same time detected. This is welcome from energy efficiency point of view, however, a question of fuel choice (see figure 1) shows that the Latvian district heating systems is dominated by two types of fuel: energy wood and natural gas, and natural gas share in the fuel mix is five times greater than that of wood.

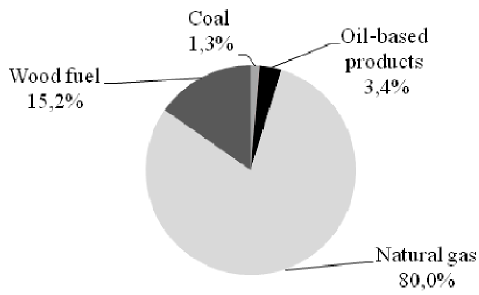

Fig. 1 Fuel mix in the Latvian district heating sector in 2009

The share of natural gas fuel for the boiler house structure is slightly less than the whole district heating sector - 63% in 2009. Fuel changes to the structure of district heating boiler houses in the last decade, illustrated in Figure 2.

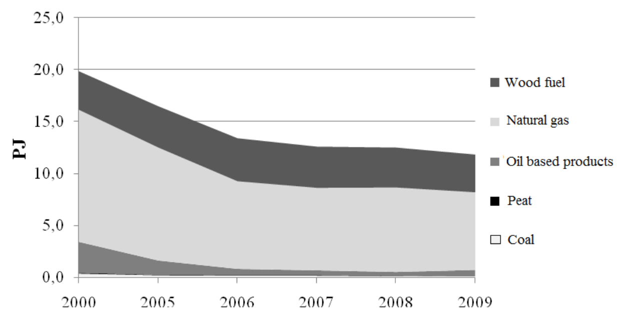

Fig. 2 Boiler house breakdown by type of fuel consumed [11].

Figure 2 shows that the central heating sector for boiler houses reduced the amount of heat produced. Most rapid decline took place between 2000 and 2006 (36% reduction) in recent years, this trend did not change so fast. Historically, the share of natural gas fuel in primary energy structure exceeds the rate of wood use. Since 2000 has reduced the oil use in district heating. Coal is used minimally.

THE PROBLEM OF SHRINKING CITIES IN RELATION TO ENERGETIC INFRASTRUCTURE

At the beginning of the 21st century, the shrinking cities phenomenon involves all Europe. This is involving in the same time Western European industrial medium-big size urban agglomerate in economic fail and to marginal, lightly populated areas in Northern Europe as well as to rural areas of South of Europe. The problem is also evident in the the postsocialism Countries in Central and Eastern Europe that have been incurred in a strong population decrease just after the politic changes in the 90es (see Figure 3). After 2000 this situation changed even more dramatically.

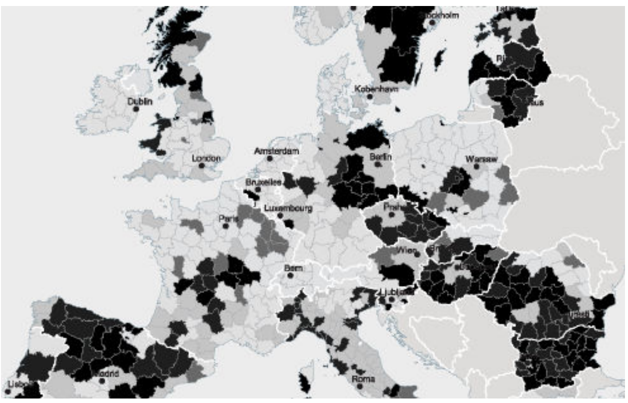

Fig. 3 Change in population in Europe 1996-1999 [12]

Few year ago the shrinkage was considered a minor development trend in specific areas but nowadays the situation is more evident and clear.

How it can be seen from Figure 3 the problem is sensitive for the post-socialism Countries such as Baltic States and East Germany.

How already mentioned urban shrinkage is a complex multi-sided phenomenon coming from different reasons and processes related to de-industrialization and out-migration due to economic crises resulting in a population decline [10]. In addition, if the attention is driven to industrialized regions these are undergoing a demographic decreasing change related to loss in fertility.

In the light of that urban planning and consequently energy infrastructural planning (i.e. maintaining, renovation and redesign of the DH system in reference to future energy demand) is a matter of concern mostly because social, environmental, spatial and energy effects can diverge. In the study of [9] are presented the diverging targets if growth or shrinkage targets are set.

In the report of Hans-Jörg Domhardt and Gabi Troeger-Weiß [13] is presented the shrinkage problem of small towns in Germany and it is proposed an interesting diagram loop that regulated the demographic change (see Figure 4).

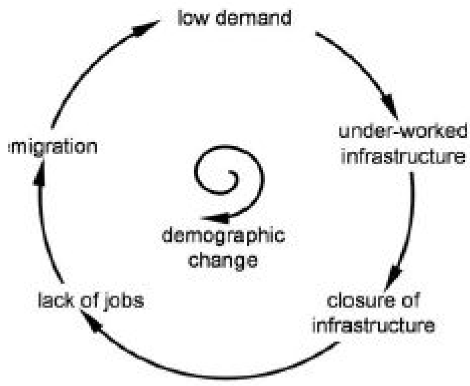

Fig. 4 The problems of small town shrinking [13]

The previous diagram can be explained by taking into account that due to under-exploitation of the industrial infrastructures, decrease of job numbers and out-going emigration for small German towns leads to a shortening of the demand for the industrial infrastructures including the energy supply system of which the DH systems is a part of it. In the same report are proposed other important aspects and results: first of all that according to the model calculations a decline about a quarter of the initial population is estimated by 2050. This decline for rural region can arise till one third of the initial population.

In relation to small town the main question is related how to optimize a energy supply facilities (i.e. DH system) taking into account the declining of population.

In fact energy infrastructure cannot be re-sized, re-designed or scale back easily since a minimum require of services (including energy supply) have to be keep steady taking into account a long term perspectives in connection with potential future population growth, and because some infrastructural network is simply stable and impossible to be re-sized or re-organized in sub-systems. In the other hand if the problem is not face with the costs for the utilities will tend to increase since the demand will decrease and the same can be reflected in the energy supply systems.

The identification of potential strategies of sustainable developments will have a primary role and again (like it was for the schemes proposed in the Neptune declaration) municipalities should be the main actor at local and regional scale. These strategies have to guarantee an improvement of the efficiency of the infrastructure guaranteeing the minimum of supply for each region or sub-region they are applied for, and the concept of sustainable development in order to contemporary match the request of future ecological, economic, social [13] and energy demands ensuring the correct balance among all these parts for the maximum sustainable development.

However if the concept of sustainability is applied to shrinking city a dilemma (or contradiction) is occurring: in fact population demand will decrease on one hand, a growth in term of comfort and request of space in the other. This effect shows again the importance of the regional planning applied for long term development in environmentally and sustainable sound direction.

In this paper are hereafter proposed an algorithm implemented in a model for the optimization of the efficiency of the energy end users within an heat supply system and the proposal of regional “green energy” planning for small district heating system in Latvia (case studies of Beverina).

ALGORITHM FOR A DEMAND SIDE MANAGEMENT PROGRAMME MODEL

Accomplishing the Neptune declaration and improving the efficiency of supply energy system to face with future “shrinking” problem hereafter is proposed an algorithm (and its implementation a calculation model). The model also quantifies the final potential savings.

Demand side management measures as they relate to energy end users begin with data collection and analysis and continue with the planning, implementation, and evaluation of energy efficiency measures. In order to receive the maximum return, a demand side management programme is necessary.

The algorithm of a demand side management programme is shown in Figure 5. It consists of eight blocks and its performance is based on three principles:

- sustainability;
- gradualness;
- continuity.

Sustainability encompasses not only the implementation of environmental, economic, and socio-economic ideas; its main goal is a long term decrease in the energy consumption of buildings at minimal cost and the development of a green mindset and awareness.

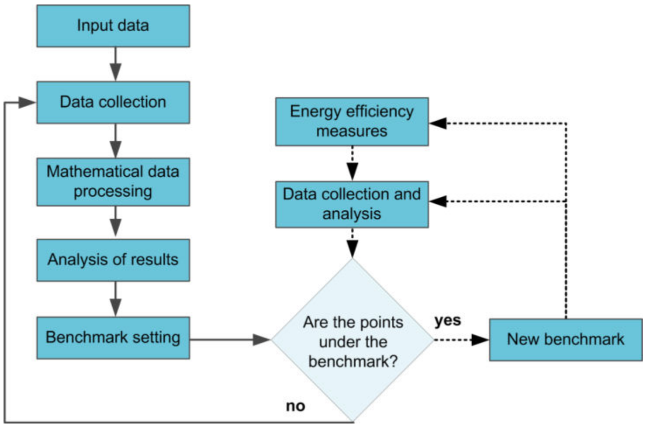

Fig. 5 Algorithm of a demand side management programme model

Gradualness is important both from the engineering and the emotional standpoint. The average energy user in Latvia is ready to accept interesting ideas. But a period of inertia must be observed between the initial introduction and the implementation of the measure for users to contemplate and weigh the positive and negative aspects. Sometimes this period of inertia can last two or three years or longer. Therefore, energy efficiency measures must be introduced gradually and move slowly towards their goal.

Continuity is important for achieving the set goal and not stopping after the completion of a certain energy efficiency measure. After the planned measures have been completed, the effectiveness of the measures must be evaluated, new benchmarks must be set, and the next measures must be planned and implemented.

The implementation of the algorithm, for example for reconstruction of renovation of buildings, requires up-front investment investments from energy end users but already with no large amount an energy savings of 10-20% of total energy consumption can be achieved .

SAVINGS

In this chapter are described the results in terms of energy savings when on the analyzed building renovation works are proposed. With the correct demand side management is possible to redefine a lower benchmarking acting on reduction of energy consumption reduction in function of the outside temperature. Results are also performed in terms of calculated and measured data.

In order to determine the potential energy savings from the planned energy efficiency measures, a simulation of the model was performed before the renovation began for the selected building. The results of the simulation model showed that the potential energy savings were up to 47%, or, 191.9 MWh/year (see Figure 6).

On-going inventory of the results are also planned after completion of the construction. The results of the data analysis show that the simulation model, which predicted the building's consumption after reconstruction, characterises the situation well and corresponds to the achieved results.

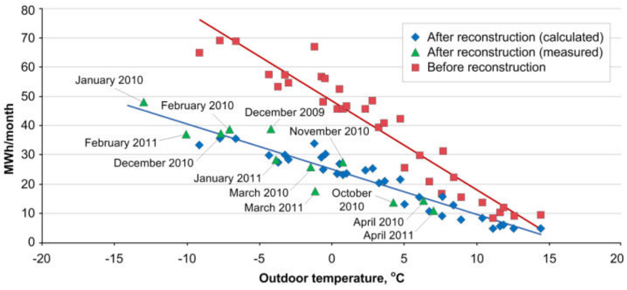

Fig. 6 Building's monthly energy consumption before and after reconstruction for calculated and measured data.

The building's monthly energy consumption depends on the average outdoor temperature. The measured data after completion of construction are coloured in green.

The data collected during monitoring (implemented by ESCO company in small municipality of Latvia) show that the energy savings fluctuate between 50% and 53%. The yearly reduction in CO_2 emissions is 54.7 tCO_2. The total planned energy savings during the duration of the energy management contract will be the decrease between 4150 MWh and the reduction in CO_2 emissions: 1100 tCO_2.

The project has received significant support from all the apartment owners and renters. They can now finally live in a safe and well renovated, comfortable building. Their expenses do not exceed and are even lower than previous expenses.

The example below presents the influence on energy efficiency improvement in end user side can reach 60%.

IMPLEMENTATION OF GREEN ENERGY PLANNING FOR SMALL SCALE DISTRICT HEATING SYSTEM

In connection to achieving sustainable development on global scale the correct and judicious use of resources, technology, appropriate economic incentives and strategic planning at the local and national levels is required. Moreover in order to face with the problem of the shrinking cities is necessary action schemes and planning option that have to face with the decreasing of the demand in terms of necessary needs and energy demand.

Since, as mentioned, the problem is on the agenda of the former East Germany several proposals of urban planning and studies are involving cities from this part of Europe [9, 13, 14]. Basically these planning are based on the urban development but the same background and ideas can be translated to development of the energetic infrastructures.

Hereafter is proposed the scheme on how urban renewal competes with shrinkage and vacancy problems and where urban "green" start to play its role (see Figure 7).

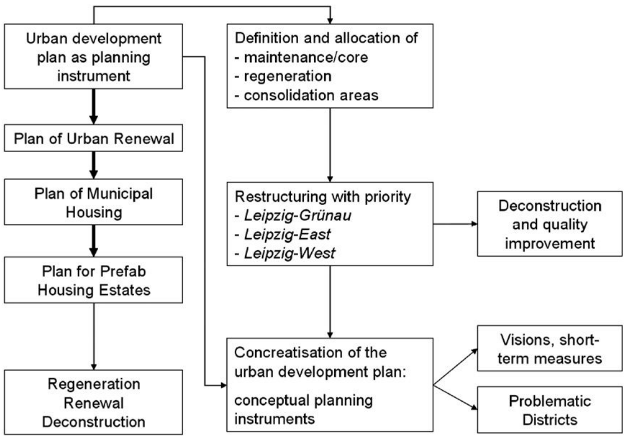

Fig. 7 Scheme of how urban renewal competes with shrinkage and vacancy problems, and where urban green comes into play [14].

The basic idea of the algorithm implemented in a planning programme in 2002 ("Stadtumbau") in Leipzig was mainly addressed to a better balance among demand and supply in the housing system. In the frame of the programme the more economically week municipality cooperative and private by the high vacancies were encouraged with supports measures to reconstruction or demolition of vacant buildings.

As mentioned also in the Baltic States the shrinking of small cities is actual and in the following are proposed algorithms and strategy suggestions for the development of the DH system in rural regions aim to optimized the overall efficiency of the whole analyzed systems. The case study of Beverina village is reported in the next paragraphs when a green energy planning is applied.

LATVIAN CASE STUDY

The study involved one region where after energy audit of the actual status of the DH system possible green planning solutions are provided.

Beverina

The problems related to the development of Beverina district heating system are complex. This is due to the fact that the district municipalities present centralized, partially decentralized and/or fully decentralized heating system.

The development of alternative heating systems strategies for Beverina region is based on the analysis of the situation in each district municipalities. The first stage of energy audit has allowed municipalities to understand not only the current status but also define the priorities for the implementation of energy efficiency and renewable energy strategies. This was aimed to define the places where there is an urgent need for technological assistance and re-designing and areas that can wait for the introduction of the proposed measures.

The development of alternative heating systems evaluation for Beverina village selected has involved three parishes:

- Murmuizas woodchip boiler house;
- Residential building „Lazdas" in Cemp, where apartments are currently heated by electricity;
- Trikata elementary school and sport centre.

The greatest attention has been devoted to energy consumers in the implementation of the district heating management program.

Beverina village consists of 3 municipalities:

- ***Trikata*** – including the parish of Trikata (334 people), Dutka (200 people) and Udrina (50 people);
- ***Kauguri*** – including ***Murmuiza*** (500 people) Kauguri (88 people) and Lici (115 people).
- ***Brenguli*** - the urban centre of Brenguli (180 people) and Cemp (190 people);

In the parish of ***Trikata*** operates one boiler house in the culture centre, which is heating two public buildings - the recreation centre and a second municipality building - with a total area of 2073 m^2. The two buildings have a distance of 50 m and no changes of the heating system have been done since their installation.

In the boiler house in 1996 has been installed two 200 kW wood logs boilers with an average consumption of 300 m^3/year, but official records of wood fuel in the boiler house are not provided by local government. The main boiler house operating data are summarized in Table 1 but since the official actual wood consumption it is not known the following estimates may be inaccurate.

The Trikata parish central heating system supplies heat to two public buildings, but for residential buildings and other public buildings the heat is provided individually.

Table 1. Culture centre in Trikata: boiler house main data

Parameters	2011
Installed capacity, MW	0,4
Wood logs consumption, m^3/year	300
Heat production, MWh/year	266
Heat energy tariff, LVL/MWh	28
Total area, m^2	2073
Heated area, m^2	1658
The average specific heat consumption, kWh/m^2 year	160

The ***Murmuiza*** boiler house provides heat to 10 buildings with a total area of 8793 m^2. In the boiler house was installed in 2010 a woodchip boiler with a capacity of 1 MW. Wood chips and sawdust storage present a maximum volume of 400m^3.

Table 2. Murmuiza boiler house main data

Parameters	2010	2011
Installed capacity, MW	1	1
Wood chips consumption, m^3/year		3000
Sawdust consumptions, m^3/year	3793	200
Wood fuel energy, MWh/year	2503	2112
Heat energy production, MWh/year	1509	1297
Calculated efficiency, %	60	61
Heat energy tariff, LVL/MWh	31	32

As can be seen from the data compiled in Table 2, the average boiler plant efficiency is 60%. Since the boiler is not old the low efficiency can be explained by the fact that monitoring of the wood fuel is missed.

The heat supply system is 800 meters and the calculated heat losses are around 17-18%.

Murmuiza centralized district heating system is connected to 10 buildings. A centralized heating system is connected to three public buildings and seven apartment buildings.

In ***Brenguli*** has been built a centralized heating which connected 4 buildings: Brenguli primary school, where the boiler is installed, and the residential buildings „Gatves" and „Smiltāji" and the shop „Blāzma". In 2007, a residential building and the supermarket refused the connection to the district heating system. These buildings are currently heated by individual stoves and electric heaters.

The Primary School is located in a building of '60s. The primary school is hosting a kinder garden (20 children), a primary school (36 children), and the Latvian Post Office

Cempi village is one of those Latvian villages in which the district heating system was destroyed in the ‘90s.

In the village of Cempi the heating is provided in each building individually - with wood stoves and/or electrical heating. Cempi is composed by 5 blocks of residential buildings.

Energy audits have been carried out in the residential building of "Lazdas" and “Jaunceltnes". In the residential building "Lazdas" heat is provided solely by electric heaters, thus the costs for the thermal energy per month is rather high. Together the two residential buildings present a total number of 18 apartments.

In the residential building "Jaunceltnes", built in 1963, residents have installed individually wood-burning stoves and electric heaters are used in some places. The energy audits conducted in 2010 showed a specific heat consumption of 290 kWh/m^2 per year.

Kauguri village has four heat energy end users: Kauguri school, Kauguri Culture Centre and two residential buildings. The first two present a centralized system using wood logs while the other two installed single wood log stoves.

Around 8-10 years ago it was installed a boiler 200 kW in the Kauguri school, which provides heat for the school and the Culture Centre, located 50 meters far from. Boiler house is composed by 4 stoker burners. Hot water is provided by electric boilers.

Heat supply system development plan for the assessment of the situation

Heating system development plan includes joint activities for the whole Beverina village and specific tasks for each community separately.

It is important to set priorities and sequencing the implementation. Below are summarized four groups of measures.

1. ***Development of a local planning of energy strategy***

Beverina village energy sector include all the components for the implementation of a territorial green energy strategy. The strategy should include energy efficiency and renewable energy implementation activities in terms of:

- horizontal measures - related to energy sources and resources, heating networks and energy end users, such as energy wood terminal setup - like:
  - the identification of the municipality and the end users on which applied the measures;
  - the identification of the supporting measure for the business of biomass terminal;
  - the determination of the wood volume related to local businesses and the establishment of a data base for the wood demand in the energy administrative office in the local administration.
- Vertical measures (detailed in each area), like: energy consumption management, efficiency operational solution, insulation. In reference to the Beverina village this can addressed to:
  - the performance analysis of Murmuiza boiler house and recommendations for its improvement,
  - reduction measure of the energy consumption for Trikata school;

2. ***Energy user behaviour change***

Energy user behavioural change measures include:

- energy monitoring system for energy users;
- district energy management program for the consumers;
- implementation of energy efficiency measures in municipal buildings;
- development of a policy of uniform treatment of the apartment building heating;
- joint procurement documents;
- establishment of a single contract form;
- ensuring transparency in the tariff.

3. ***Boiler house adjustment measures***

Boiler house adjustment measures are related to relatively low cost with a maximum effect on the overall cost reduction:

- stoker installation and maintenance training course;
- establishment of a proper fuel accounting system;
- establishment of fuel storage close the boiler;
- boiler energy consumption reduction by implementing energy management programs.

4. ***Readjustment* of the heat grid system**

The most important measures from the municipality side for the improvement of supply heat systems are five:

- analysis of actual trend from the heat energy audits,
- organization of the heating system in accordance with the forecast the heat development, analysis of building or reconstruction trends in accordance with specific indicators;
- heat supply system construction, reconstruction procurements and contract unification;
- calls for tenders, evaluation of applications and contract stipulation;
- construction supervision.

In the light of the audit performed for the Beverina village a summary of the main impressions and solutions for the improvement of the DH system are hereafter listed:

- the current situation Beverina village, about the heat supply in the municipal and residential building, is characterized by heat source and energy resource diversity. As well thermal energy consumption in buildings varies considerably. This suggests that in each heat supply element is possible to bring energy efficiency measures that will significantly reduce the energy consumption in the region. A possible calculated reduction in average energy consumption is accounted in the range of 40 to 60%.

- reduce the energy consumption in Beverina village is one of the highest priority; this is related to the establishing of an energy management service. Initially, this service might be one person who monitors and analyzes the first energy consumption reduction in the municipal building without significant or minimal capital investments. The financial resources should be redirected to organize procurement documents, to pay salaries to energy managers and to ensure co-financing to energy efficiency projects.
- the analysis for the improvement of Murmuiza heat energy supply system shows that the priority has to be devoted to the introduction of energy measures which do not require big funds, but can increase boiler house efficiency by 10 to 15%. Other measures to be introduced for the boiler house adjustment in addition to the already existing equipments are: accumulation tank installation and deep cooling equipment installation.
- In the residential building in the village Cempi "Lazdas" the analysis suggests that the abandonment of the electrical heating is economically justifiable. A sustainable solution is central for the heat supply system: the insulation of the whole is a priority. Economically is also feasible to install a wood pellet boiler in the basement of the building or in a container. However, in order to implement all the measures mentioned above, it is necessary the government moral and a financial support for the pilot project.
- For Trikata School and the municipal building the analyses show that there is a complex energy management to be implemented. Nevertheless is mandatory to initiate reconstruction of the heat sources. Economic calculations show that the shortest payback time is for the case when the school administration renounce to the diesel boiler and installed a 100 kW wood pellet boiler, which would cover the base-load of the building.

DISCUSSION

There is little direct research available on the management of energy infrastructure in the context of population decline. In the other side shrinkage of the city has been understood as a process that is actual in wider regions of Central and East Europe. Shrinking of the cities has also to face with future growths targets. In fact the situation is a multi-faced problem that consequently ask planners and policy-makers a difficult task since long-term energy planning are needed in order to reduce the risk perception for private investors and accomplish the guidelines proposed in the Neptune Declaration.

The use of renewable energy technology in small DH network can be reliable since provide energy facilities based on renewable sources present higher flexibility in terms of their location and a higher adaptation in relation to demand changes. Again in relation to the problem of shrinking cities it can be mentioned that a redundancy in the energy infrastructures is not a negative aspect since is difficult to predict what will happen in the future and because this can provide s well back-up system for the whole network. Nevertheless when demand dramatically decrease energy efficiency measure are essential in order to avoid an uncontrollable increase of the tariffs for the inhabitants.

Within the paper has been discussed the importance of energy planning in relation to small DH system and have been proposed a method aimed to optimize small DH in terms of final demand side management and an implementable algorithm.

On the basis of Beverina case study green energy planning has been proposed for the any Baltic village. In specific in relation to the end user demand side management have proposed different solutions that can be generalized in an algorithm that is proposed hereafter.

During the implementation and building of possible green energy strategies for the optimization of the DH system of small municipalities have been pointed out the central role of the local government, authorities and local stake-holders.

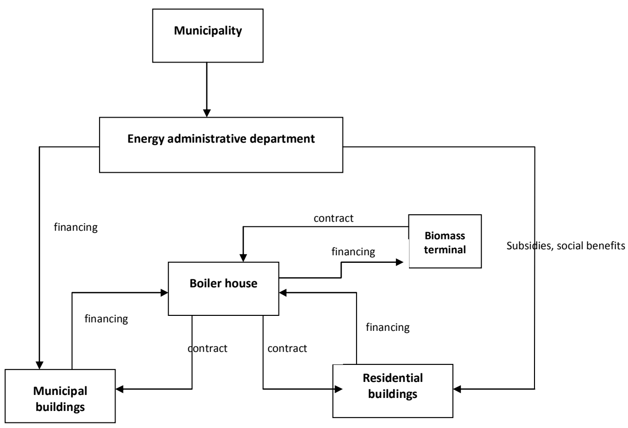

Fig. 8 Energy financing and contractual framework to organize municipal district heating system

Basically private boiler energy consumption reductions and cost savings are possible if the municipality are also implementing centralized monitoring systems of all buildings within the district for the energy consumed per day, week, month and year. Another possible alternative is to propose an energy management financing system and contractual framework for the municipal district heating system as illustrated in Figure 8. The main idea is to create energy management system paid by savings.

As it possible to see from the previous figure 8 municipalities have to implement important policy measures based in financing to municipal building (in form of renovation investments) and favourite subsides and social benefits for renovation of residential building. Moreover the scheme proposes a key role of the biomass terminal necessary for a sustainable planning.

CONCLUSIONS

In the paper has been presented an analysis of future development of thermal energy supply systems for small DH system in Latvia.

In the paper has been also highlighted the diffusion of the problem of the "shrinking" cities in the former Soviet Countries (e.g. East Germany and Baltic States) at different scale: medium-big town and small town and/or villages of rural areas.

In the paper is also proposed an algorithm for the energy demand side management and the results on real case that shows potential energy savings up to 47%.

Moreover has been proposed a green energy planning in any Baltic municipality. The proposed scheme for the implementation of the strategy pointed out the key role of municipalities and local governments in order to implement important policy measures based in financing to municipal building (in form of renovation investments) and favourite subsides and social benefits for renovation of residential building. Moreover the scheme proposes the central role of the importance of the sustainability within the planning.

It can also be concluded that due the variety of situations related to the renovation and redesigning of the DH supply system different ad-hoc strategic solution and schemes have to be adopted for each town.

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CONSEQUENCES OF PART LOAD EFFICIENCIES ON PRIMARY ENERGY FACTORS FROM COMBINED HEAT AND POWER PLANTS CONNECTED TO DISTRICT HEATING GRID

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Keywords: Primary Energy, CO_2 equivalents, Combined Heat and Power, Energy efficiency

ABSTRACT

Application of Combined Heat and Power (CHP) plants utilizing biomass have been introduced as means to increase overall energy efficiency and use of renewables both by the European Union (EU) and International Energy Agency (IEA).

The environmental impact of a CHP energy system is characterized both by Primary Energy Factors (PEF) and CO_2 emissions per produced kWh power and heat, as described in the Directive of Energy Performance of Buildings[1] (EPBD) and appurtenant the European standards EN 15603 [2] and EN 15316 [3]. Usually, yearly average efficiencies are used in those calculations/standards.

This study has examined the impact utilization of seasonal efficiencies instead of annual values for calculation of PEF for four different CHPs.

Case studies were carried out for steam cycle and combined cycle CHPs. Heat was supplied to a district heating grid with different energy densities, supply and return temperature for different seasons. Steam Pro [5]and GT Pro [5] were used for simulation of part load behaviour, for steam - and combined cycle CHPs of different sizes.

The results demonstrate both the importance of detailed calculation and the need for a strict standardized calculation method. Utilization of different fuels will also have an additional impact on the efficiency of the CHP and thereby the total PEF for heat in the district heating system. In addition, other allocation methods like energy instead of the power bonus method (alternative production) will reduce the impact of exported power.

INTRODUCTION

During the last decades reduced energy consumption, increased energy efficiency and utilization of renewables have gained interest whilst different technologies have matured. Combined heat and power (CHP) has been introduced as a mean to reduce dependency of fossil fuels and import of fuels to the EU environment and the associated countries.

The Brundtland report "Our common future" [6] introduced the term sustainable development, where both reduction of energy consumption and changes from fossil fuels to renewables were mentioned as an important part of the needed alteration.

EC/EU has introduced and enforced directives like The “Energy Performance Directive”[1] The “Renewable Directive” [7], The “Cogeneration Directive” and appurtenant standards in order to reduce energy consumption.

Primary energy PE and CO_2 emissions have been selected as the most relevant parameters describing the energy efficiency and the environmental impact of an energy system (EN 15603). This means that the energy supplied to a building shall be calculated as the sum of kWh delivered energy per energy carrier multiplied by the Primary Energy Factor for each energy carrier. The primary energy factor takes into account all the energy that is needed to deliver 1 kWh power/heat/cool to the end user and the CO_2 equivalents is the CO_2 that is emitted from extraction to delivery. The Intergovernmental Panel on Climate Change (IPCC) has decided to apply the CO_2 equivalent which consists of emissions from CH_4 and N_2O with a global warming potential of respectively 21 and 310. Thereby, this method will promote energy efficient systems and/or renewable energy systems with low CO_2 equivalent emissions.

Although the standards are supposed to describe methods, several of them open up for some national adjustments. For example; each country can decide whether infrastructure is included in the calculation of PEF and CO_2 emissions, and have a possibility to decide the values on a national level. Different parameters prevent reliable comparisons between different studies. Another problem is the lack of detailing level which might cause misleading results when average values are applied instead of seasonal values.

This study examines the impact of applying seasonal energy efficiency for the CHP instead of utilizing annual average values. Thereby the part load behaviour will be taken into account.

Calculation of PEF and CO_2 equivalents

EN 15603 [2] describes how the PEF and CO_2 emissions from an energy system can be calculated.

In two previous studies [10] [12] which are based on EN 15316-4-5 [23] further explain what major parameters should be included in the calculation of an energy system as shown in Figure 1.

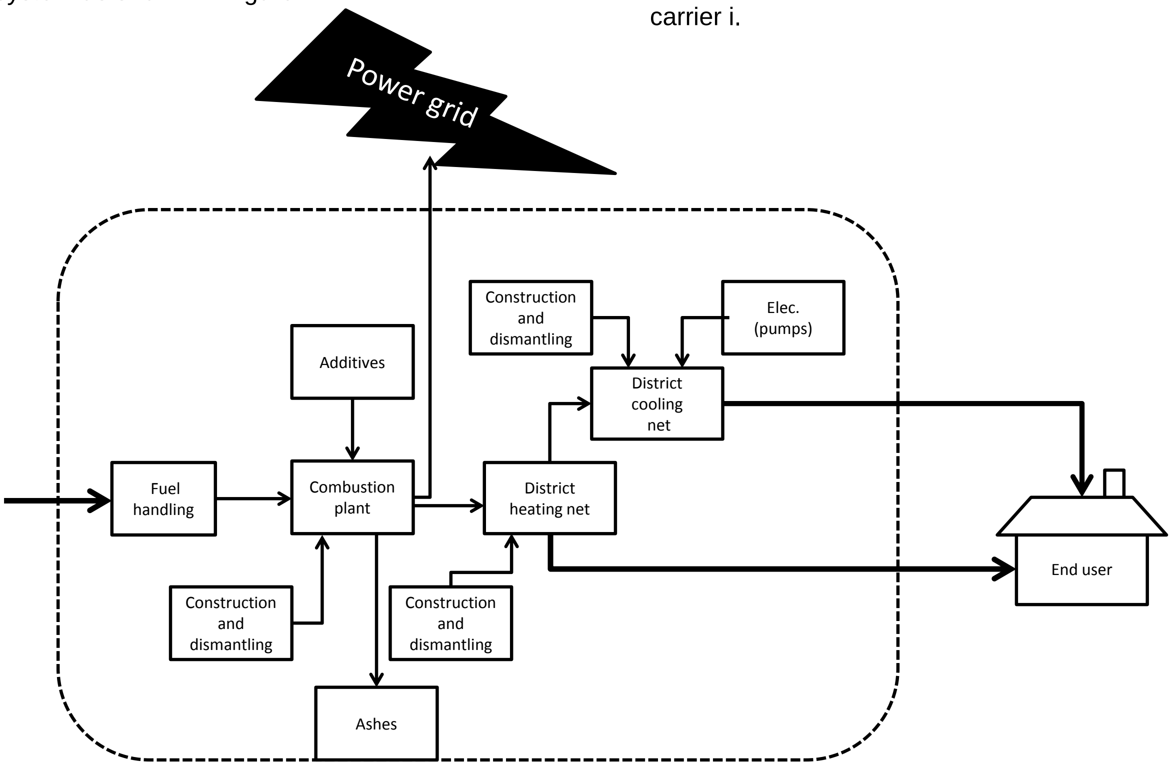

Figure 1 Principal figure of an energy system with CPH

In accordance with [23] the Primary Energy related to the system is described as:

$$E_p = \sum(E_{del,i} \cdot f_{P,del,i}) - \sum(E_{\exp,i} \cdot f_{P,\exp,i}) \quad (1)$$

- E_p – Primary energy, input to the system
- $E_{del,\ i}$ – Delivered energy, energy carrier i
- $f_{P,del,i}$ – Primary energy factor, delivered energy carrier i
- $E_{exp,\ i}$ – Exported energy, energy carrier i
- $f_{P,expl,i}$ – Primary energy factor, exported energy carrier i

In addition to the actual energy delivered to the system, energy and emissions related to the building process, demolition, maintenance and operation could be included.

Likewise, the CO_2 equivalents can be calculated;

$$m_{CO2} = \sum(E_{del,i} \cdot K_{del,i}) - \sum(E_{\exp,i} \cdot K_{\exp,i}) \quad (2)$$

- m_{CO2} – emitted mass of CO_2
- $K_{del,i}$ – CO_2 emission coefficient delivered energy carrier i.
- $K_{exp,I}$ – CO_2 emission coefficient exported energy carrier i.

METHOD DEVELOPMENT

A model for a combined heat and power plant connected to the district heating grid are developed in several previous studies [9]-[12]

The method describes the fuel delivered to the CHP plant, building and dismantling of both the CHP and the district heating grid, additives that are supplied to the CHP and ash removed. Power consumption for pumps and internal application in the CHP are also calculated.

PE and CO_2 emissions for the district heating are calculated based on a LCA methodology and energy calculation [10]. The efficiency of the CHP for variable loads is simulated by Steam Pro and GT Pro.

The district heating grid

In order to calculate pressure and heat loss for a realistic combination of pipeline sizes the grid are designed according to a Nordic medium sized district heating grid, with different piping diameters [13] .

The layout of district heating grid is based on two average Norwegian grids with an energy density of 3, 8 and 15 MWh/m. The environmental impact of the building (and operation of the district heating grid and the power plant is calculated by SimaPro [14] a Life Cycle Assessment (LCA) tool utilizing the Ecoinvent database [15].

Each pipeline consists mainly of PEH (polyethylene) and is insulated with PUR-foam, the weight of the materials are based on information from www.powerpipe.se for the different dimensions. Weight is therefore the basis for the LCA calculation as shown in

Table 1. Ideally, the production of the pipelines should have been based on actual data from the producers. Usually, this will lead to an underestimation of the environmental impact since only energy and emissions are related to the pipelines and insulation and not other necessary processes like internal transport, maintenance and percentage share of waste from the production [16].

Table 1 Example on PE and CO_2eq.related to production of different sizes of pipelines

Name	DN 80 Pipeline single	DN 80 Pipeline Twin	DN 200 Pipeline Twin	DN 600 Pipeline single
PEF Non-renewable , fossil [kWh/m]	233,3	194,8	724,5	2452,7
PEF Non-renewable , nuclear [kWh/m]	45,5	40,9	171,9	387,2
PEF total Non-renewable [kWh/m]	278,9	235,7	896,4	2839,8
kg CO_2 eq/m	73,2	48,1	270,2	322,8

The trenches are calculated based on [21] where the width of the trench depends on the size of the pipes. In urban areas asphalt is removed and replaced with a transporting distance of 30 km for asphalt, pebbles and gravel. 20% of the mass is reused and no asphalt is laid in rural areas. For this study the economical lifetime is estimated to 30 years, although several studies have shown expected lifetime of more than 60 years [19].

Man and machine hours for excavation are based on average values from a large contractor in Norway [18].

Data for each dimension are aggregated to prevent revealing trade secrets, especially connected to pricing of the excavation - see Table 2.

Originally, the calculation were carried out for three different locations; urban, semi-urban and rural areas. The difference between urban and semi-urban areas was less than 5 %, and only results from urban and rural areas are presented.

Table 2 Example PE and CO_2eq. for trenches for different sizes of pipelines

Name	DN 25	DN100	DN200	DN600
Urban area				
Total PEF [kWh/m]	383,0	707,4	1339,5	3960,7
PEF - renewable [kWh/m]	4,4	5,6	9,1	14,3
CO_2 eq kg [CO_2-eq/m]	59,2	136,3	267,9	488,5
Rural area				
Total PEF [kWh/m]	170,6	337,1	906,6	3726,4
PEF - renewable [kWh/m]	0,5	0,6	1,0	12,7
CO_2 eq kg [CO_2-eq/m]	35,8	106,0	216,8	452,2

Load pattern is based on load curves from two Norwegian and a Swedish district heating companies. These load curves are divided into three different seasons; winter, spring/fall and summer. This corresponds to respectively 100%, 56.5% and 26% load. Temperature levels are assumed to be typical for Nordic district heating grid.

Table 3 Temperature levels at different seasons

Season	% of the year	Temperature supply/return

		[C]
Winter	25	105/50
Spring/autumn	50	80/40
Summer	25	70/35

The flow, velocity and friction will vary depending on the heating need [17], and the head loss, heat loss and pump energy are calculated based on average values for the different seasons.

Together with the LCA for the pipelines/trenches the heat loss and energy used for pumps are distributed on the produced heat kWh. Here, a lifetime of 30 years is assumed. Since the heat loss depends on the energy density three different density levels were selected.

Table 4 PE values and CO_2 equivalents for different grid densities [MWh/h].

Grid	**Energy density in grid (MWh/m)**	**PEF (kWh /kWh delivered heat)**	**CO_2-eq (g/kWh delivered heat)**
Low density	3.0	0.0116	2.86
Medium density	8.2	0.0042	1.16
High density	15	0.0008	0.20

The CHP plant

[10] and [12] describes the calculation process of the PE and CO_2 emissions related to construction and dismantling of the CHP plants of different sizes. At present, only a few inventories are available, and a linearization is chosen in order to compensate for magnitude of size. By this method it is possible to relate the PE and CO_2 emissions according to the maximum capacity of the plant.

Different CHP technologies

At present, several technologies are available for CHP depending on size and fuel e.g.; combustion turbines with heat recovery, steam turbines, combined cycle, internal combustion reciprocating engines, fuel cells and Stirling engines, whereof the two last are in limited use. Generally, the sizes of Norwegian plants are significantly smaller than in many countries due to fewer inhabitants per m^2. Therefore, sizes between 2 MW_{el} and 25 MW_{el} have been selected.

In [12] only yearly average values for efficiency for the possible technologies are applied, which might give misleading values at part loads. The intention with this study is to examine the impact of part load behaviour.

In [15], case studies were carried out for a steam cycle and a combined cycle CHPs supplying heat to a district heating grid with different energy densities, supply and return temperature for the different seasons. Steam Pro and GT Pro were used for to simulate part load behaviour, for respectively steam cycle and combined cycle CHPs of different sizes; 2, 10, 25 MWel.

Selected technologies used in this study;

I. Steam Turbine, grate boiler, 2 MWel
II. Steam Turbine, grate boiler, 10 MWel
III. Steam Turbine, Fluidized bed (CFB boiler), 25 MWel
IV. Combined Cycle, 22,7 MWel

In [22] the simulation of the steam turbines and combined cycle are described in detail. The results are shown in Figure 2.

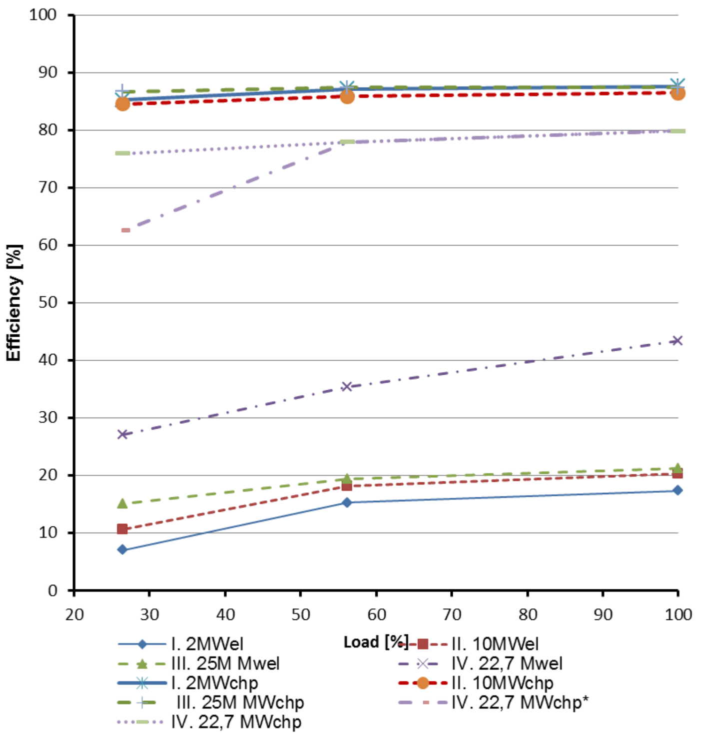

Figure 2 Energy efficiency at different load levels, index el indicates power efficiency (η_{el}) whilst index CHP indicates CHP efficiency (η_{CHP}), (η_{CHP}*) represents the total efficiency for the combined cycle when heat is cooled off.

The steam turbines have rather stabile part load behaviour both for overall efficiency (η_{CHP}) and power (electricity) (η_{el}).

The combined cycle show a different pattern. This combined cycle cannot operate at a lower part load than 15.1 %. This correspond to a district heating load of 35.8% (of maximum load) since the temperature is altered for the different seasons. If the waste heat is utilized and do not need to be cooled off, the upper curve for the combined cycle can be applied. An advantage with the combined cycle is the large power efficiency, at an expense of the production of heat. Therefore, the power to heat ratio for the combined cycle will be much higher than the steam turbines. The power to heat ratio is defined as,

$$\alpha = \frac{W_{el}}{Q_{CHP}} = \frac{\eta_{el}}{\eta_{CHP} - \eta_{el}}$$

Where

- α - power to heat ratio
- W_{el} - produced power [W]
- Q_{CHP} – produced heat [W]
- η_{CHP} – energy efficiency CHP [%]
- η_{el} – energy efficiency power production [%]

Comparing the steam turbines, technology I-III, shows that part load behaviour is improved with increasing size.

The combined cycle has a higher power to heat ratio than the steam turbines, but is more expensive and have a significantly drop in power to heat ratio at part load.

For a CHP supplying heat to a district heating net without possibilities for utilization of the excess heat e.g. for cooling at part load, the overall efficiency will be influenced. The overall efficiency η_{CHP} will be reduced from around 80% down to 60% (denoted η_{CHP}*) when the heat cannot be utilized.

Table 5 Power to heat ratio for the different technologies

Load [%]	**I.**	**II.**	**III.**	**IV.**
100	0,244	0,307	0,321	1,188
56,5	0,212	0,267	0,285	0,833
26	0,09	0,145	0,211	0,76/0,55*
Annual	0,188	0,246	0,276	0,90/0,855*
Reduction [%]	23	20	14	24/28

*) Heat not utilized

Table 5 shows the difference between annual distribution and different load. Based on a yearly approach instead of maximum load, the power to heat ratio will be reduced by 14 % to 28%. The largest reduction/deviation compared to maximum load is for combined cycle.

Often, the power to heat ratio is an important aspect when selecting CHP technology. Usually, the actual profit of a plant is dependent on the exported power which can be sold at better price than heat.

Based on the seasonal distribution on 100%, 56.5% and 26% load both the overall and power efficiency will be reduced see Table 6 under.

Table 6 Changes in annual efficiency based on seasonal variations in load.

	I.	**II.**	**III.**	**IV.**
η_{CHP} average load	87,61	86,44	87,4	79,84
Seasonal η_{CHP}	86,73	85,58	86,53	77,8/74,57*
Difference [%]	<1	<1	<1	2,56/6,6*
η_{el} average load	17,36	20,32	21,26	43,36
Seasonal η_{el}	13,73	16,80	18,79	35,30
Difference [%]	20,9	17,3	11,6	2,55/18,6*

*) Heat not utilized

Comparing the different CHP shows significant variations in annual power and CHP energy efficiency, especially power efficiency are influenced. When calculation the overall environmental impact of different technologies the difference between maximum and average values should be clarified.

APPLICATION OF THE POWER BONUS METHOD

Both the “Directive of Cogeneration” [8] and EN 15316-4-5 [23] describes a methodology for calculation of the environmental impact of a CHP where power is exported.

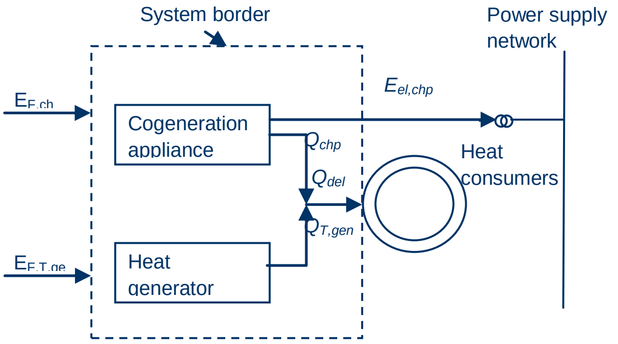

Figure 3 Abridged/simplified schematic description of the CHP exporting power to the grid.

An energy balance [9] of a district heating system located outside a building (within the same time span) provides the PEF value for the district heating grid;

$$PEF_{P,dh} = \frac{\Sigma_i E_{F,i} \bullet PEF_{P,F,i} - E_{el,i} \bullet PEF_{P,el}}{\Sigma_j Q_{del,j}}$$

(4)

Where:

- *$PEF_{P,dh}$* – Primary energy factor, district heating system
- $Q_{del,j}$ – Heat delivered at the border of the supplied buildings
- $f_{P,el}$ – Primary energy factor, replaced electrical power (exported)
- $E_{el,\ chp}$ – cogenerated electricity
- $PEF_{P,F,i}$ – Primary energy factor, i-th fuel
- $E_{F,i}$ – Final energy i-th fuel

Calculation of PEF

The previous developed tool [12] with seasonal adjustments was applied to calculate the impact of different allocation methods.

CHP I-III used wood chips with a PEF=1.19 whilst IV was operated on natural gas where PEF =1.05, assuming an PEF value for power based on Nordel

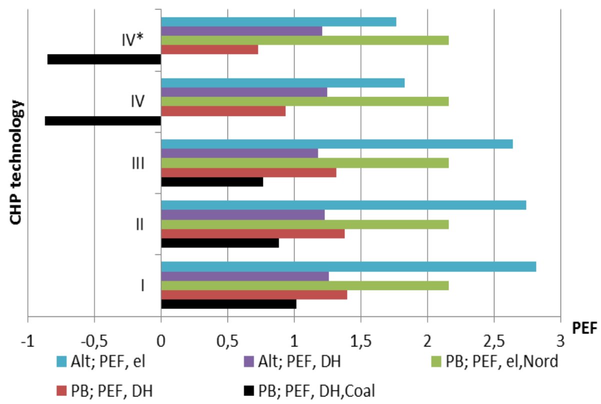

Figure 4 Calculated PEF values for different technologies; PB indicates Power Bonus Method, Alt. represents Alternative production method.

For the power bonus (PB) method the PEF values for power will depend on the PEF values for power that might be substituted. Thereby the PEF values for the district heating will be reduced by the same amount. Increasing the PEF value e.g. by marginal European power production based on coal will further reduce the PEF for the district heating.

The alternative power production method, divides the impact on heat and power as if they were produced separately. In this case assumes $\eta_{CHP}$of 90% and η_{el} of 38% for I-III, and respectively 90% and 58% for IV. This alters the PEF values changing from power bonus method to alternative production method;

- PEF_{DH} for I-III will be slightly reduced while PEF_{el} will increase.
- PEF_{DH} for IV will increase and PEF_{el} will be reduced significantly from 2,1 to approximately 1,6
- Replacing PEF_{el} Norel = 2,5 with PEF for marginally produced power from coal condensing power plants will especially reduce the PEF_{DH} for IV Combined cycle to a negative value. According to the standard should a value never exceed unity, and shall be calculated as 1.

The choice of allocation method has substantially impact on the PEF values for the different technologies.

Other allocation methods like energy, exergy would also have provided different PEF values.

CONCLUSION

Different technologies will influence the overall efficiency, PEF and CO_2 emissions. When designing an energy supply system the annual load profile is essential. This study has focused on two main technologies; steam turbines and combined cycle. The simulation of different CHPs demonstrates the impact of part load behaviour on power and CHP efficiency, power to heat ratio and also PEF.

In the simulation an average low load is presupposed 26% of maximum load and the energy density assumed 8 MW/m. Real CHP plants connected to district heating might have another annual distribution than assumed. Some might provide heat for customers with a constant yearly demand, which prevents operation at low part load. On the other hand might new technology like plus houses and ZEB buildings (Zero Emission Buildings) reduce future needs for heating, thereby reducing the energy density.

Heat load must be the base load according [8] and [23], this implies that the power bonus method only can be applied under those conditions. If the primary energy production is power the PEF values for the district heating system will increase.

CHP technology should be selected according the load profile, in this study a district heating net is designed with seasonal heat loads of 100%, 56.5% and 26%.

Ideally, the efficiency of the power plant, head loss, friction etc. should have been calculated on an hourly basis i.e. dynamic simulation. The intention with this study has been to demonstrate the impact of different parameters influencing the PEF and CO_2 emissions from a CHP based on bio, delivering heat to a district heating grid.

ACKNOWLEDGEMENT

This work is made possible by the PhD project; Primary Energy Efficiency (PEE) where Nordic Energy Research is the main financial contributor with additional support from the district heating/energy industry in the respective participating countries.

Also, the simulation carried out in [22] has been an essential part of this study.

FURTHER INFORMATION

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ENERGY AND EXERGY ANALYSIS OF DISTRICT HEATING SYSTEMS

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Keywords: exergy, district heating

ABSTRACT

The concept of exergy is defined and applied to district heating systems. The influence from different reference state conditions and system boundaries are explained in some detail. The aim is to show the simplicity and value of using the concept of exergy when analyzing district heating processes. The exergy factor is introduced and applied for a number of Swedish and Danish district heating systems. This varies from 14.2% to 22.5% for Swedish district heating systems. The higher the exergy factor, the more the exergy losses in the passive conversion towards space heating. Large losses revealed in an exergy treatment of a process should be seen as a challenge to achieve technical improvements of the system.

INTRODUCTION

The exergy concept is of essential importance to engineering in the design of energy systems and in order to meet environmental constraints. A thorough understanding of exergy, providing valuable insights into the concepts of efficiency, environmental impact and sustainability of energy systems are required by any engineer or scientist working in the area of energy systems and the environment [1].

Energy is related to the first law of thermodynamics, and exergy is related to the second law of thermodynamic. Energy is neither produced nor consumed; it is only converted from one form to another. Energy is always conserved and balanced in accordance with the first law of thermodynamics. In real processes exergy is always partly destroyed, the total exergy input always exceeds the total exergy output, this imbalance is due to exergy destruction, which is also called availability destruction, irreversibility, and lost work.

The exergy method is a useful tool for furthering the goal of more efficient energy-resource use, for it enables the locations, types, and true magnitudes of wastes and losses to be determined. The applications of exergy method are applied in a wide field. It covers society (e.g. [2-4]), industry (e.g. [2, 5]) as well as biological processes (e.g. [6]) and ecosystems (e.g. [7]).

District heating system is a system to distribute hot water to a number of buildings for space heating and hot water services. Earlier studies were dealing with energy, and rarely using exergy analysis. Only some studies of district heating system based on geothermal heat have used exergy analysis [8-14]. These studies focus on exergetic and exergoeconomic analysis of different geothermal district heating systems in Turkey.

EXERGY

Energy is sometimes defined as work which is not correct. Work is but a form of energy. Energy should instead be defined as motion or the ability to produce motion. [2] This is certainly a less specific but a more correct definition. Energy is also conserved in all processes.

In 1824, Carnot published a relation between heat and work, which Kelvin later made explicit and finally resulted in formulation of the second law of thermodynamics [15]. Gibbs expressed the general relation for work as early as 1873 [16]. But not until 1956 did Rant [17] suggest the name exergy and a general definition was given by Baehr [18] in 1965. These works are some of the important steps in the definition of exergy.

Exergy is the maximum amount of work that can be extracted from a system [6]. If exergy is defined as the maximum work potential of a material or of a form of energy in relation to its environment, then the environment must be specified, i.e. a reference environment. Usually average values of the earth are selected, i.e. reference temperature T_0 is 298.15 K and the reference pressure P_0 is 1 atm. However, the earth is not in equilibrium, actually it is far from equilibrium. The temperature varies from place to place. In some cases a local temperature should be used as reference temperature, e.g. when considering space heating or air-conditioning systems [6].

Thus, the energy and exergy concepts can be expressed in the following way: (1) energy is motion or ability to produce motion and (2) exergy is work (ordered motion) or ability to produce work [2]. The laws of thermodynamics may be formulated accordingly: (1) energy is conserved in a process (1st law, law of energy conservation) and (2) exergy is conserved in a reversible process, but consumed in an irreversible (real) process (2nd law, law of exergy).

The exergy E of a system is expressed by:

$$E = U - P_0 V - T_0 S - \sum_i \tilde{\mu}_{i0} n_i \tag{1}$$

where U, V, S, and n_i denote extensive parameters of the system (internal energy, volume, entropy, and the number of moles of different chemical materials i) and P_0, T_0, and $\tilde{\mu}_{i0}$ are intensive parameters of the environment (pressure, temperature, and generalized chemical potential). These terms may be described accordingly: U is the energy carried within the system itself, part of this energy is used as work, i.e. exergy. This part is defined by the last two terms. P_0V is the work captured as a volume V that occupies a space of the environment of pressure P_0. This is pure work. T_0S is the part of the energy U, which is useless due to lack of order S, or heat at ambient temperature T_0. Similarly, the last term is another useless part of the energy U. In this case it is as substances at ambient states. The energy that is carried by substances can only be used "down to" the level that is given by the environment. This is similar to the available potential energy of a waterfall or the carrying capacity of a ship, which is the total capacity minus the ballast. The exergy E of a system may be written as:

$$E = S(T - T_0) - V(P - P_0) + \sum_i n_i(\mu_i - \mu_{i0}) \tag{2}$$

We clearly see that exergy approaches zero as the system approaches equilibrium with the environment, i.e., $T = T_0$, $P = P_0$ and $\mu_i = \mu_{i0}$. The effects of electricity, magnetism, gravity, radiation, etc. can also easily be added to this expression.

Analogously, the exergy of a flow can be written as:

$$E = H - T_0S - \sum_i \tilde{\mu}_{i0} n_i \tag{3}$$

where H is the enthalpy, which captures the internal energy U and the external energy P_0V in a way that simplifies calculations.

Reference temperature

It is important that the reference state is fully specified completely for an exergy analysis. This includes the temperature, pressure and chemical composition of the reference environment. Consequently, the results of exergy analyses are relative to the specified reference environment. In this paper exergy is only related to temperature which is modelled after the actual local environment, i.e. the outdoor temperature. The heat loss and temperature drop along the district heating pipe is neglected in this study; and the phase of hot water is not changed.

Exergy factor

Exergy factor is defined as the relation between exergy and energy, i.e. E/Q, where E is the exergy and Q is thermal energy or heat.

The exergy factor of energy transferred as heat at a constant temperature T, i.e., a heat reservoir, in an environment of temperature T_0 then becomes

$$\frac{E}{Q} = \left|\frac{T_0 - T}{T}\right| \tag{4}$$

which is represented by the upper curve in Fig. 1. The ratio $(T_0 - T)/T$ is also known as the Carnot factor. We also see that a cold system contains exergy which increases rapidly with decreasing temperature.

The exergy factor of energy transferred as heat from a limited system at temperature T, e. g., a substance m with specific heat $c_p(T)$, becomes

$$\frac{E}{Q} = \frac{\int_{T_0}^{T} \frac{T - T_0}{T} m c_p(T) dT}{\int_{T_0}^{T} m c_p(T) dT} \tag{5}$$

If we assume that the specific heat is a constant, this becomes

$$\frac{E}{Q} = 1 - \frac{T_0}{T - T_0} \ln \frac{T}{T_0} \tag{6}$$

see the lower grey curve in Fig.1

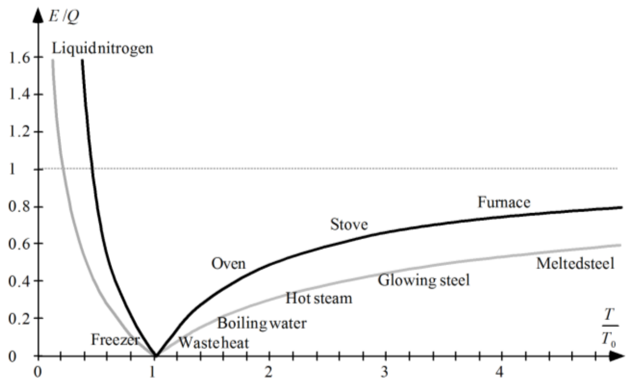


Fig. 1 Exergy factor (E/Q) of heat and cold as a function of ratio of temperature to environment temperature.

Space heating based on district heating, a network of hot water distribution for several houses and regions, is common in many colder parts of the world. The exergy factor of district heat becomes

$$\frac{E}{Q} = 1 - \frac{T_0}{T_s - T_0} \ln \frac{T_s}{T_0} \tag{7}$$

where T_s is the temperature of the supplied heat, i.e., the temperature of the hot water used by the consumer for space heating. This supply temperature in the distribution system varies from 55 °C to 200 °C [19] on different distribution systems. For a system the temperature maintained at about 85 °C (T_s = 358.15 K) at outdoor temperatures above +2 °C (T_0 = 275.15 K) and is subsequently raised in inverse proportion to the outdoor temperature, up to 120 °C (T_s = 393.15 K) at an outdoor temperature of below -20 °C (T_0 = 253.15 K). The exergy factor will thus vary with the outdoor temperature according to the lower grey curve in Fig. 2. The exergy factor is varying stepwise between about 0.10 and 0.22 when the temperature decreases from +20 to -30 °C.

But, since only a part of the supplied heat is used by the consumer, i.e., the water is returned at a temperature above the outdoor temperature, the exergy factor of the actually used heat becomes

$$\frac{E}{Q} = 1 - \frac{T_0}{T_s - T_r} \ln \frac{T_s}{T_r} \qquad (8)$$

where T_r is the temperature of the returned water. When this is assumed as 55 °C (T_r = 328.15 K), we instead get the upper black curve in Fig. 2, which is, of course, above that of the delivered heat. As we expected the exergy factor becomes higher, since the heat now is taken out at a higher average temperature. It now varies stepwise between about 0.15 and 0.32.

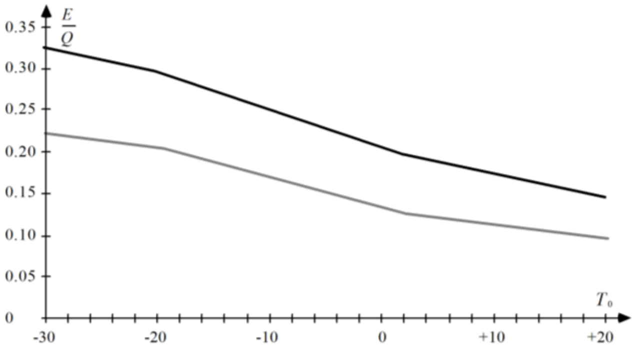


Fig. 2 Exergy factor (E/Q) of district heat.

EXERGY IN DISTRIBUTION SYSTEM

District system in Helsingborg and Marstal

As case study we will examine two district heating system: Helsingborg and Marstal district heating system.

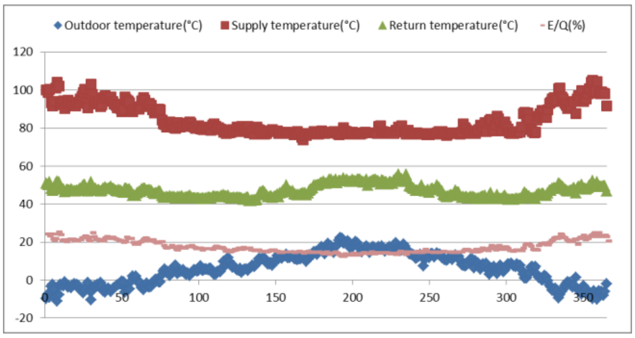
Helsingborg had a population of 129000, of which 96% lived in urban areas. During 2010, the district heating system had a heat supply of 4207 TJ to the network. The corresponding quantity of heat sold to customers was 3715 TJ, which gave a relative annual distribution heat loss of 11.7%. This heat loss share is somewhat higher than the typical average system, since 38% of all one-family buildings are connected to district heating in Helsingborg [19].

Helsingborg district heating system (shortly called Helsingborg later) mostly come from Öresunds power plant, and it had an annual average supply temperature of 84 ºC and an annual average return temperature of 47 ºC with an annual average outdoor temperature of 5.8 ºC during the analysed year.

Marstal district heating system (shortly called Marstal later) is the biggest solar district heating energy system in the World; it is in operation found in Denmark at the small town Marstal. It comprises arrays of solar collectors with a total active area of 18000 m^2 are placed on the ground. Seasonal storage is performed in a large insulated pond. Marstal had an annual average supply temperature of 74 ºC and an annual average return temperature of 36 ºC with an annual average outdoor temperature of 10.9 ºC during the analysed year.

The Marstal management has hereby proven that it is possible to operate a whole district heating system very near to the theoretical supply and return temperatures. Most Swedish district heating systems obtain substantially higher return temperatures than what should be obtained from an error free substation with respect to available technology and system solutions [18].

The average supply and return temperatures of Helsingborg district heating system are 10 ºC more than Marstal district heating system. The temperature in Marstal is about 5.1 ºC warmer than in Helsingborg.



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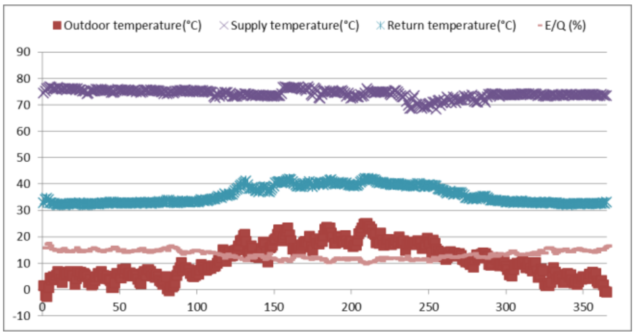


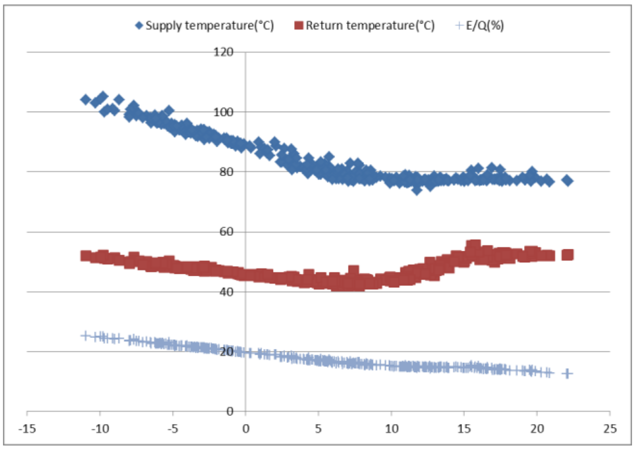
(b)

Fig. 3 Average outdoor temperature, average supply and return temperature and exergy factor (E/Q) vs. days (from 1st January to 31st of December) during one year in (a) Helsingborg district heating system, Sweden (b) Marstal district heating system, Denmark.

Figure 3 shows the average outdoor temperature, average supply and return temperature and exergy factor (E/Q) from 1st of January to 31st of the December for the two systems. The average E/Q is 0.174 for Helsingborg, and 0.133 for Marstal since the Helsingborg has higher supply and return temperature than Marstal, they use higher quality energy. The higher temperature is used, the more exergy is destroyed. From this point view, Marstal is better than Helsingborg.

Exergy factor is related to supply and return temperature and outdoor temperature as shown in Figure 4. When the outside is cold weather, the supply temperature is higher in Helsingborg as well as higher exergy factor. Let look at both systems when the outdoor temperature is around 0 °C, the supply/return temperature is 88/45 °C and 76/34 °C and the exergy factor is 0.19 and 0.16 for Helsingborg and Marstal respectively. During summer season space heating is not need, the supply and return temperature is closer, the lower exergy factor, i.e. less exergy losses.

Figure 5 shows the variations take place seasonally for the daily energy and exergy loads. The energy load is more than the exergy load during to exergy is a part of energy which can be utilized. The variation of energy load is greater than the variation of exergy load. Both energy and exergy loads are minimal during summer season since only hot water need for the domestic use. However, the energy load is dropped much more than the exergy load during the low quality of energy.



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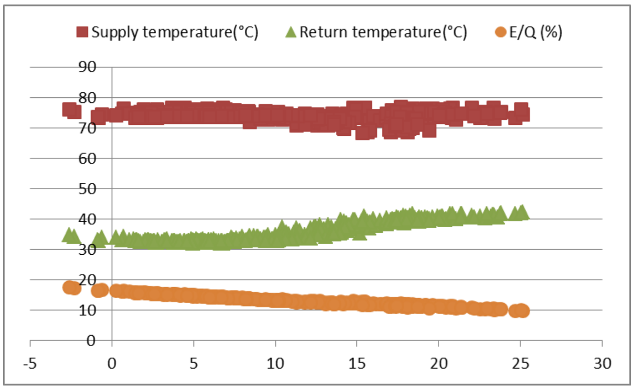


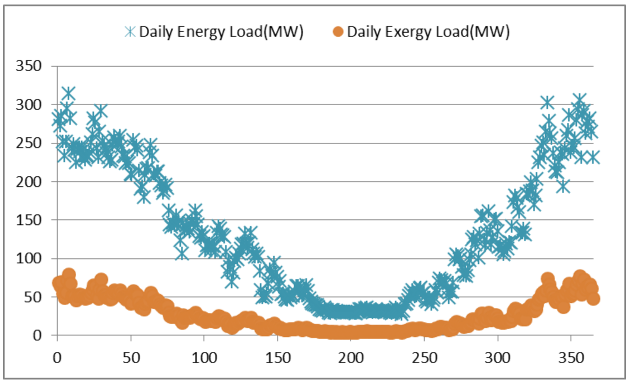
(b)

Fig. 4 Average supply and return temperature and exergy factor (E/Q) vs. outdoor temperature during one year in (a) Helsingborg, Sweden (b) Marstal district heating system, Denmark.

142 district systems in Sweden

Figure 6 shows exergy factor (E/Q) of 142 district systems in Sweden. The annual supply temperature varies from 66.7 °C (case 41) to 115.1 °C (case 117), and the annual return temperature varies from 37.5 °C (case 1) to 72.2 °C (case 142) where the outdoor temperature varies from -0.1 °C (case 132) to 10.3 °C (case 128) as listed in Table 1.

Among the 142 district systems the maximum exergy factor is 0.225 in case 139 which has the annual average supply/return and outdoor temperature is 110/64 °C and 6 °C respectively. The minimum exergy factor is 0.142 in case 4 which has the annual average supply/return and outdoor temperature is 70/40 °C and 8 °C respectively. The average exergy factor is 0.174.



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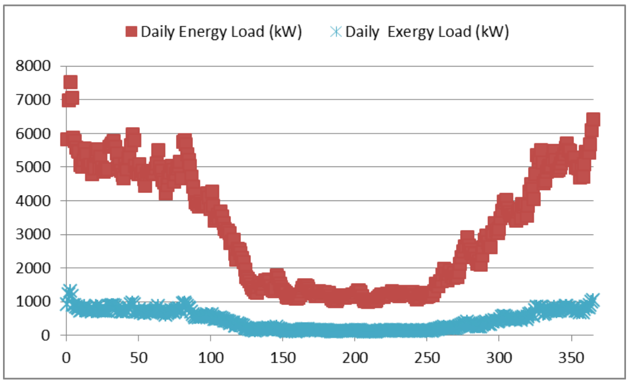

(b)

Fig. 5 Average daily energy and exergy loads vs. days (from 1st January to 31st of December) during one year in (a) Helsingborg, Sweden (b) Marstal district heating system, Denmark.

Table 1 List of cases with maximum/minimum and average of supply/return and outdoor temperature and exergy factor in 142 district system.

Case	**T_s (°C)**	**T_r (°C)**	**T_0 (°C)**	**E/Q**
41	66.7	45.6	7.6	0.147
117	115.1	51.1	9.1	0.206
1	82.4	37.5	7.0	0.158
142	94.6	72.2	6.8	0.215
132	85.6	53.8	-0.1	0.203
128	80.6	53.1	10.3	0.166
4	69.6	40.0	8.0	0.142
139	110.4	64.1	6	0.225
Avg. of 142	84.2	48.1	6.8	0.174

Comparing these two systems they have similarly outdoor temperature, however, larger difference in supply/return temperature, it causes the different exergy factor. Case 139 has the highest exergy loss among 142 district systems.

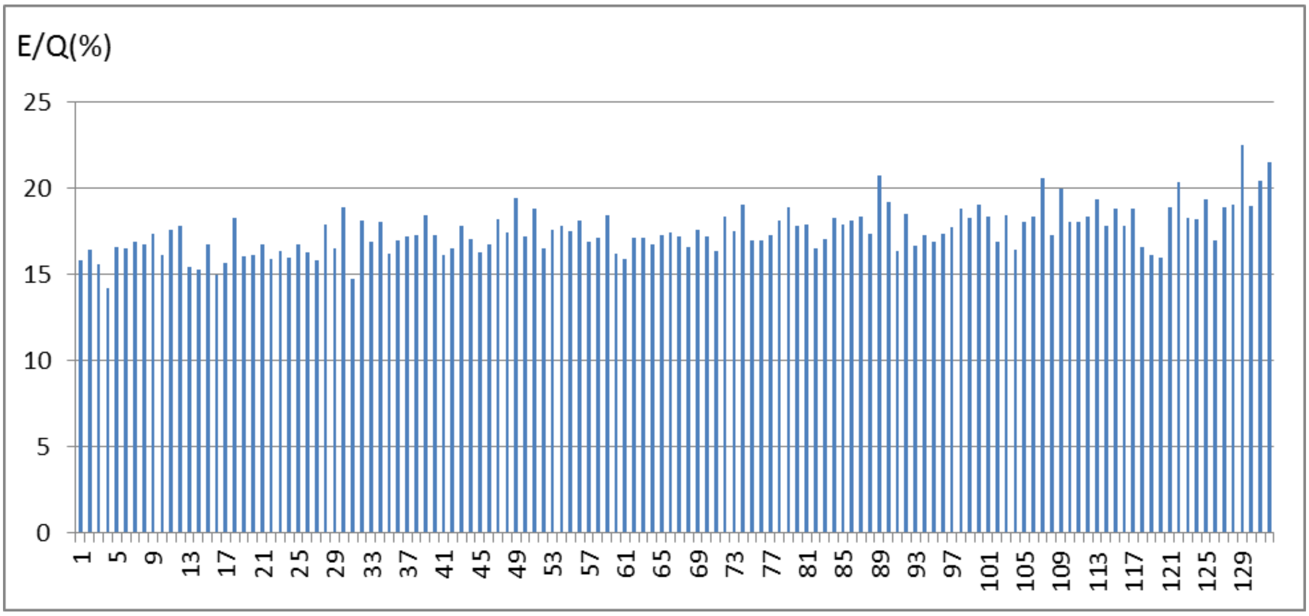

Fig. 6 Exergy factor (E/Q) for 142 district systems in Sweden.

CONCLUSION

In this paper 142 district systems in Sweden and Marstal district heating system in Denmark were examined with the exergy factor. E/Q varies from 14.2% to 22.5% for Swedish district heating systems, which the average E/Q for Marstal is 13.3%. The lower the exergy factor, the better district system is from the point of meeting the exergy need by the user, i.e., a space heating system. The exergy factor varies from system to system, and it is more related to supply and return system.

In this study the exergy loss is neglected which should be considered in future studies. Exergy analysis of the whole distribution system needs to be furthered studied in order to find out the more inefficient process.

FURTHER INFORMATION

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PRICING HEATING AND COOLING IN NON-PROFIT UTILITY ORGANIZATION

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Keywords: energy, exergy, costing methods, district energy

ABSTRACT

One of the basic ideas behind non-profit utility organization is that the prices of for instance provided heating and cooling should only be reflected by the production costs and expenses and not by the market prices. When the energy utilities are produced by the same thermal system to different costumers, apportioning the costs to each product and thus pricing them individually is nontrivial. In this study two thermoeconomic methods for apportioning the costs to heating and cooling provided simultaneously by an ammonia heat pump is demonstrated. In the first referred as energy costing a conventional thermoeconomic analysis is used. Here the ammonia heat pump is subjected to a thermodynamic analysis with mass and energy balance equations. In the second referred as exergy costing an exergy based economic analysis is used, where exergy balance equations are used in conjunction with mass and energy balance equations. In both costing methods the thermodynamic is followed by an economic analysis which includes investment and operating costs. For both methods the unit cost of heating and cooling is found and compared. The analysis shows that the two methods yield significantly different results. Energy costing tends to overprice the cost of cooling and may obstruct efficient use of energy. Exergy costing provides the most rational cost apportioning for the heating and cooling costumers.

INTRODUCTION

Energy reduction by means of heat recovery is considered to be an effective way of reducing CO_2 emission. Simultaneous heating and cooling systems where heat is moved from one client to another client instead of rejecting it to the environment is an example of this. By using district cooling and heating this can be realized in a large scale due to its flexibility. In Denmark (2011) for instance, more than 60% of the household heating installations are district heating [1] and the district heating companies are non-profit company according to the law of heat supply [2]. With the ever increasing focus on energy efficiency thermal process companies, hospitals, supermarkets etc. should utilize waste heat from their cooling systems.

The premise for this study is a scenario where both heating and cooling are supplied by a non-profit company. One of the basic ideas behind such an organization is that the prices of the products should only be reflected by the production costs and not by the market prices. When the products are produced by the same thermal system to different costumers, apportioning the costs objectively to each product individually is nontrivial.

A good cost/pricing method should promote lowest possible energy uses and somehow be rational to both the heating and cooling costumers.

In this study two cost apportioning methods referred as energy costing and exergy costing are presented and compared. The first is an ad hoc energy based method. The second is an exergy based method.

The total cost of a district heating and cooling system consists of the cost of conversion, transportation and distribution; where conversion is in this case the owning and operation of the heat pump. With focus on comparison of costing methods only the conversion cost is analyzed in this study.

Several studies have been performed on apportioning the cost in multiple products thermal systems. In [3] a non-exergy based method is used for apportioning cost to electricity and heating in a monopoly company. In [4] an exergy cost accounting method with a non-exergy method is used for a co-generation of power and desalted water. In [5] it is suggested that the heating cost should also be reflected by the temperature and exergy loss and not only by the amount of heat transfer in a district heating transmission line.

The cost apportioning methods can be divided in two categories: non-exergy and exergy based. Common for the non-exergy based methods is the lack of coherency and clear structure and can therefore be called ad hoc methods. Many researchers recommended that cost accounting based on exergy instead of energy is the most rational way of distributing the costs to various streams of a thermal system [6-8]. This will be demonstrated in this study.

The exergy methods have been developed for more than two decades in the quest for optimizing complex thermal systems. Several branches of exergoeconomic have emerged with [9-12] as some of the first original guiding studies. Some of these provide methods for allocating the cost to each stream of a system and can thus also be used for apportioning the product costs. One of these is the SPECO method [13] which will be used in this study.

Even though cost allocation methods have been demonstrated to various complex systems with success, they have not been adopted by the non-profit organizations. This study will therefore demonstrate the two costing methods on an ammonia heat pump providing simultaneous heating and cooling. The unit costs of heating and cooling with respect to the associated temperatures are to be found. As a case the cooling capacity is fixed while the heating capacity will vary according to temperatures of the heating and cooling sides of the heat pump.

MODELS AND METHODS

The schematic diagram of the heating and cooling ammonia heat pump system is shown in Fig. 1. The heat pump consists of four components: evaporator, compressor, condenser and valve. The evaporator and the condenser are both water coupled intended for district cooling and heating respectively. The following general assumptions are made:

- The processes are in steady state.
- Non-isentropic process for the compressor with fixed efficiency.
- State 1 is saturated vapor i.e. quality = 1.
- State 3 is saturated liquid i.e. quality = 0.
- Heat transfer with the ambient is neglected.
- Kinetic and potential energy changes are neglected.

Thermodynamic analysis

In order to determine the power consumption P an energy analysis of the cycle is applied. For conducting exergy based economic analysis later on an exergy analysis is also applied. The governing equations for the different components are listed below. h refers to the state point enthalpies, $\dot{m}$ to mass flows, η to efficiencies, $\dot{W}$ to power, $\dot{Q}$ to heat transfer, $\dot{E}$ to exergy transfer, e to specific exergy and $\dot{E}_D$ exergy destruction. The subscript should be self-explanatory. For the compressor (c), the isentropic efficiency $\eta_{is,c}$, energy and exergy balance we have respectively:

$$\eta_{is,c} = \frac{h_{2s} - h_1}{h_2 - h_1}, \tag{1}$$

$$\dot{W} + \dot{m}_{NH3}(h_1 - h_2) = 0 \tag{2}$$

and

$$\dot{W} + \dot{m}_{NH3}(e_1 - e_2) - \dot{E}_{D,c} = 0. \tag{3}$$

The power consumption is found by:

$$P = \frac{\dot{W}}{\eta_{mo}} \tag{4}$$

where η_{mo} is the electric motor efficiency of the compressor.

For the evaporator (ev):

$$\dot{m}_{NH3}(h_4 - h_1) + \dot{Q}_{cold} = 0, \tag{5}$$

$$\dot{Q}_{cold} = \dot{m}_{H2O}(h_8 - h_9), \tag{6}$$

$$\dot{m}_{NH3}(e_4 - e_1) - \dot{E}_{D,ev} - \dot{E}_{cold} = 0 \tag{7}$$

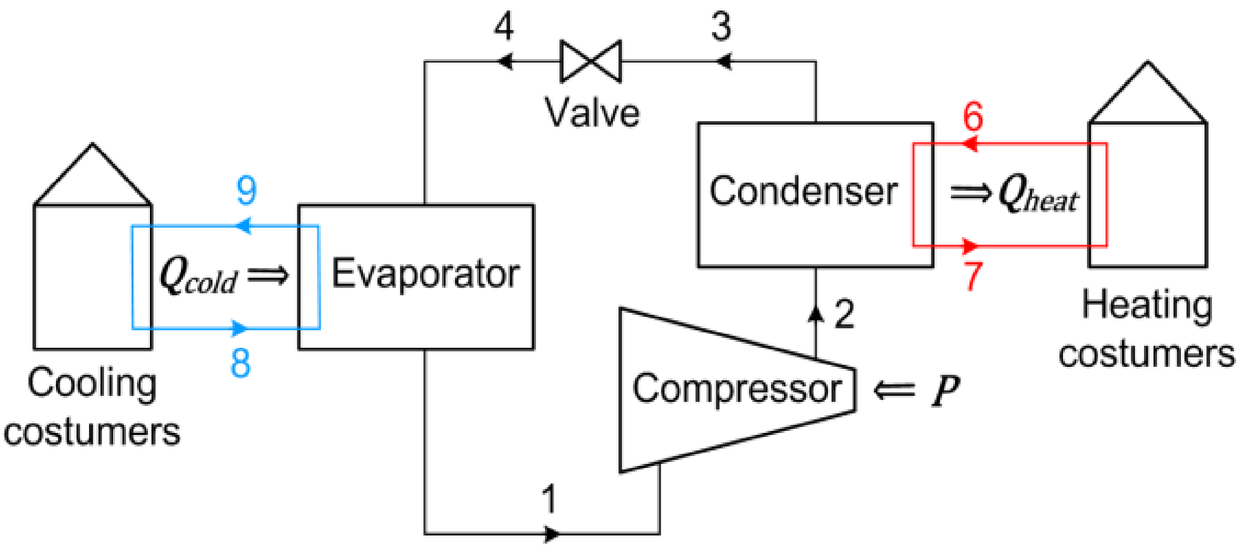

Fig. 1 Schematic diagram of the heating and cooling system.
Numbers refer to state points used in the analysis.

and

$$\dot{E}_{cold} = \dot{m}_{H2O}(e_9 - e_8). \tag{8}$$

For the condenser (co):

$$\dot{m}_{NH3}(h_2 - h_3) - \dot{Q}_{heat} = 0, \tag{9}$$

$$\dot{Q}_{heat} = \dot{m}_{H2O}(h_7 - h_6), \tag{10}$$

$$\dot{m}_{NH3}(e_2 - e_3) - \dot{E}_{cold} - \dot{E}_{D,co} = 0 \tag{11}$$

and

$$\dot{E}_{heat} = \dot{m}_{H2O}(e_7 - e_6). \tag{12}$$

For the valve (va):

$$h_3 - h_4 = 0 \tag{13}$$

and

$$\dot{m}_{NH3}(e_3 - e_4) - \dot{E}_{D,va} = 0. \tag{14}$$

Exergy of the stream at state k:

$$e_k = (h_k - h_0) - T_0(s_k - s_0), \tag{15}$$

where T and s is temperature and specific entropy respectively and the subscript 0 denotes the dead state.

Economic analysis

In this analysis only costs that are related to the thermodynamics of the heat pump will be considered. Costs of installation, land, contractor profits etc. are not considered or included. These costs must therefore be added to the costs that are found in this study to find the final prices.

The following general assumptions are made:

- Independent of size and operation condition the purchase costs of the components is constant. The validity of this will be shown later (Fig. 6).
- The heat pump system is not optimized thermoeconomically. However the design and operating condition are the same for both methods.

General economic analysis

As in a general economic analysis the cost balance of the heat pump system can be written as

$$C_{P,tot} = C_{F,tot} + Z_{tot} \tag{16}$$

It expresses that the total cost of producing the products $C_{P,tot}$ consists of the total fuel cost $C_{F,tot}$ and the total capital investment, maintenance and other costs Z_{tot}. Since the purpose of the heat pump is to provide both heating and cooling, we have to ensure that

$$C_{P,tot} = C_{heat} + C_{cold}, \tag{17}$$

where C_{heat} and C_{cold} are the heating and cooling cost respectively. The only energy source for the heat pump is electricity, so

$$C_{F,tot} = C_{el}, \tag{18}$$

where C_{el} is the cost of electricity consumption found by

$$C_{el} = uC_{el} \cdot OH \cdot P. \tag{19}$$

Here uC_{el} is the unit cost of electricity given in DKK per kWh. OH is the annual operation hours and P is the power consumption found previously in the thermodynamic analysis.

For simplicity only capital investment are considered here and thus

$$Z_{tot} = Z_c + Z_{ev} + Z_{co} + Z_{va}. \tag{20}$$

The capital investment of the component k is found by

$$Z_k = PC_k \frac{i(1+i)^n}{(1+i)^n - 1}, \tag{21}$$

where PC_k is the purchase cost, i is the effective annual interest rate and n is the number of year of the payment.

The final goal of the economic analysis is to find the unit cost of heating and cooling given in DKK per kWh. For the heating and cooling product we have respectively

$$uC_{heat} = \frac{C_{heat}}{Q_{heat}}, \tag{22}$$

and

$$uC_{cold} = \frac{C_{cold}}{Q_{cold}} \tag{23}$$

where Q_{heat} and Q_{cold} are the heat transfers found in the thermodynamic analysis. Below two costing methods of finding C_{heat} and C_{cold} are given. Here the subscripts en and ex indicate respectively that energy and exergy costing method is used.

Method 1 - energy based economic analysis

In this method the cost of the products reflects only on the amount of heat transfer, i.e. for heating

$$C_{heat,en} = \frac{Q_{heat}}{Q_{cold} + Q_{heat}} C_{P,tot} \tag{24}$$

and for cooling

$$C_{cold,en} = \frac{Q_{cold}}{Q_{cold} + Q_{heat}} C_{P,tot}. \tag{25}$$

In this way we ensure that equation (17) is fulfilled.

Method 2 - exergy based economic analysis

This method is based on the specific exergy economic thermoeconomic (SPECO) method [13]. The method involves setting up the cost balance for each component.

For the compressor (c):

$$c_2\dot{E}_2 = c_1\dot{E}_1 + c_c P + \dot{Z}_c. \tag{26}$$

For the evaporator (ev):

$$c_1\dot{E}_1 + c_{cold}\dot{E}_{cold} = c_4\dot{E}_4 + \dot{Z}_{ev} \tag{27}$$

and

$$c_1 = c_4. \tag{28}$$

For the condenser (co):

$$c_3\dot{E}_3 + c_{heat}\dot{E}_{heat} = c_2\dot{E}_2 + \dot{Z}_{co} \tag{29}$$

and

$$c_2 = c_3. \tag{30}$$

For the valve (va):

$$c_4\dot{E}_4 = c_3\dot{E}_3 + \dot{Z}_{va}. \tag{31}$$

The variables in these balances consist of the unit exergy cost c [DKK/kJ], capital investment cost rate $\dot{Z}$, exergy rate $\dot{E}$ and the power consumption P. The last two variables are found in the thermodynamic analysis. The capital investment cost rate $\dot{Z}$ for each component is found by:

$$\dot{Z}_k = \frac{Z_k}{OH}. \tag{32}$$

c_c is the unit cost of electricity which is assumed to be given. In equations (26) to (31) the unit exergy costs:c_1, c_2, c_3, c_4, c_{cold} and c_{heat} are the unknowns to be found. Completing this will determine the thermo economic model of the heat pump completely. Then the cost of heating and cooling can be found by respectively

$$C_{heat,ex} = \dot{C}_{heat} \cdot OH \tag{33}$$

and

$$C_{cold,ex} = \dot{C}_{cold} \cdot OH, \tag{34}$$

where $\dot{C}_{heat}$ and $\dot{C}_{cold}$ are defined as respectively

$$\dot{C}_{heat} = c_{heat}\dot{E}_{heat} \tag{35}$$

and

$$\dot{C}_{cold} = c_{cold}\dot{E}_{cold}. \tag{36}$$

Again as in the energy based method, these definitions ensure that equation (17) will be fulfilled.

RESULTS AND DISCUSSION

The equations specified in previous section are implemented in the equation solver program: Engineering Equation Solver - Commercial V.8.948 with built-in fluid properties, where *Water* is used for the H_2O and *R744* is used for the NH_3.

To avoid pinch problems in the heat exchangers following constraints are used:

$$T_7 = T_3 \tag{37}$$

and

$$T_9 = T_4 + 3\,°C. \tag{38}$$

To keep the water mass flow “fairly” constant, when T_9 is varied :

$$T_8 = T_9 + 6\,°C. \tag{39}$$

Without this constraint the mass flow will become infinity large when T_9 is varied towards T_8.

If otherwise stated the nominal input data given in Table 1 is used.

Table 1. Nominal input parameters.

T_6 [°C]	40	P_6 [bar]	3
T_7 [°C]	70	P_7 [bar]	3
T_9 [°C]	10	P_8 [bar]	3
T_0 [°C]	20	P_9 [bar]	3
P_0 [bar]	1	PC_c [DKK]	200,000
$\eta_{is,co}$ [%]	75	PC_{ev} [DKK]	100,000
η_{mo} [%]	90	PC_{co} [DKK]	50,000
$\dot{Q}_{cool}$ [kW]	250	PC_{va} [DKK]	20,000
OH [h]	2,000	i [%]	5
uC_{el} [DKK/kWh]	1	n [-]	20

As a result of the energy balancing equations, the constraints in equations (37) to (39) and the nominal input parameters in Table 1, the cycle of the heat pump and the temperatures of the cooling and heating fluids is shown in Fig. 2.

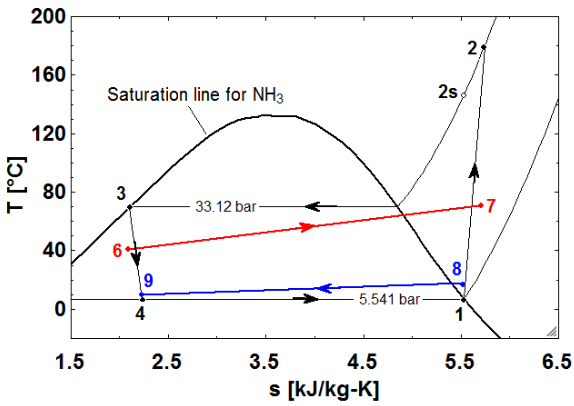

Fig. 2 Temperature – entropy diagram of the heat pump cycle with heating and cooling fluids.

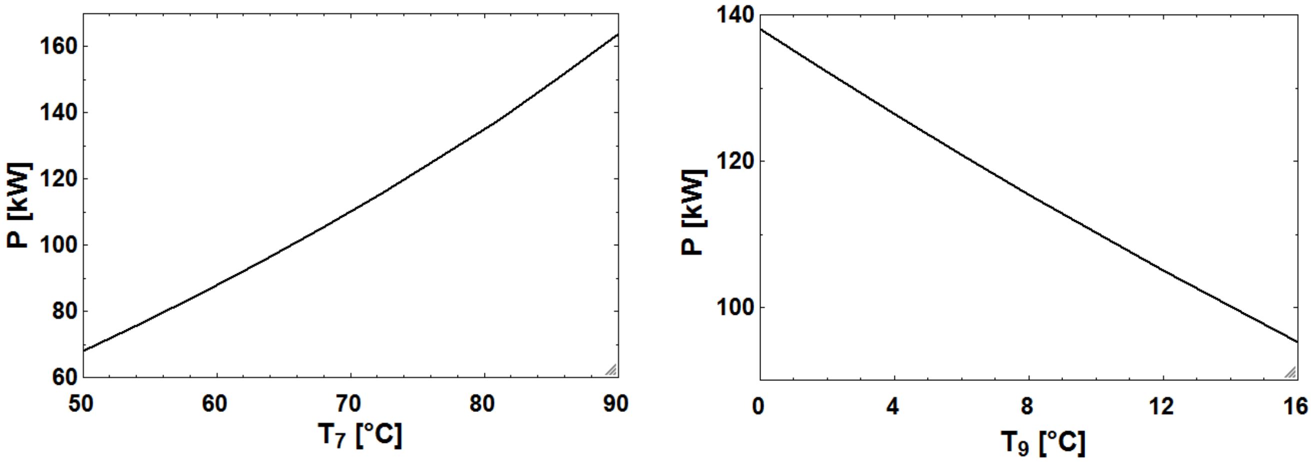

Fig. 3 Power consumption.

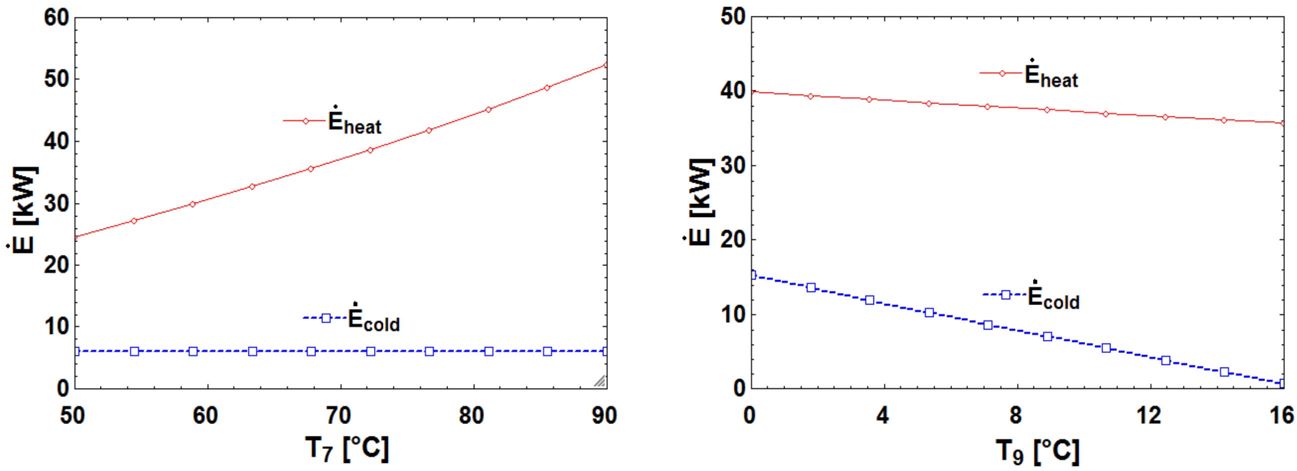

Fig. 4 Exergy transfer to the cooling and heating costumers.

Parametric studies on the temperatures T_7, T_9 and T_0 is carried out to investigate their effect on the thermodynamic performances and the costs. T_7, T_9 and T_0 are referred to as heating, cooling and surrounding temperature respectively. As expected the power consumption increases when the heating temperature increases (Fig. 3 left) or when the cooling temperature decreases (Fig. 3 right). This will reflect the costs as discussed below.

Fig. 4 shows respectively the exergy transfers to the cooling and heating clients with respect to the corresponding temperatures. Increasing the heating temperature will increase the exergy transfer to the heating clients (Fig. 5 left). This will also reflect the costs discussed below. Again similarly effects exist for the cooling temperature (Fig. 4 right).

Fig.5-7 show the costs of cooling and heating with the energy and exergy costing methods. For verification Fig. 5 shows the total annual cost expressed by equation (16) and (17). It shows as expected that the total annual cost is independent of costing method used but is of course dependent of the cooling and heating temperatures, which is in agreement with Fig. 3 and 4. This is due to higher electricity consumption and recall that the purchase costs of the components is assumed to be constant.

The unit costs however depend strongly on the costing method as shown in Fig.7. As shown for the energy costing method, the unit costs are the same for cooling and heating. This means that when the heating temperature increases it will be more costly for the cooling clients even though the cooling temperature and thus the cooling quality remains constant (Fig. 6 left). This seems to be irrational. This irrationality is not seen with the exergy costing method. Here the heating clients will almost entirely be accounted for the increase heating temperature. Again similar effects exist for the cooling temperature (Fig. 6 right). If the energy costing method is used there is little motivation for the heating clients to relax their temperature demand, which at the end yield less total energy efficiency.

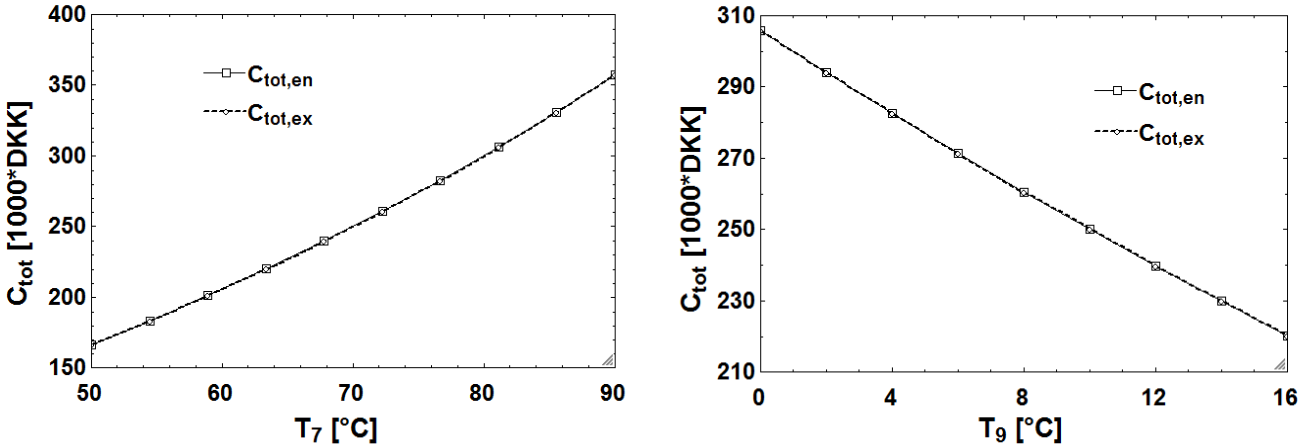

Fig. 5 Total annual costs with energy and exergy costing method.

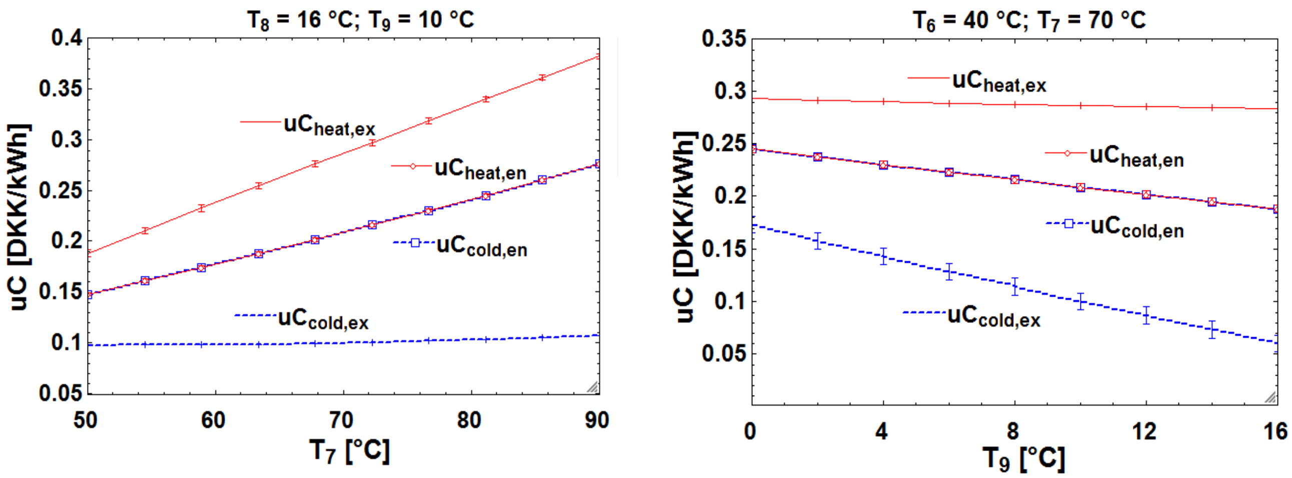

Fig. 6 Unit costs with energy and exergy costing method.

It is also most reasonable that heating is more costly than cooling, since there is most exergy transfer to the heating clients. In other words the heating clients have the highest thermodynamic demand, and therefore should pay the most.

Note that the results in Fig. 6 are shown with error bars which account for the uncertainty of the purchase cost of the heat exchanger. For the heating unit cost the uncertainty is +/-50% for the condenser and likewise for the cooling unit cost and the evaporator. It shows that the assumption of constant purchase cost of the heat exchangers is acceptable.

Fig. 7 shows the surrounding temperature and thus seasonal effect on the unit costs. With the energy costing method the cooling and heating unit costs are the same regardless of the surrounding temperature. Again this seems to be irrational. When the surrounding temperature decreases towards the cooling temperature and below, its cost should decreases since the cooling clients can achieved cooling by cheaper mean like for instance free cooling. If this is not the case there is no motivation for the cooling clients to be connected to this type of simultaneous cooling and heating system. Again the energy costing method seems to obstruct efficient use of energy.

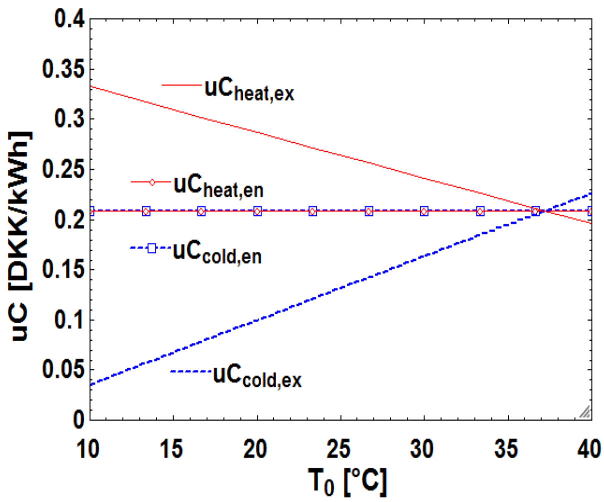

Fig. 7 Unit cost with respect to the surrounding temperature.

FUTURE WORK

It should be repeated that the costs found in this study are only the costs that can be apportioned thermodynamically and economically. Costs of installation, land, contractor profits etc. are not included. Also the costs of transportation and distribution (piping and heat/exergy losses) should be included to price the products finally. The latter can be done in similar way as done in this study using the SPECO method of exergy costing, since the method general which can be used for all type of thermal system.

In this study the electricity price is fixed and no discussion of taxation of this has been done. It has been demonstrated that cost apportioning based on exergy are the most rational method and it would be interesting to investigate how exergy costing methods can be incorporated in taxation of energy in general.

CONCLUSION

It this study the cost of heating and cooling provided simultaneously by an ammonia heat pump has been apportioned with two costing methods – energy and exergy costing. Parametric study on the heating, cooling, and surrounding temperature has been carried out. It has been demonstrated that the two methods yield significant different results. Energy costing prices the unit cost of heating and cooling equally independent of the quality heat transfer, and it tends to overprice the cost of cooling in an irrational matter. Energy costing will also not encourage rational heating and cooling temperature demand and thus promote efficient use of resource. These flaws are not seen with exergy costing, since it has taken the quality of heat transfer in to account. It can therefore be concluded that exergy costing is the most rational thermo economic method.

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A METHOD FOR ASSESSING AND COMPARING STRATEGIES FOR THE REDUCTION OF CO_2 EMISSIONS ON A DISTRICT HEATING NETWORK – APPLICATION TO A CASE STUDY IN POLAND

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Keywords: District Heating Network, CO_2 mitigation, CO_2 abatement cost, Combined Heat and Power, Energy mix

ABSTRACT

District Heating (DH) is widely recognized as a technology that can have a significant role in the reduction of CO_2 emissions and the development of local and renewable resources. But fossil fuels still remain the predominant source of primary energy. To meet the growing constraints on CO_2 emissions, it is a matter of urgency to set up solutions to reduce fossil fuel emissions from DH networks

This study aims to assess and compare, from an economic and environmental point of view, the actions potentially available to reduce CO_2 emissions on DH networks: energy efficiency, renewable resources, carbon capture and storage, etc.

In this purpose, a model has been developed to simulate the operation of the DH network and its production units. The model is calibrated on a reference case which describes the operation of the existing installations. Subsequently, each action is evaluated in terms of CO_2 reduction potential and cost per ton of CO_2 avoided, compared to this reference case.

This methodology has been applied to a DH network in Poland, providing heating for 250,000 people and emitting 1.5 $MtCO_2$/year. A CO_2 abatement curve has finally been constructed with the aim of ranking these actions by merit order.

INTRODUCTION

Fossil fuels (coal, natural gas, and oil) represent the greater part of the primary energy consumption of District Heating networks in Europe and more particularly in Central and Eastern European countries [1]. Meanwhile, District Heating network operators have to face growing regulatory and economic constraints on CO_2 emissions (European Union - Emission Trading System, European Union climate and energy package, increasing fossil fuel cost …). It is a matter of urgency to imagine and to set up solutions to reduce fossil-fuel CO_2 emissions related to European District Heating networks.

The purpose of this study is to help District Heating network operators and decision-makers selecting the most cost-effective strategies to reduce their CO_2 emissions. Previous works or studies already tried to answer this question but proved either to be too generic (e.g. McKinsey's Pathways to a Low Carbon Economy [2]) or, on the other hand, too specific (e.g. feasibility studies) to assess and compare all the actions potentially available to reduce CO_2 emissions on a given District Heating network. Based on this observation, a method and a tool have been developed to simulate the operation of the District Heating network and evaluate each action in terms of CO_2 reduction potential and cost per ton of CO_2 avoided.

DESCRIPTION OF THE METHOD

The purpose of the study is to compare all the actions or strategies leading to CO_2 emission reduction, for a specific District Heating network. This comparison will be carried out on the basis of the potential for reduction of CO_2 emissions (CO_2 abatement potential) and the cost per ton of CO_2 avoided (CO_2 abatement cost).

For each of the strategies, the magnitudes involved (potential for reduction of CO_2 emissions and cost per ton of CO_2 avoided) are evaluated compared to the benchmark of facility operating data for the reference year. For this purpose, a technical and economic model in Excel format has been drawn up, describing the entire energy conversion process, from primary energy consumption (fuels) to final energy production (electricity, heat). These energy calculations are made on an annual value basis and are used as entry data for the economic and environmental (CO_2) balance sheets. The strategies were documented from a number of different sources (feasibility studies, experience feedback, Veolia Environnement Research & Innovation expertise or bibliography).

The main steps of the method are summarized in Fig.1.

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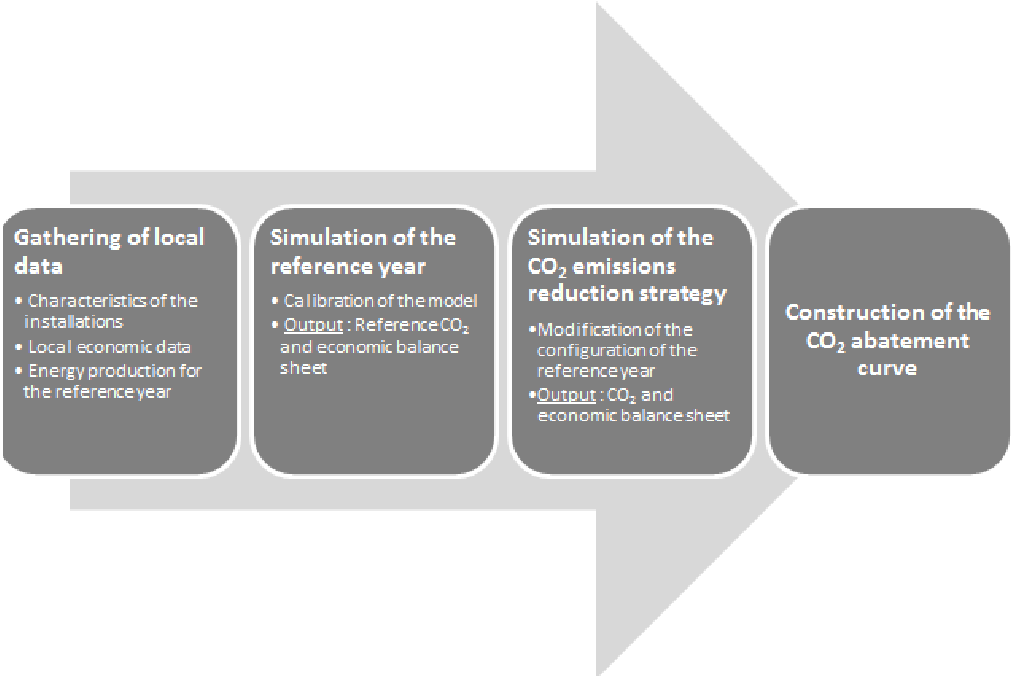

Fig. 1 General description of the method

Main energetic assumptions of the model

The different strategies were modeled by changing the configuration of the reference year. Consequently, a number of hypotheses were adopted in the different models.

The first and the most important function of a cogeneration production unit is to meet the demand from the district heating network at all times. Except when otherwise stated, all simulations are performed on the basis of constant heat demand by the district heating network, equal to the demand of the reference year. The same principle is applied to the electricity production: for each strategy, the electricity output has to be strictly identical to the output value of the facility reference year, any shortfall or surplus in plant power output being compensated for by MWhe taken off from or fed into from national grid.

By default, the performances of the different elements of the installation (boiler efficiency, turbine efficiency, heat distribution efficiency) are supposed unchanged, equal to the value of the reference year.

For all the actions implying either a modification of the heat consumption on the network, or the addition of a new production unit, the following assumptions are made:

- The proportion of each fuel in the primary energy mix of each production unit is supposed to remain unchanged, equal to the value of the reference year.

- The load adjustment between the production units is not modeled;

- The new production units (mainly renewable or waste heat resources) are supposed to be operated as base-load units.

Main economic assumptions of the model

The economic balance sheet is calculated taking into account:

- Revenues from energy selling (electricity to the national grid and heat to the clients of the District Heating network) and expenditure on fuel. If applicable, feed-in-tariffs rewarding the production of electricity from renewable or waste heat resources are considered.

- Additional operation & maintenance expenses (OPEX) compared to the reference year.

- Additional capital expenditure (CAPEX), compared to the reference year. CAPEX balance sheet includes, for all the strategies, the expenditure on equipment and the costs arising from design, engineering, construction works and civil engineering.

Trading in CO_2 quotas from European Union Emission Trading System (purchase of quota shortfall, resale of quota surplus), is not included in the economic balance sheet.

The lifetime of the emission abatement project is assumed to be 20 years for all strategies contributing to it. No discounting to present day values of the costs or benefits has been performed. The balance sheets are drawn up excluding VAT and similar, and before corporation tax. Finally, tariff data (electricity feed-in tariff, price for sale of heat, price of fuel, etc.) are assumed to be constant and unaffected by inflation.

Main assumptions for CO_2 emissions calculation

The calculation of CO_2 emissions takes into account direct fossil CO_2 emissions i.e. the emissions resulting from the combustion of fossil fuels.

Besides, as stated before, the simulations are carried out at constant net electricity production, any shortfall or surplus in power output compared to the reference year being compensated by MWhe from national grid. The CO_2 impact of the MWhe taken off from or fed into the national grid, characterized by a given CO_2 content in $kgCO_2/MWhe$, is taken into account in our CO_2 emissions calculation.

The amount of CO_2 emissions avoided (in $ktCO_2/year$) for each strategy is thus calculated following the formula (1)

$$\Delta CO_2{}^{strat} = \sum_{fuel}[(q_{fuel}{}^{ref} - q_{fuel}{}^{strat}) \times f_{CO_2,fuel}] - (E_{el}{}^{ref} - E_{el}{}^{strat}) \times f_{CO2,grid} \quad (1)$$

Where q_{fuel} is the annual amount of *fuel* consumed

$f_{CO2,fuel}$ is the CO_2 emission factor of the *fuel*

$f_{CO2,grid}$ is the CO_2 emission factor of the electricity from the national grid

E_{el} is the annual electricity production

When a CO_2 capture system is present, the annual amount of CO_2 captured is subtracted from formula (1).

APPLICATION TO THE STUDY OF A DISTRICT HEATING NETWORK IN POLAND

Context

The method has been applied to a district heating network in Poland, providing heating for more than 250,000 people and emitting 1.5 $MtCO_2$ per year (2008). Table 1 gives the main characteristics of the network.

Table 1 Main characteristics of the District Heating network

Type	Hot water network (110-70°C/50°C)
Length of the network	500 km approx.
Eq. inhabitants	250,000+
Heat consumption	1 100 GWh/year for heating 500 GWh/year for Sanitary Hot Water

The District Heating network is fed by three coal fired cogeneration units (pulverized coal boiler and steam turbine) and two fossil fuel boilers operated as peak load units. The reference year chosen for this case study is 2008. Table 2 sums up the characteristics of the production units and their heat and electricity production for the reference year.

Table 2 Main characteristics of the production units

Number of production units	3 coal-fired cogeneration units 2 peak-load boilers
Nominal thermal power	800 MWth
Nominal electrical power	275 MWe
Fuel mix	Coal (95%), biomass, fuel oil (HFO and LFO)
Energy production for the reference year (2008)	1 900 GWh of heat 1 000 GWh of electricity
CO_2 emissions for the reference year (2008)	1 500 $ktCO_2/year$

As for parameters related to electricity production, the values of electricity feed-in tariffs for the reference year are given by Table 3, and the CO_2 content of an electrical MWh on the polish national grid is taken equal to 1.1 tCO_2/MWh_e[2].

Table 3 Electricity feed-in tariffs for the reference year in Poland

	Feed-in tariff (2008)
Base tariff	€41/MWh_{e_net}
+ Red certificate (cogeneration)	€5/MWh_{e_gross}
+ Green certificate (renewable)	€62/MWh_{e_gross}
+ Yellow certificate (gas cogeneration)	€30/MWh_{e_gross}
+ Purple certificate (biogas/biomethane)	€15/MWh_{e_gross}

The following CO_2 emission abatement actions have been studied, using the methodology and the model previously described:

- Efficiency improvement (boiler retrofit, steam cycle retrofit, district heating network refurbishment)

- Energy mix modification (biomass co-combustion, gas cycle)

- Inclusion of renewable or waste heat resources for the production of heat and/or electricity (solar thermal, geothermal, municipal waste incineration, biogas and waste heat recovery from sewage plant, solar photovoltaic and wind power)

[2] Value calculated using the inventory data from Ecoinvent database 2.2 for the supply mix in Poland (processes / energy / electricity country mix / type of voltage + import, at grid, PL) and following the characterisation factors for greenhouse gases defined by IPCC [3]

- Carbon Capture, transport and Storage (CCS)

Comparison of the strategies: CO_2 abatement curve

As a result of the simulations, a CO_2 abatement curve (Fig. 2) has been constructed. For each strategy, the potential for reduction of CO_2 emissions can be read on the X-axis (width of the segment, in $ktCO_2$/year), and the cost per ton of avoided CO_2 can be read on the Y-axis (absolute cost, in €/tCO_2), the uncertainty in regard to this cost being if necessary represented by dotted lines. Only the strategies actually reducing CO_2 emissions are presented. For comparison purpose, the strategies are presented by rising cost per ton of CO_2 avoided.

This CO_2 abatement curve indicates that a certain number of strategies offer a reduction of CO_2 emissions combined with economic gain (negative cost per ton of CO_2 avoided):

- Incinerator strategy, whose gain per ton of CO_2 avoided is in the range of 100 €/tCO_2. This strategy benefits from the green certificates attached to the biogenic portion of municipal waste and the revenues from waste handling (also known as gate fees). The negative cost indicates that, in this particular configuration, the incinerator would have a lower production cost than the existing cogeneration units.

- Wind power strategy produces a benefit of around 50 €/tCO_2, due to the coverage of production entirely by green certificates.

- Steam turbine retrofit strategy on the oldest unit of the installation, whose gain per ton of CO_2 avoided is in the range of 20 to 50 €/tCO_2.

- Biogas recovery for energy production at a nearby Waste Water Treatment Plant. The benefit here is around 5 €/tCO_2, under the effect of the purple certificates that reward biogas-fired cogeneration.

- Conversion of one of the coal boilers into a 100% biomass boiler, whose CO_2 cost per ton of CO_2 is approximately nil. The initial revenues from the green certificates almost wholly offset the additional cost of fuel and the capital expenditure on changes to the boiler.

Other strategies present a cost per ton of CO_2 avoided close to 20 €/tCO_2:

- Gas Cycle whether via a Simple Cycle configuration (25 €/tCO_2) or a Combined Cycle configuration alongside an existing steam cycle (25 to 30 €/tCO_2).

- Carbon Capture, transport and Storage strategy, whose cost per ton of CO_2 avoided is in the range of 40 €/tCO_2.

In terms of the potential for annual reduction of CO_2 emissions, the most interesting strategies are Carbon Capture, Transport and Storage (1,100 $ktCO_2$/year), the coupling of a gas turbine in single cycle (500 $ktCO_2$/year) or STAG Combined Cycle[3] configuration (350 $ktCO_2$/year), the conversion of one of the coal

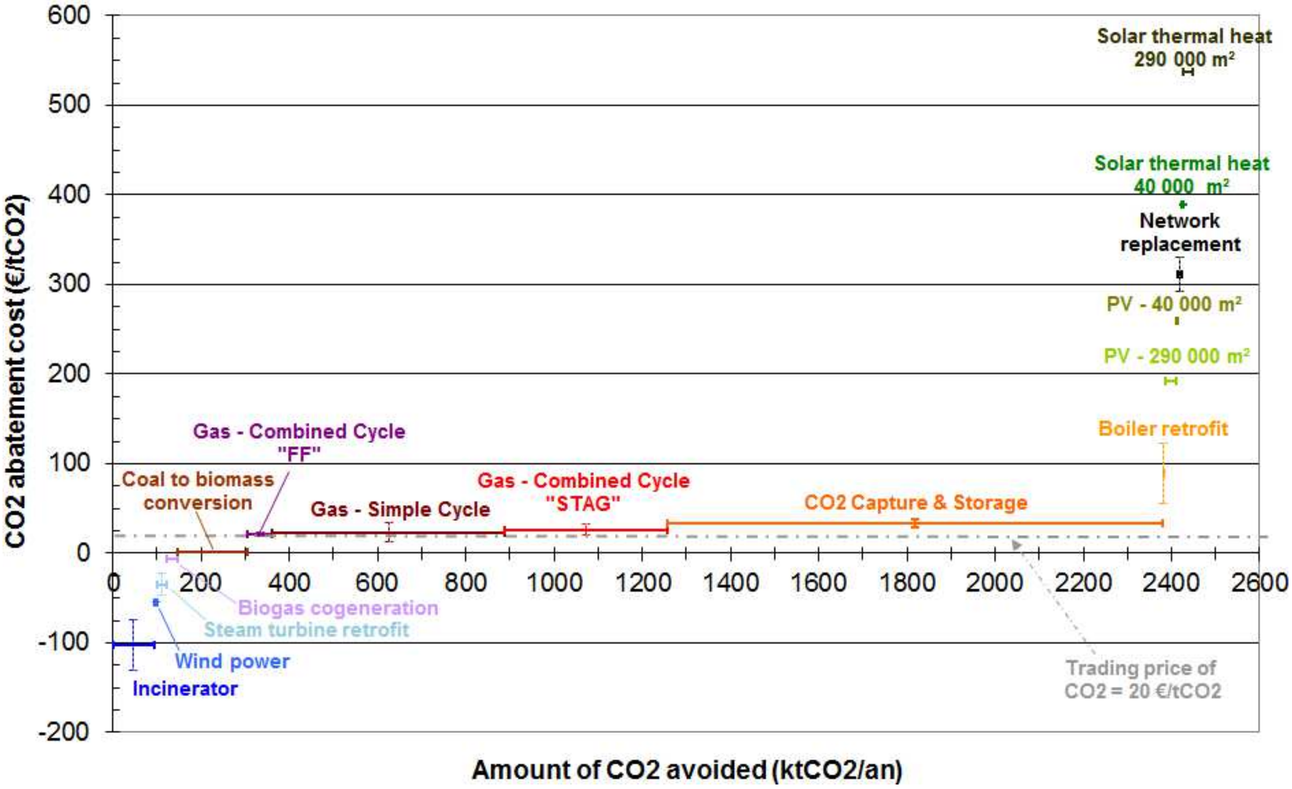

Fig. 2 CO_2 abatement curve – case study of a District Heating network in Poland

[3] Replacement of steam cycle boiler by heat recovery steam generator, operating on gas turbine flue gases

boilers to 100% biomass-fired (150 ktCO_2/year), and to a lesser degree the coupling of an incinerator (80 to 100 ktCO_2/year). It should be remembered that the total quantity of CO_2 emissions in facility reference year 2008 was 1,500 ktCO_2/year.

The Waste Heat Recovery from Waste Water Treatment Plant, Geothermal and End-User strategies are not represented, as they lead to a net increase in CO_2 emissions. Indeed they all entail a reduction in electricity output as a consequence, either of the reduced need for heat output from the main cogeneration units (Waste Heat Recovery from Waste Water Treatment Plant, Geothermal and End-user), or as a consequence of the rise in electricity self-consumption (Waste Heat Recovery from Waste Water Treatment Plant and Geothermal).

Limits of the results presented

The results presented here are only valid within the framework of the assumptions set out earlier. In particular, it is important to bear in mind that:

- The potential for reduction of CO_2 emissions through these strategies cannot be aggregated. Similarly, the cost per ton of CO_2 avoided presented above will probably be changed if another strategy has been introduced earlier.

- The results are strongly dependent on the modeling assumptions adopted. The highest impact assumptions of the model are keeping the electrical and thermal efficiencies of the facility reference year unchanged.

- Change over time of electricity feed-in tariffs (base tariffs and certificates) and the fuel price (coal, biomass, natural gas) were not taken into account.

Our comparison based on the energetic, economic and CO_2 aspects must be completed with considerations of technology maturity. As an example, the Carbon Capture, transport and Storage technology is not expected to be commercially available before 2020-2030.

CONCLUSION

In the specific context of this polish District Heating network, the study on the Strategies for the reduction of CO_2 emissions brought to light the fact that a series of strategies, some of them already economically attractive, can be implemented to significantly reduce the CO_2 emissions related to the network and its production units.

Following up the interpretation of the CO_2 abatement curve, a roadmap describing the successive stages to achieve a given CO_2 emissions reduction target has been sketched out jointly with the operators of the network. This roadmap is based on the most cost-effective actions and takes into consideration technical and operational constraints related to these technologies. This kind of road-map can be considered as an interesting operational translation of the abatement curve and proves to be a powerful tool for decision-makers.

With the experience acquired along this study, Veolia Environnement can directly re-use and apply this methodology on other District Heating networks, may they have a similar or different configuration compared to this particular case study (in terms of technologies, energy mix, network length or annual heat production).

More generally, Veolia Environnement has adapted and is still adapting this work to assess any facilities or group of facilities where the decrease of CO_2 emissions or fossil fuel energy consumption is under study (incineration plant, waste water treatment plant, seawater desalination plant), up to the scale of a Sustainable City project, including coupling with other models describing sectors responsible for a great part of cities' CO_2 emissions (transport, buildings etc.).

In Poland, Dalkia and Veolia Environnement Research & Innovation are currently reinforcing their works on these topics by setting up a dedicated research team in Warsaw (where the largest urban district heating system of the EU is operated by Dalkia), who will thus join the existing Veolia R&D network.

ACKNOWLEDGEMENT

The authors would like to acknowledge Dalkia Polska, and more particularly Piotr Nowak, for its technical support.

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EXPERIENCES FROM DEVELOPMENT OF SUBSTATIONS THROUGH CERTIFICATION

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Keywords: Substation, Certification, Standardization, Energy labeling

ABSTRACT

Euroheat & Power together with several European companies and institutes are planning for a common European working agreement for standardization and energy efficiency of district heating substations. In Sweden standardization and certification have been implemented since 1999. This has contributed to development in quality as well as to reduced prices. The requirements are continuously developed according to market demands and technological progress. Lately energy efficiency has been in focus.

Through standardization a minimum level for quality is set and by continuous third party control and transparency identification of problematic components and solutions are facilitated. By regularly being updated, the standards guide development according to market demands (district heating companies and property owners) in cooperation with technological progress and possibilities (designers and producers). Correct positioning of heat meters, enhanced control of domestic hot water production and quality of couplings and gaskets are examples of developments in recent years in Sweden. Further, production processes have become more efficient due to standardized products and thereby prices have decreased.

The Swedish District heating Association in cooperation with SP Technical Research Institute of Sweden works with certification and research projects to enhance substations. Examples of this are the Swedish standard for substation testing, F:103, a project to test substations that have been used for 10 years and another project to develop a system for energy labeling of substations. Results from these projects will be implemented in the certification process.

A common European or international standard would enhance processes and products even further than national standards. Even though district heating conditions differ among countries, many requirements for components and technical solutions could be basically the same. We have seen in Sweden that standardization has assisted in finding and solving quality problems and this should be extended to a broader market. Further, through a common standard comparability of products is simplified and the market would become more open, which usually also contributes to reduced prices.

INTRODUCTION

Euroheat & power has begun working for standardization of district heating substations. The Swedish District Heating Association together with SP Technical Research Institute of Sweden has certified substations since the end of the 90's. This article describes the impact that standardization has had on substations and the market.

TESTING METHOD

The Swedish certification, handled by the Swedish District Heating Association in cooperation with SP Technical Research Institute of Sweden, includes testing of performance – capacity, district heating return temperature and temperature stability of domestic hot water – verification of components and documentation and annual control of production facilities. For single family houses almost all substations comply with the standard. A prerequisite to be able to use the full potential of standardized substations is conforming DH nets.

The technical regulations for substation testing, published by the Swedish District Heating Association, F:103 [1], consist of:

- Static test of space heating circuit capacity at 100-x°C / 60-80°C and 65-x°C / 45-55°C.
- Static test of domestic hot water production capacity at 65-x°C / 10-50°C [1].
- Dynamic tests of the domestic hot water function at 3 different conditions. (see figure 1)
- Testing of the control equipment at low domestic hot water flow rates, showing no-load characteristics and domestic hot water response time.
- Annual manufacturing inspection by third party to ensure that certified substations put on the market comply with the specification of the actual unit that was submitted for certification testing.

Historically the hardest tests to pass are the dynamic tests, especially since the possibility to change the settings of the hot water regulator between different test points was removed. The hot water temperature must stabilize in 100 seconds after a change in the hot water flow, and must not rise over 60°C. See figure 2 for an example.

ENERGY LABELING

When testing substations according to F:103 as a basis for certification, it is mainly performance and function of newly constructed substations that are tested.

Some parameters that are affecting the energy efficiency of the substation are already included in F:103, for example return temperature. However an overall view of energy efficiency has so far been lacking in the Swedish standardization.

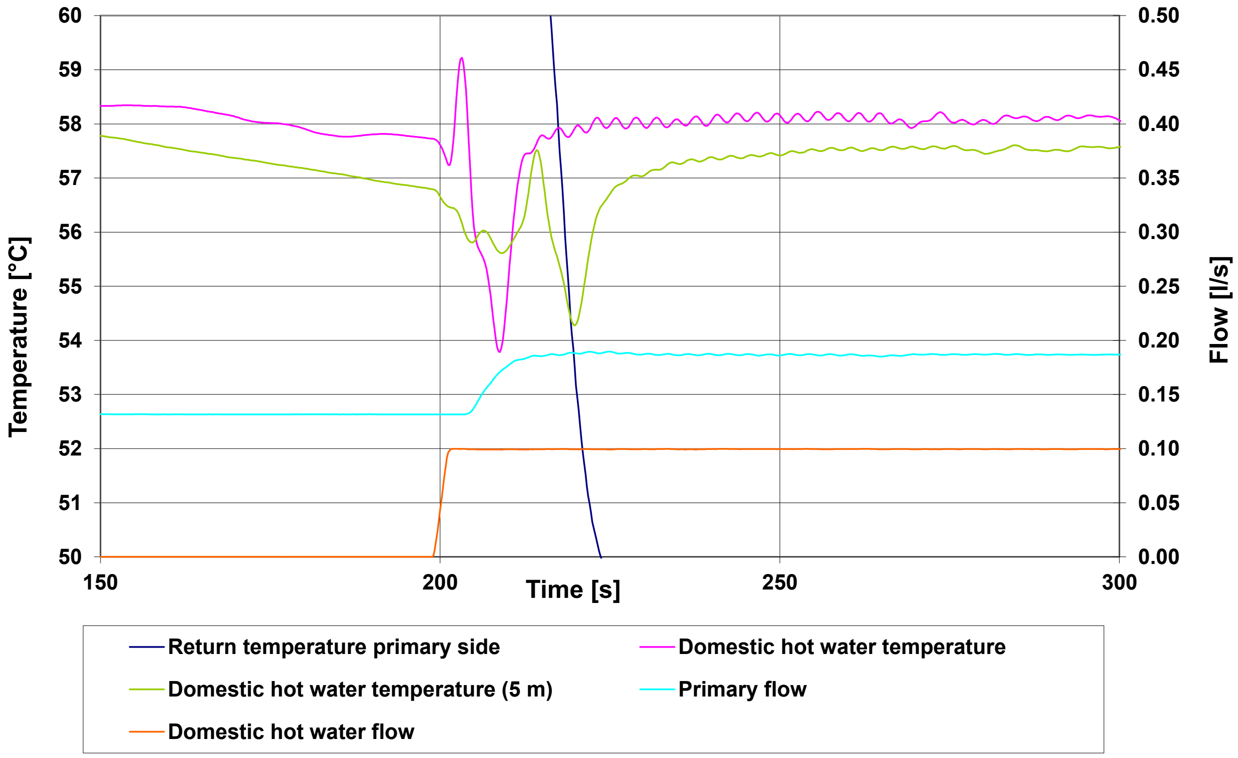

Figure 1. Example of dynamic test of domestic hot water according to F:103 [2]

[1] 55°C for units with hot water circulation

Therefore a method for energy labeling of substations has been suggested through a project performed by SP Technical Research Institute of Sweden and funded by the Swedish District Heating Association [3].

The aim of this project was to assess the potential for improving energy efficiency of district heating substations and to propose a method for energy labeling. The basis is district heating substations customary among Swedish detached houses and multifamily houses, and Swedish district heating networks. Several parameters possibly influencing the energy use have been analyzed:

- Heat losses space heating
- Heat losses domestic hot water
- Electrical energy use
- Return temperature
- Maximum thermal power

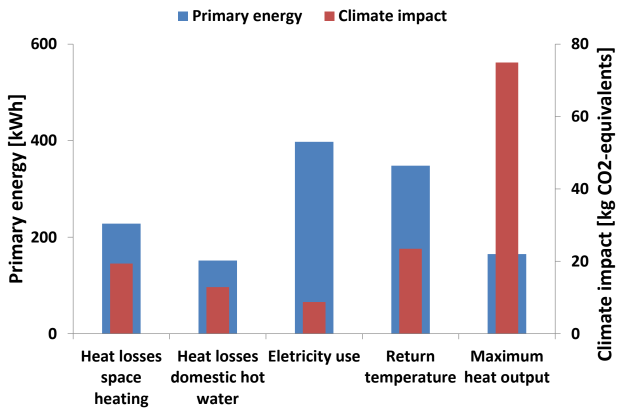

Figure 2. Potential for efficiency improvements for different parameters

In order to assess the importance of return temperature and maximum thermal power, influence from the substation performance on other parts of the district heating network has been considered. The potential improvement of the most energy using substations was estimated to roughly 5-10 % of annual heat demand, calculated as primary energy or climate change. To achieve this all the parameters listed above are relevant, see figure 4. Therefore an energy labeling system including all of them is proposed.

The proposal includes methods on how to measure and assess separate parameters as well as how to summarize the partial results. Primarily test methods used in the certification procedure are suggested in order to allow coordination of the two systems. European standards are further suggested in order to facilitate a possible joint system for energy labeling in the future.

The suggestion of how to calculate the energy class is shown in Table 1 below.

Table 1. Weighted score of efficiency improvements

Parameter	Score	Weight	Weighted score
Heat losses from substation	x_1	0,3	$0{,}3 \cdot x_1$
Heat losses from domestic hot water during stabilization	x_2	0,1	$0{,}1 \cdot x_2$
Electricity use for pumps	x_3	0,2	$0{,}2 \cdot x_3$
Return temperature during space heating	x_4	0,1	$0{,}1 \cdot x_4$
Return temperature during domestic hot water use	x_5	0,1	$0{,}1 \cdot x_5$
Function for heat power reduction	x_6	0,2	$0{,}2 \cdot x_6$

TEST OF OLD SUBSTATIONS

The testing of district heating substations that is the basis for certification only focuses on the function of new substations. The substations long term performance, maintenance requirements and wear and tear are not covered by the technical evaluation. To address these shortcomings, the Swedish District Heating Association funded a project to look into this.

The project called “Certified substations 10 years old – do they fill the bill?” [4] tested a few of the certified substations that have been in operation for 10 years. By conducting the test in the same manner as the certification test the results were comparable and it was possible to examine how well the substations function after 10 years of use. Interviews with repairers/people responsible for maintenance of substations were conducted in order to find out which components that have been replaced. The goal of this project was to determine if there are any weaknesses in the existing substations and how these can be addressed, for example through changes to the rules for certification and continuous monitoring.

General performance is good after 10 years. The only general deterioration that could be detected was a raising of the return temperature from the hot water exchanger. The performance on the heating side is just as good after 10 years and the dynamic regulation on the hot water side has not deteriorated.

Four of five substations pass the test program which was used when the substations were type-tested, even after 10 years of usage. The margin of the return temperature at the static water capacity test was so large at the type tests that the substations met the requirements even after 10 years. For the dynamic tests and static heat capacity, the results were as good as a new substation of the same type. The specimen that failed to reach the same level of requirement had a significantly inferior output, suggesting that regulation has failed in some way.

None of the five substations can handle the requirements of today's test program, F:103-7. The thermal temperature regulators are unable to maintain the temperature between 50°C and 60°C for both summer and winter situation in the dynamic tests. In recent test programs, no changes are allowed to be made between the dynamic test points (summer and winter), which was allowed in previous test programs.

The two most common reasons for fault complaint are leakage and problems with hot water. Leakage problem can have three different causes; gaskets that dry, leach or resize depending on temperature; connection surfaces that do not fit the gasket; installation errors of various kinds, such as gaskets to tightly/loosely fitted or tensions in the construction. Hot water problems usually derive from regulator problems which sometimes can be addressed by exercising the regulator, although most times the regulator must be replaced entirely, which is an expensive operation.

As a result of these complaints, SP have started a project to look into the long-term properties of domestic hot water regulators.

CONCLUSION

Standardization contributes to development in quality as well as to reduced prices. Correct positioning of heat meters, enhanced control of domestic hot water production and quality of couplings and gaskets are examples of developments in recent years in Sweden. The possibility to use prefabricated pipes, have less stock and more efficient production methods have led to lower prices for the end user. A simple way to compare the quality of different products has led to more efficient procurements.

In the project “Energy rating of substations” a method for energy labeling of substations has been suggested. Altogether the potential is estimated to 5-10 % reductions in primary energy and climate gases. Parts of the suggestion for assessing energy efficiency will most probably be implemented in the Swedish certification process next year.

The project “Certified substations 10 years old – do they fill the bill?” showed that substations generally don’t deteriorate significantly during the first 10 years. It also showed a need to look into the durability of certain susceptible components. An ongoing project, “Long-term testing of domestic hot water regulators” is addressing one of these issues. This project will probably result in new requirements regarding durability tests in the Swedish certification process.

A common European or international standard would enhance processes and products even further than national standards. Even though district heating conditions differ among countries, many requirements for components and technical solutions could be basically the same. We have seen in Sweden that standardization has assisted in finding and solving quality problems and this should be extended to a broader market. Further, through a common standard comparability of products are simplified and the market would become more open, which usually also contributes to reduced prices.

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ROADMAP FOR DISTRICT ENERGY TECHNOLOGY

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Keywords: Roadmap, regulation, district energy technology

ABSTRACT

Flexibility and integration are key concepts for future energy systems, and are also properties that characterize heating technology. District energy will be an important part of the energy infrastructure, and implies change of district energy technology.

Key priorities comprise interactions with other parts of the energy sector as well as the buildings. Regulation also needs to be revised, in order to facilitate the key role for district energy.

Regulation of the Danish energy sector facilitates the pursuit of the dual objective of climate mitigation and liberalization. Climate mitigation sets the direction of the energy sector, whereas liberalization characterizes the regulation of the electricity sector.

The Danish district energy sector is - like the electricity sector - facing a process of diversification of the energy production, which imply redefinition of the role of combined heat and power production. Update of the regulation of the heating sector to reflect the complexity and the new priorities of the society is crucial for securing the contribution of the district energy sector to obtaining the climate targets.

INTRODUCTION

Development of technology – and in particular a very diversified technology like district energy – which also will have an increased interaction with other parts of the energy system and e.g. the building sector, should be regulated according to the actual targets for the society (now being climate mitigation).

In Denmark concrete actions have been made to facilitate the development of the district energy technology by establishing an association (District Energy Development Centre), which has members from district energy utilities, suppliers and knowledge institutions.

A key objective is to demonstrate the strengths and possibilities of district energy. A project on formulation of a roadmap for district energy was carried out in 2011 – this is currently being further elaborated.

RETHINKING DISTRICT ENERGY

In the recent years many studies of how Denmark can be fossil free by 2050 it is agreed that district energy will play a crucial role. District energy is an important factor of phasing out fossil fuels in an energy-and cost-effective way. However, district energy technology must be changed in order to meet the new challenges.

The future heat demand – size of investments

The future heat demand must be the result of a cost-effective optimization of reduction of heat demand, improvements to the district energy system (all parts, including lowering the return temperature) and the cost of different energy sources (some of which have free fuels - solar, geothermal, wind, and to some extent, waste heat from industry). In short, demand is unpredictable, but a reduction from the current heat demand per. m^2 can be expected – maybe down to 25% of the current heat demand.

The district energy sector may risk investing in renewable energy plants (first in biomass boilers, which cannot be used during their lifetime and then in geothermal, which is oversized in relation to future heat demand). This will make the heat supply more expensive than necessary. It would be a much better situation for the district energy companies' economy to reduce the heating needs of their customers as quickly as possible before investing heavily in geothermal plants. In the short term the economy can be ensured by introducing mandatory connection and rules prohibiting the use of other heat sources in district energy areas and supporting VE-based district energy.

Definition of district energy technology

The concept of district energy technology is defined here with the purpose of forming a conceptual basis for describing the changing demands of future district energy compared to existing technology.

District energy is defined as a “technology” as opposed to a “technique” referred to in [1]. This highlights that district energy technology is inextricably linked to a particular knowledge and organization in order to provide a particular product.

Achievement of policy objectives in the energy policy leads to changed requirements for the product of district energy technology. In the future, district energy technology is not just distributing warm water in pipes. It must do so in a particular and new context and in a determined and innovative way. This places new demands of technology, both as to organization and in this connection also to knowledge.

There seems to be a direct correlation between the driving purpose and the choice of organizational model [1]. Thus, the district energy systems in major cities connected to the power / thermal utilization and systems associated with disposal of waste are typically municipal (or Russian government) owned, while the district energy supply arising from a consumer-comfort approach typically (in Denmark from 1965-1973) is consumer-owned.

An EU judgment regarding Fernwärme Vienna. The judgment is based on Fernwärme Vienna was created specifically to provide district energy for housing, etc. in Vienna, and, to that end use energy from burning waste, with the purpose of supplying a number of buildings with district energy. On this basis, the Court established that the supply of an urban area with environmentally friendly heating is undoubtedly a task of general interest. [4]

According to this judgment district energy may thus have a wider general interest than just the production and sale of heat.

Based on the above descriptions, one can formulate different definitions of district technology depending on the specific context [2]:

Supply of steam in pipes with the purpose of eliminate waste and to utilize energy for heating public buildings, organized as a municipal utility.

Supply of steam in pipes in order to utilize waste heat from power generation to heat nearby buildings organized as a municipal utility or a part of an electricity company.

Supply of hot water in pipes produced in central oil-fired boilers in order to facilitate the operation and avoiding boiler room, boilers and chimneys in newly built houses organized by consumer-owned co-operatives.

Knowledge for the first two came from Germany. Knowledge of the third came from the Danish cooperative tradition in the form of an organizational model.

An appropriate definition of district energy technology depends on the specific context. Such a definition can be used to define and understand the required changes for the future district energy technology. The point is that the context changes in order to meet future energy policy goals.

Denmark has formulated a policy objective of using no fossil fuels by 2050. All recent analyses indicates that district energy plays an important role in obtaining this objective. District energy allows for utilization of waste, industrial waste heat and geothermal as well as an appropriate use of heating from CHP with heat storage and heat pumps and solar heat and helps with flexibility in relation to integration of wind power and other resources in the electricity supply. But it is also emphasized that district energy technology must be developed so that in future it can interact with low energy housing, i.e. systems with less heat loss than at present.

One suggestion for a definition of future district energy technology could be:

- Supply of hot water in pipes at low temperatures and small losses for low energy buildings in order to recover heat sources such as geothermal, solar and heat from CHP in a way that ensures an appropriate interaction with the integration of renewable energy in electricity supply and low fuel consumption of energy supply.

Compared to the current district energy technology, the future district energy technology requires a wide range of knowledge in various fields such as:

- Operation and construction of low-temperature solutions and their interaction with low-energy housing
- Operation and establishment of flexible CHP-production (including geothermal, waste, solar, heat pumps and storage, etc.) and their interaction with a flexible power supply
- Organization, including forms of ownership and tariffs and incentive systems, etc.
- Public planning (integrated energy planning / heat planning)

The strengths of district energy technology

The objective of redefining the role of district energy makes it relevant to apply the “Blue Ocean” theory. Even though district energy is not a commodity in the traditional sense, it is facing competition in relation to other heat sources. This section contains considerations which may help to rethink DH, addressing the need for concretization of the role of district energy in future energy solutions, the strategic advantages of district energy, and focusing on the customer.

The Blue Ocean Strategy [5] implies boosting the demand and make competition irrelevant. The Danish regulation based on non-profit principle implies that profit does not drive the process, as with more traditional products (including competing solutions to meet heating and cooling needs). All component suppliers and consultants have an incentive to increase sales, so do district energy companies, although in their case it is not as directly motivated by profit.

The starting point is the value for the customer. The product must provide "exceptional value" for the customer. There are four guiding principles to create a strategy for blue oceans:

Six ways to create a market without competition

Alternative industries, strategic groups, buyer groups, complementary product and service offerings, an industry-functional-emotional orientation and time

1) Second Planning Process
   a) From a gradual improvement to value innovation
2) The market
   a) Increasing demand by focusing on commonalities among non-customers
   b) In contrast to a finer segmentation in order to accommodate existing customer preferences, which often results in reduction of the target markets
3) Business Model
   a) Sequence Strategy: user value, price, cost and acceptance

The Six Way Frame implies basic ways to redefine the market boundaries:

1. Keep an eye on alternative industries
   a. Substitutes (same functionality or core utility), alternatives (same purpose but different functions and form)
2. Keep an eye on strategic groups within industries
3. Keep an eye on the chain of buyers (buyers, users, influencers) – which buyer group should you focus on?
   a. This is relevant in relation to who are the key players for the development of district energy - is it e.g. the district energy companies?
4. Look for complementary product and service offerings
   a. Individual heating and cooling, natural gas
5. Keep an eye on the functional or emotional appeal to buyers
   a. Which image has a district energy
6. Keep an eye on future trends
   a. Collective mindset or individuality? Time frame for decisions

Value innovation places equal emphasis on value and innovation, i.e. there is no trade of between creating value for customers and the costs of doing so. Strategy in a blue ocean means to achieve both differentiation and low cost. Hence, focus is on what creates value for the customer, and with this knowledge to differentiate themselves from competitors (here, other heating and cooling options). District energy often involves low costs due to utilization of excess heat. The barrier is to organize the investments in the infrastructure that makes it possible to move the excess heat to where you need it.

District energy has a number of benefits that are unique. The price of heat is a critical parameter, but it is not the only parameter. Flexibility in relation to the energy sources that can be used provides both security of supply and reduces the risk of high prices.

The big challenge for district energy is to ensure optimum operation (in the broad sense, including also the right investment decisions). Customers need an assurance that the costs will not be too high, once they are connected to district energy. To consider district energy as an ordinary commodity and not tie consumers with mandatory connection or high fixed payments (if any) may be a good consideration as a significant barrier to district energy would then when minimized - to be part of a collective system which may lack transparency.

To increase demand, we can direct our attention beyond the existing demand. This is a crucial prerequisite for achieving value innovation. Traditionally you focus on existing customers and to increase the segmentation of the market with the purpose to address the different types of customers. Hence, the traditional approach is to maintain and expand the number of existing customers.

The point is to focus on non-customers and find effective common denominators of what customers consider important. I.e. focus is on commonalities rather than differences and reduce segmentation before further segmentation of the market.

For this use some analytical tools - strategy canvas and four-phased framework for action can be applied:

A useful tool is a "strategy canvas". Value curve is the basic component of a strategy canvas”. It is a graphical representation of a company's relative performance in relation to industrial competitiveness factors. On the strategy canvas competitive factors are on the x-axis and the relative performance on the y-axis.

Parameters on the x-axis are for example security of supply, comfort, price, climate impact.

If you want to create a new value curve, and avoid the trade-off between differentiation and low cost, one can consider which factors in relation to the industry standard should, respectively. 1) be removed, 2) not be prioritised, 3) be given priority, and 4) be created. The first two provide insights into how costs can be reduced. The latter two factors provide insight into how you can increase buyer value and create new demand.

When preparing a strategy – business model – for district energy the following can be considered (in priority): user value, price, cost and acceptance.

HOW SHOULD DISTRICT ENERGY BE REGULATED?

One of the main obstacles to the expansion of district energy is to establish an organization. In Denmark we have had regulation (mandatory connection and “non-profit”-principle) which has facilitated the implementation of district energy. The “non-profit”-principle has been - and is - important for the protection of consumers, but there may be a drawback in that the principle does not sufficiently provide for an incentive for development.

Top-down regulation is essential to creating the framework for the development and expansion of district energy (also abroad). It is also important to focus on who can make this development.

Dimensions of supply, low socio-economic costs, climate, etc. arising from the overall regulatory framework to be followed by some "what's in it for me" approaches in relation to the players who will drive the development and dissemination of district energy. That is, suppliers, district energy companies, but particularly the consumers, who are the ones who ultimately demands the product.

Therefore, it may be useful to focus on how the strategy for development of district energy can the organized with focus on the needs of the costumer. The customers' demand for new solutions can drive the process. It may be, however, that the district energy companies, also by virtue of regulation has the socio-economic aspects into consideration, must take the initiative and help customers define their needs. The task is to clarify what is demanded by customers, and identify the actors who can develop the products in demand.

It is the energy policy goals, which requires district energy in a new form.

The regulation of district energy sector in Denmark is influenced by both achieving climate targets and by liberalization. Supply and employment (jobs and export earnings) are other essential policy priorities which district energy contributes significantly to achieve, and which therefore has implications for how district energy is regulated.

Achieving climate targets require adjustment in one form or another - politically defined, market-based, or a combination (as is the case with the quota system and the allocation of quotas).

There are different political views. Some want to liberalize (companies) and thus attract private capital for development of utilities, including district energy sector. Others want to continue to maintain ownership of municipalities or consumers that promote efficient financing with low interest loans.

Both options require a dynamic and predictable regulation [3]:

- Flexibility (dynamic setting of climate goals according to new knowledge and adjusting to e.g. market failure of the CO2-quota market) and
- Predictability (investment climate should be predictable)

The district energy sector in Denmark with the "non-profit"-principle and consumer protection is heavily regulated.

The need for development of district energy – with for example cooling and additional services for customers – leads to consideration of whether the regulation should be amended, including to provide resources to the development of district energy. This could be done by equating heating and cooling in terms of loan guarantees and it can be done by allowing parallel activity that promotes socio-economic attractive solutions at the customers' side.

The following qualities of district energy should be included in the assessment criteria in the selection of heat supply: Environment, energy security, price, stability and robustness, climate and comfort. Protecting consumers against high prices (due to abuse of the monopoly position of district energy), has been the main priority in the regulation of district energy as it is conceived in legislation and administrative practice. There is left a large degree of discretion in the administration. Parameters other than price, such as comfort, security and climate can, in theory, be recognized and weighed along with environmental impacts.

Consumer protection should not be jeopardized - it is crucial to more widespread use of district energy that consumers are not imposed unreasonable costs. There may be contradictions between an economic and a user-economic optimization. But this can be handled by regulation, for example by ensuring the development of district energy, without the risk that consumers will pay more than "absolutely necessary". Development should be regarded as necessary both for the social optimization in the short and long term, and of the customer-economic optimization. In this perspective there should be no contradiction between socio-economics and user economy.

The heating sector is experiencing a process of increased diversification of production - geothermal, solar, etc., where several sources contribute to the same heating system. A challenge in the planning of district energy is to ensure the lowest possible total production of heat. That is, there is a need for capacity that does not have as many hours of use, but which is necessary in order to meet the heat demand. Here it is important that regulation does not constitute a barrier to new technologies. Increased diversification of heat production also places new demands on the operation, i.e. also technical and organizational challenges, and thus the need for development.

Regulation (e.g. Heat Supply Act) may require adjustments in relation to fuel choice, demands for CHP, and penetration rates for new projects. The bonds in a given context can make good sense, as they support some priorities, but are not necessarily universal. Regulation contains several other restrictions than fuel restriction, for example, CHP is required in central CHP areas, penetration rates for new projects. In a Danish context, priority for natural gas loses its topicality along with lower self-sufficiency and the depreciation of the natural gas grid. CHP is basically a good idea because of the good use of resources and a high degree of coverage that ensures production of a certain size.

The goal is the widest possible connection to district energy, where it is the best solution in terms of socio-economic criteria, i.e. taking into account all socioeconomic costs.

The main challenges in relation to regulation today are:

The Building Code enforces economically unprofitable investments in climate-screen on new buildings in district energy areas, whereby the consumer cannot also afford to pay for connection to district energy

The building code forces new buildings to choose solar and heat pumps because it thereby gives them approx. 30% discount on energy frame. The building code for energy renovations to the "low energy class" forces the consumer to implement even highly socioeconomic profitable investments in the building envelope.

There is no similar requirement to renovate the heating and transition to low-temperature heating in the building.

The building code for the renovation to the "low energy class" forces the consumer to install local generation, which is not economically advantageous. Moreover, the consumer might also choose to opt out of district energy, which can be done with the current regulation for connection, as connection for low energy houses can be waived.

EU-regulation related to district energy

Urban opportunities highlighted in the latest EU Energy Efficiency Plan 2011, which introduces the concept of "Smart City" which includes "smart grid" for electricity, heating, cooling and natural gas. These networks are taking advantage of the city's density, and they play together in an integrated "intelligent energy" in an interaction with "intelligent buildings". Thus, the plan illustrates the ideas behind the EU's comprehensive legislative package in the energy field. The EU has drawn inspiration from the Danish legislation in the energy sector. The inspiration comes mainly from the Electricity Supply Act of 1976 and the Heat Supply Act of 1979, which really sparked the application of district energy in combination with natural gas.

The common objective of all the directives is to reduce dependence on fossil fuels in a cost-effective way and to increase competitiveness and prosperity for the future of EU citizens. The directives aim at a combination of market forces and planning of urban infrastructure. [2]

- The Directive on renewable energy recommends that cities should plan where it is cost-effective to establish district energy and cooling in order to utilize renewable energy in the buildings.
- Similarly, the directive on Energy Efficiency recommends that cities must plan where it is cost-effective to establish district energy and cooling in order to utilize cogeneration to supply buildings. Furthermore, the Directive recommends that new power plant capacity normally only be located where excess heat can be utilized (a provision introduced in Denmark in the Electricity Supply Act in 1976).
- In this vein the Buildings Directive recommends that buildings be designed with a good indoor climate in a cost effective manner taking into account the local conditions and that the use of fossil fuels must be reduced to almost zero. In line with the other directives this will take into account the possibilities of using CHP and renewable energy through district energy and district cooling where it is cost effective compared to individual supply.

There should be an overall coordination of the relevant sectors requiring cost-effectiveness (or economics), as evidenced by the Directive on Strategic Environmental Assessment, which is precisely aimed at, that there should be an inter-sectoral coordination of all major policies, plans and programs within the individual sectors, including electricity, gas, district energy and buildings.

Since all member states must implement the directives, there will be a huge single market for the solutions that are most competitive in terms of meeting the requirements of the directives. As many other countries see the EU as a model, the real market for the efficient solutions will become even greater.

CHALLENGES OF REGULATION

Regulation of the Danish energy sector facilitates the pursuit of the dual objective of climate mitigation and liberalisation. Climate mitigation sets the direction of the energy sector, whereas liberalisation characterises the regulation of the electricity sector. The Danish district energy sector is - like the electricity sector - facing a process of diversification of the energy production, which imply redefinition of the role of combined heat and power production, which constitutes an important connection between the liberalised electricity market and the regulated heat market. Update of the regulation of the heating sector to reflect the complexity and the new priorities of the society is crucial for securing the contribution of the district energy sector to obtaining the climate targets.

Regulation might be principles-based or more specific and detailed. There is a general trend - in Denmark but also in the EU - for more detailed regulation, which takes precedence over the more general legislation (e.g. Heat Supply Act). Detailed regulation reduces the possibility of assessments made by the administration, and thus to make an overall assessment based on the purpose and intentions in the law. This underlines the importance of detailed regulation to be updated so that it is consistent with society's current priorities. [6]

A more principles-based regulation requires a high social capital, whereas detailed regulation is appropriate for a low social capital societies. Society saves transaction and control costs, the more social capital there is in society. The amount of social capital is difficult to measure but can vary widely between different countries. Denmark has a very high social capital for example, while other EU countries like Britain and Germany has a social capital which is significantly lower than the Danish. The point is that the Danish regulation is becoming more and more influenced by EU regulation, which is characterized by a "lowest common-denominator" with regard to social capital. This may help to explain the change of the Danish regulation from principle-based, towards more detailed regulation. [7]

Stronger regulation can set the framework for change, while a softer regulation may involve inefficiencies in the implementation of major changes. "Soft" regulation is defined as only applying market-based approaches.

A hypothesis is that regulation must encompass more than market-based approaches, to create a framework for a comprehensive change of heat supply. A market-based approach requires clearly defined actors. The easiest thing for the players will be "business as usual" - a radical change in the business of such utilities is cumbersome and requires more than ordinary optimization of the business.

Regulation – cases to illustrate the challenge

One case concerns Thisted Heating Supply [8] takeover of Hillerslev CHP (natural gas fired). The latter passes to peak and reserve load, where-by there is a socio-economic cost, while the project will be user-economically and environmentally advantageous and therefore outweigh the negative socio-economic result. Energy Board decision shows that the municipality can exercise a wide discretion in relation to weighing the different criteria (energy, environment, economics, corporate economics and user economy), and that "corporate economy" means the applicant company (in this case the heat supply company) and not e.g. natural gas company or other suppliers. This decision does not clarify how the weighting should be made, only that it can be done by the municipality. The Board indicates a broad interpretation of socio-economy, implying that the project can be classified as being socio-economically advantageous. This broader interpretation involves criteria "scarce resources", "employment", "security of supply", without specifying how they should be weighted, while further other criteria can be included. Hence, the criteria for weighting are not objective. Energy Complaints Board's decision was appealed to the Western High Court where it was upheld.

In Helsingør [9], there has been a similar case where the Energy Board in the same way refers to the municipality's right to exercise discretion in the weighting of different criteria. This project has a negative socio-economy, but corporate-economic, user-economic and environmental benefits. However, the different environmental consequences should be identified, as some improved, while others deteriorate with the project.

In Aalborg [10], there has been a case of connecting the heating areas to heat and power produced at a central power plant, whereby the existing natural gas-fired plants shifted to be peak and reserve load. The Energy Board finds in this decision, the general view that a project can be approved, although it is not advantageous at all five criteria (energy, environment, economy, socio-economic, corporate-economy and user-economy). Energy Appeals Board, however, defines how the CO2 is weighted, and that environmental consequences should be recognized in the socio-economic assessment. Energy Board also believes that in a situation where the project is estimated to be neutral in relation to the socio-economy and environment, corporate economy and user economics can be included in the assessment. Hereby the Energy Board states that the environment should be recognized in the socio-economic calculation (consistent with the revised Heat Supply Act), with estimated valuation of CO2 load (not authoritative), and that factors other than socio-economic and the environment are secondary and cannot compensate for an socio-economically and environmentally detrimental project.

In Hundested [11] there has been a similar case, but here is the municipality's approval of project proposals from Hundested Varmeværk amba repealed by the Energy Board. The reasoning is the same as in the above case in Aalborg, the project in Hundested was assessed not to balance in socio-economic terms, whereby other benefits such as corporate-economic and user-economic cannot be recognized. The socio-economic disadvantage is calculated to be DKK 41 million, while the reduction in CO2 emission is 78%. There may thus be inferred indirectly a cost reduction of CO2 emissions that are judged to be too high. This is a barrier to include other benefits of the project. In this case it may be stated that the municipality's right to exercise discretion was not sufficient to approve this project. Hence, apparently there is a scale for the cost of reducing emissions, which defines when the municipalites right to exercise discretion, without being explicitly expressed.

From the Energy Board practice it can be concluded that there is no basis for recognizing other criteria (e.g. technology, comfort, or other criteria), although it is might be possible to include other criteria. A municipality may attempt to include other criteria in the assessment base for a concrete project and in this way to test what is possible to recognize. This "trial and error" approach could be replaced by a general political discussion of the calculation, with subsequent adjustment of the Heat Supply Act. This would also be more adequate to the Energy Board, which has unclear competences in relation to uncover this gray area.

A 2006 study finds that only 8% of the municipalities engaged in cooperation with other municipalities on the administration of heat supply. This raises the issue of lack of resources, as many municipalities have only one employee dedicated for the task of heat planning. Another point in the study is that municipalities will find it administratively simpler to use the Planning Act and not the provisions of the Heat Supply Act regarding mandatory connection. This may imply that the socio-economic assessments, which are part of the Heat Supply Act, will not be made.

District energy systems are covered by quotas for CO_2, while individual forms of heating are not included. The cost of CO_2 allowances therefore distorts competition between district energy and individual forms of heating. This is an example of market-based approaches to needs to be designed carefully. This problem should be addressed at EU level.

ROADMAP – PRIORITIES

Formulating a roadmap for district energy technology comprise a wide range of issues. The following list illustrates this [2]:

- Research capacity building
- System analysis and planning in the energy sector
- Technology development
- Focus on district energy customers
- Export of district heating (components and solutions)

Priorities of district energy utilities

A survey among district energy utilities in Denmark was performed in 2011. The survey was made in two stages; the first stage was a top-of-mind analysis, indicating the main area of research in the short and the main area in the long term. Similarly, indications were given on one non-important area of research in the short term and one in the long term. The survey yielded a total of 742 responses, and showed two trends:

Among the “most important issues” the primary theme was organization and planning of comprehensive energy solutions (it comprised 365 out of 581 responses). Of these, 100 emphasized solutions with focus on district energy consumers' demands, wishes and general consumption behavior.

The top-5 issues within strategy and planning are (total 365, not all are represented in the list):

1) Liberalisation and competitiveness
2) Marketing and political visibility
3) Coordination within the sector
4) Taxes
5) Price development, feasibility, security of supply

The “non-important” issues, was more difficult to point out, but within strategy and planning they comprised (total 102, not all are represented in the list):

1) Data collection and control
2) Coordination within the sector
3) Taxes

Some issues are represented on both lists (“coordination within the sector” and “taxes”). This is not further analysed. An explanation for the different perception of “Coordination within the sector” could be that there is a need for adaption to the new challenges (thus also regarding the organization of the sector), as well as a requirement for efficient cooperation (e.g. by reorganizing and consolidating the organization of the sector instead of establishing new organizations for new purposes).

The second most indicated theme regarded technology areas, addressing the development of renewable energy technologies. The total number of responses for “important issues” was 216, whereas the total number of responses for “non-important issues” was 59.

The most important issue was research, development and demonstration within renewable energy sources. This is addresses the challenge for district energy of increasing the diversity in heat production. Other “important” issues were piping and low temperature district energy.

The “non-important” issues were few, but comprised energy savings at the district energy plants, fossil fuels and research, development and demonstration.

In conclusion, the main priority is organization and planning, emphasizing the role of district energy as energy infrastructure. In general, focus is on the interactions with the other parts of the energy system and on developing district energy according to the requirements set be the customers and to include the customers as part of the district energy system, also in terms of behavior.

Roadmap – objectives

The objectives:

1. **Long-term strategic and targeted** research, development and demonstration
2. **Savings in space heating demand** and the return temperature is lowered in both new and existing buildings.
    a) A forced renovation of the existing building stock reduces unnecessary investments in excess capacity for heat production
3. **Tomorrow's energy system** will be based on:
    a) Wind and biomass as the primary sources of energy
    b) District energy must be developed to provide the flexibility that allows for the restructuring of in an energy efficient manner
4. **The primary heat sources** will be:
    a) Biomass, renewable gas, heat pumps, solar and geothermal
    b) Development of large heat storages, storage of biogas and waste management. Excess heat / CHP will continue to be significant

Roadmap – requirements

The objectives require:

1. District energy technology must be developed
    a) Operation and establishment of **low-temperature solutions** and their interaction with low-energy housing
    b) Operation and the establishment of **flexible CHP-production capacity** (including geothermal, waste, solar, heat pumps and storage, etc.) and their interaction with a flexible power supply
2. **Large interdisciplinary projects** involving both organizational, technological and market aspects
    a) **Organization**, including forms of ownership and tariffs and incentives, etc.
    b) **Public planning** (integrated energy planning / heat planning)
    c) When pilot projects should develop into general solutions, it requires investment in **marketing and communications**

CONCLUSION

District energy has a key role to play in the future energy infrastructure, in order to meet the climate goals.

Rethinking district energy technology is necessary, since the complexity will increase, in terms of all aspects of technology.

Regulation provides the framework for district energy, and should be adjusted to the new requirements of society. Methodology of socioeconomic calculations is a key parameter for the real possibility to implement new district energy projects.

ACKNOWLEDGEMENT

Part of the findings are from the project "Roadmap for fjernvarmen – fjernvarmens rolle I energisystemet" (Roadmap for district energy – role of district energy in the energy system), financed by the Danish programme EUDP and Dansk Fjernvarmes F&U Konto. The project is described at www.fvu-center.dk (in Danish).

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Low temperature district heating and district heating to low energy housing

RESULTS AND EXPERIENCES FROM A 2-YEAR STUDY WITH MEASUREMENTS ON A NEW LOW-TEMPERATURE DISTRICT HEATING SYSTEM FOR LOW-ENERGY BUILDINGS

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Keywords: low-temperature district heating, low-energy buildings, substations, distribution heat losses

ABSTRACT

A new low-temperature district heating system for low-energy buildings that operates with supply temperatures slightly above 50°C was presented at the 11th International Symposium of District Heating and Cooling in 2008; the design includes newly developed substations and efficient distribution pipes, resulting in reduction of heat losses up to 75% compared to traditional layouts. Since then, the first area using the new system has successfully been put in operation. This paper presents the results of a 2-year study with detailed measurements of a low heat density area with 40 low-energy terraced houses in Denmark. The investigations include the determination of the heat losses from the distribution network, the pumping electricity consumption, the user behavior in terms of indoor temperature and domestic hot water consumption as well as detailed simultaneity factors to be used for network design. Moreover, the paper presents solutions for using the return water of existing networks to supply district heating to newly build areas and summarizes in general on how to integrate low-energy houses and district heating systems. Finally, it points to the potential of integrating low-temperature district heating systems in existing buildings as an effective solution towards energy-sustainability in the heating sector.

INTRODUCTION

An innovative Low-Temperature District Heating (LTDH) system for low-energy buildings that operates with supply temperatures slightly above 50°C has been successfully put in operation in 2010. This paper presents the results of a 2-year study with detailed measurements of a low heat density area with 40 low-energy terraced houses and a communal building in Lystrup, Denmark, see table 1 and figure 1. The project dealt with the integration of sustainable solutions both for the end-user side and the energy supply side and aimed to:

- Demonstrate the operation and energy demand of District Heating (DH) applied to low-energy buildings and that the heat loss in the network can be maintained below 15-20% of the total delivered heat.
- Evaluate the simultaneity of the heat demand in case of low-energy buildings.
- Test two designs of low-temperature DH substations.
- Evaluate the user behavior in terms of indoor temperature and Domestic Hot Water (DHW) consumption

Table 1: Basic information on the project.

Project information	
Owner	Housing association BF Ringgården
Year of construction	2008-2010
Site area [ha]	1.7
Building units (residential)	40 terraced houses
Residents	Seniors, young families
Number of residents	92 (estimated)
Building units (tertiary)	1 communal building
Heated area [m^2]	4115
Plot ratio[1]	0.24

[1] built floor area/site area

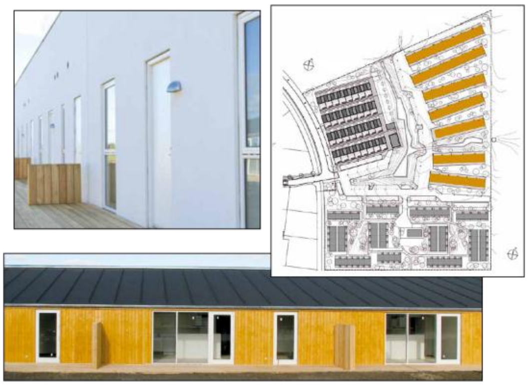

Figure 1: The terraced houses and their spatial layout.

TECHNICAL DESCRIPTION

Heat demand

The Danish Building Regulation 2008, later superseded by the Building Regulation 2010, set the maximum building primary energy demand for new constructions at the time of the project implementation. There were separate targets for residential building (Space Heating (SH), DHW and the electricity use to the related installations, but not including lighting) and non-residential buildings (including lighting). The requirement in residential building was defined as follows:

$$E = 70 + 2200/A \ [kWh/(m^2 \cdot yr)] \qquad (1)$$

where E is the maximum annual primary energy demand and A is the gross heated area [m^2]. The energy requirements also include two classes of low-energy buildings, which energy demand limit is calculated as follow:

$$\text{Low-energy class 1: } E = 35 + 1100/A \ [kWh/(m^2 \cdot yr)] \qquad (2)$$

$$\text{Low-energy class 2: } E = 50 + 1600/A \ [kWh/(m^2 \cdot yr)] \qquad (3)$$

Primary energy factors of 2.5 for electricity and 1.0 for fuels and district heating are used. The settlement in Lystrup is designed for low-energy class 1. The design primary energy use for SH in the houses was 30 kWh/(m^2·year), see table 2. The insulation thickness of the building envelope is as follows: roof, 450 mm; external walls, 335 mm. The U-value of the windows are 1.1 W/(m^2K). The layout of dwellings consists of seven blocks of houses, divided in 2 size categories: size C1 (87 m^2) and size C2 (110 m^2), see table 3.

Table 2: Building regulation design values.

Specific heat demand (design) [$kWh_{th}/(m^2 \cdot yr)$]	
Specific SH demand	30
Specific DHW demand	13.1*
Total	43.1

* Based on annual DHW use of 250 liter/m^2 and ΔT=45°C and design indoor temperature of 20°C as used in the Danish reference software Be06.

Table 3: Type and floor area of the buildings.

Block Number	**Total size [m^2]**	**Number of dwellings**	
		Type C1	**Type C2**
1	771	5	3
2	727	2	5
3	594	3	3
4	528	1	4
5*	479	1	2
6	484	3	2
7	532	6	0

* Including the communal building, A=170 m^2

Building installations

The building installations, in terms of heating system, consist of a combination of radiators – based on design supply/return/room temperature of 55/25/20°C – and floor heating in the bathroom. The DHW is prepared by one of the low-temperature DHW systems described in [1], [2]: the low-temperature Instantaneous Heat Exchanger Unit (IHEU) and the low-temperature District Heating Storage Unit (DHSU), see figure 2.

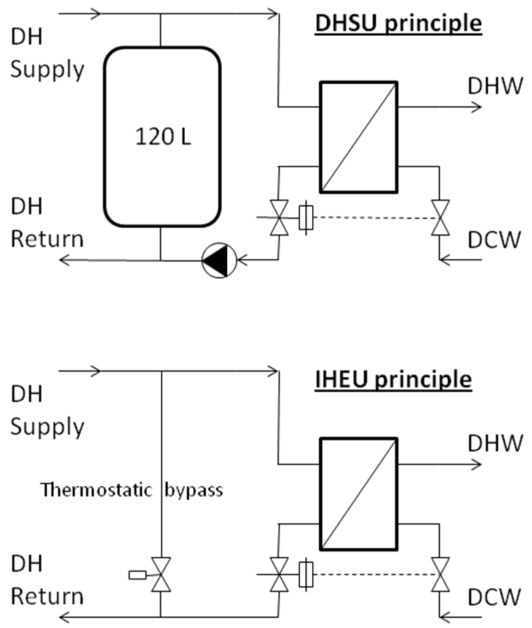

Figure 2: Sketch of the DHSU and IHEU principles of DHW production.

The layouts of the DHW distribution pipes and the floor plan of the dwellings were carefully designed, so that there is a separate pipe supplying each DHW fixture and the length of the pipe is minimized, see figure 3. Consequently, the water content in each DHW supply line, including the volume in the secondary side of the DHW heat exchanger, is kept to a minimum and it is below 3 liter: this is the allowable water content for instantaneous DHW systems to assure safety in relation to the Legionella risk, even without any treatments (thermal, UV-rays or chemical), according to the German guidelines for DHW systems (DVGW, W551).

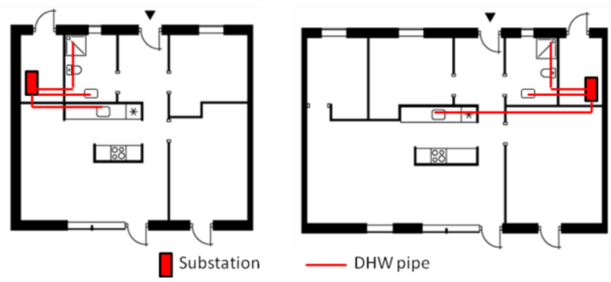

Figure 3: Sketch of the floor plans with the layout of the DHW distribution pipelines. Type C1 (left), type C2 (right).

Heat distribution network

A sketch of the DH network with the location of flow meters for monitoring is seen in figure 4. Besides the normal end-user heat meters and the main meter placed at the pumping station two additional meters are placed at the end of two different streets. One meter is measuring a part of the network with 11 DHSU‟s, the other is measuring on a network part with 11 IHEU‟s.

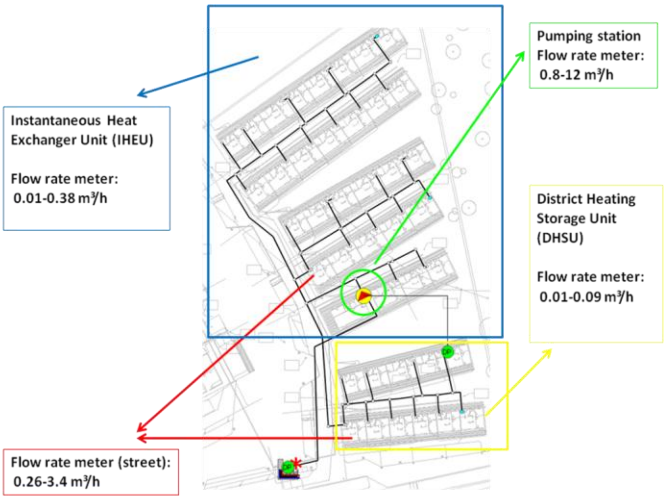

Figure 4: Sketch of the low-temperature network with the location of the meters. DH is delivered from the utility Lystrup Fjernvarme to the pumping station.

Network Dimensioning

The network consists of flexible plastic twin pipes for dimensions up to DN32 and of steel twin pipes for larger dimensions. Heat loss coefficients are calculated according to [2] and pipe manufacturer data, figure 4.

The other assumptions for the design were:

- Maximum pressure level: 10 bar. It is reasonable to design the network according to the maximum hydraulic load that can be withstood by the distribution pipeline; in the case the limit is drawn by the plastic service pipes, which requires pressure levels below 10 bar. In fact the pipeline systems must by regulations withstand pressures 1.2-1.5 times the nominal value.
- Thermostatic by-pass valves of IHEU‟s set to 40°C, in the customer‟s substation at the end of each street line and set to 35°C, in all the other customers‟ substations.
- Design supply temperature from the mixing shunt: 55°C; design return temperature: 25°C.
- Maximum water velocity: 2.0 m/s; also in branch pipes.
- The simultaneity factor was assumed to be 1.0 in case of DHSU, due to the low semi-constant flow the unit was designed for. The simultaneity factor for the IHEU was the traditional consumer dependent approach used in Denmark. Design loads are for DHSU: 3 kW, for IHEU: 32.3 kW
- Minimum supply/return pressure difference at the end-user‟s substation: 0.3 bar

Table 4: Pipe specifications. Alx: Aluflex twin pipes; Tws: Steel twin pipes, series 2, diffusion barrier at the outer casing.

	Inner diameter [mm]	[W/(m·K)]		Roughness [mm]	Length [m]	Estimated cost in 2010 [€/m]	
		$U_{11}=U_{22}$	$U_{12}=U_{21}$			Purchase	Total
Alx 14/14-110	10	0.05	0.035	0.02	123	47	162
Alx 20/20-110	15	0.065	0.037	0.02	221	56	166
Alx 26/26-125	20	0.071	0.049	0.02	155	67	207
Alx 32/32-125	26	0.088	0.053	0.02	130	78	211
Tws-DN 32	37.2	0.085	0.056	0.1	90	82	240
Tws-DN 40	43.1	0.099	0.053	0.1	32	88	246
Tws-DN 50	54.5	0.096	0.06	0.1	16	122	268

Heat sources

The distribution network in this case study is a typical example of how a low-temperature DH scheme can be integrated in an existing network that has higher operating temperature. There are no heat sources on the site. The heat is provided directly from the medium-temperature DH utility Lystrup Fjernvarme. A pumping station and a mixing shunt are placed in the communal house. The pump is operated based on a pressure difference sensor placed at the critical point in the network. The mixing shunt is controlled by a return valve and a temperature sensor in the main supply pipe to the low-temperature network. The system is seen in Figure 5 together with the pressure line drawn from the pumping station to the end-user.

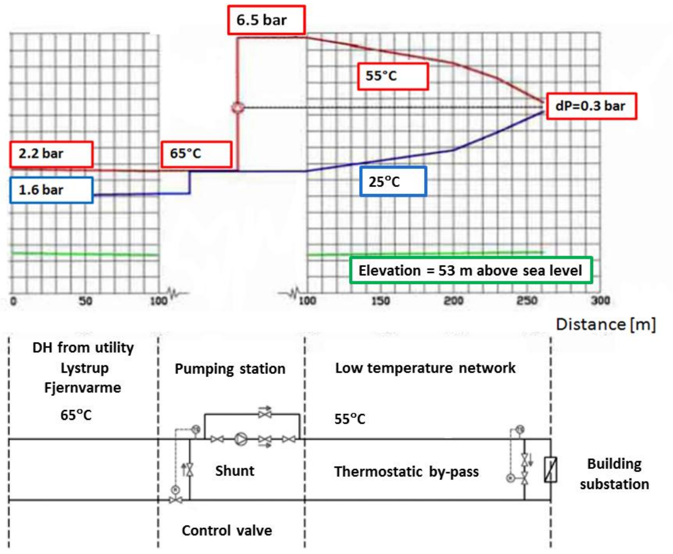

Figure 5: Simplified pressure line/temperature diagram of the mixing shunt during typical operating conditions.

MONITORING

An extensive monitoring program and data acquisition system was established; the measurements presented here are mainly from the first monitoring period conducted during the weeks 26-47, 2010 with the main meters and individual meters in 22 dwellings in place; in these dwellings both DH meter, meter for DHW and a room temperature sensor were installed. Late 2010, DH meters in the remaining 19 dwellings were connected and the monitoring has continued ever since and will go on until end of 2013.

Space heating and domestic hot water

Based on the measurements in the first monitoring period, a heat load vs outdoor temperature curve was established, see figure 6. For IHEU the standby heat loss is about 25 W; for DHSU 80 W. It is seen that the average heat load during summer (week 26-38) is higher than the standby losses which means that there has also been a SH demand in this period for some houses e.g. for floor heating of the bathroom.

Based on the curve, the SH demand per dwelling was estimated to 5.1 MWh for the Danish reference year corresponding to about 51 kWh/(m²·yr), 70% higher SH demand than building regulation design value (see table 3). It was not the purpose of the project group to look at the building „as-built" vs. designed. Analysis of the measurements also rather indicates that the reason should be found in user behavior.

Floor heating during summer is a parameter that is not taken into account in the building design values. Further, the indoor temperature, as measured in the living room, was 2-4°C above the design indoor temperature of 20°C during the heating season, see figure 7. In [1] it was shown that 1°C higher than expected room temperature can lead to 20% higher SH demand in low-energy houses, so the room temperature alone, almost explains the high consumption.

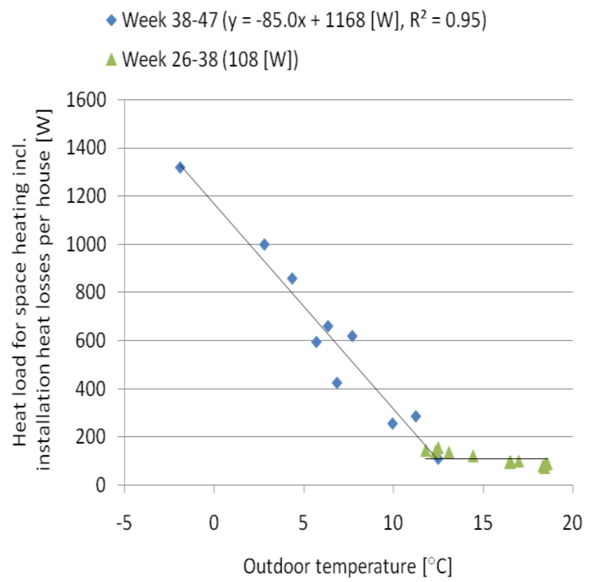

Figure 6: Heat load vs. outdoor temperature curve based on average of 22 houses monitored during the first monitoring period, week 26-38 (summer); week 38-47 (heating season).

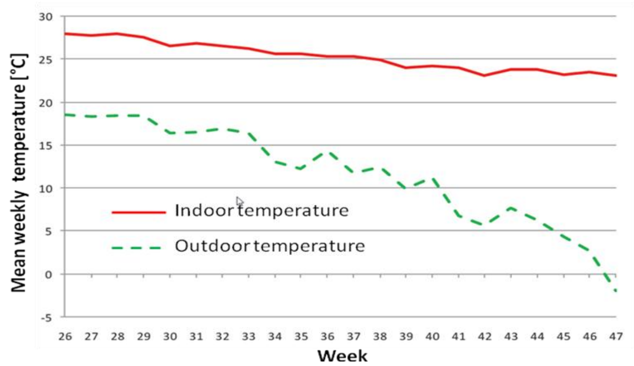

Figure 7: Mean weekly outdoor temperature and indoor temperature in the buildings equipped with room temperature sensors in the living room.

DHW consumption was measured to be 65 liter/(day·house) in average. It is a low value, which is partly related to the number of occupants and their composition. Based on an estimate of the number of residents in the dwellings, it is assessed that the DHW use was equivalent to approx. 28 liter/(day·person). It should be noticed that the average cold water temperature was approx. 15°C and the average DHW temperature was 40-45°C, giving an average temperature difference of 25-30°C in the first monitoring period. According to [8], DHW use of 30-40 liter/(day·person) and a temperature difference of approx. 40°C are typical values for Denmark. In the case study this would give an expected heat demand for DHW of 12-16 kWh/(m²·yr). In average the DHW consumption measured was 8 kWh/(m^2·yr), which is less than the design value (table 2). When added to the SH demand a total annual DH consumption of 5.8 MWh per house was found. Monitoring also demonstrated that DHW can be produced at temperatures of just 3°C below the primary supply temperature, e.g. 47°C at a DH supply temperature of 50°C as expected with the used substations.

Operating temperatures

Lystrup Fjernvarme that supplies heat to the new low-temperature area is a medium-temperature DH system. DH is supplied with up to 80°C during winter and down to 60°C during summer. In figure 8, the average weekly supply and return temperatures and heat load are seen for the 2 year monitoring period together with the

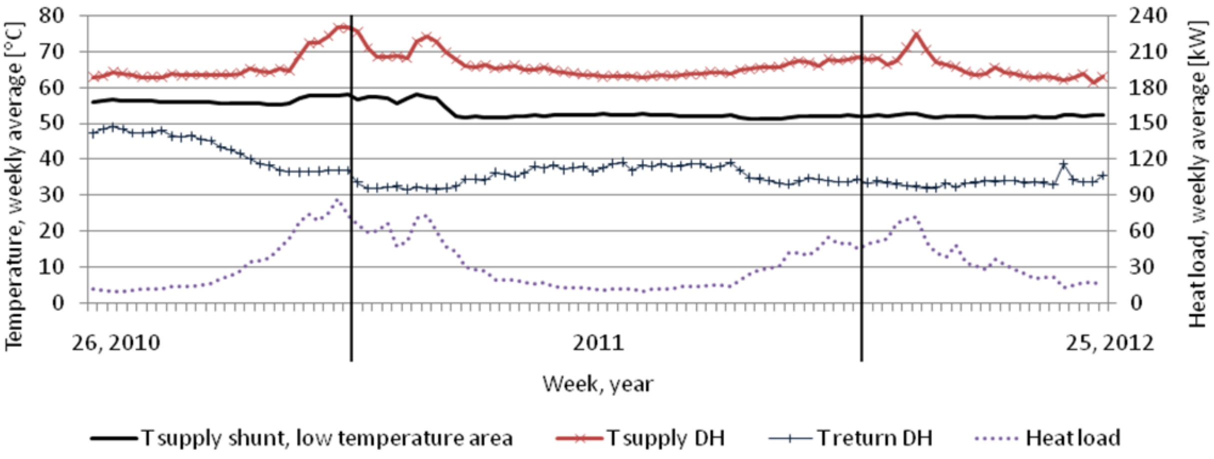

Figure 8: Average weekly supply, return, shunted supply temperatures and heat load for the 2 year monitoring period.

shunted supply temperature. The maximum monitored heat load is 161.3 kW compared to maximum weekly average of 87.4 kW. The figure shows how the shunt has been adjusted during the period in order to get the low mixed supply temperature of just slightly above 50°C. Further the result of troubleshooting in individual building installations has secured a low return temperature. This is expected to be even lower after the local „boiler man" beginning 2012 has been provided a tool that updates him every week with return temperature and other relevant data of the individual houses. Based on the tool, he can guide the users in better operation of the substations which has already been beneficial.

In the first monitoring period of 2010 the two different substation types were compared specifically. In the 11 homes with DHSU, the average return temperature was 39.4°C in the weeks 26-47; in summer – weeks 26-38 – the average return temperature was 43.6°C. The high return temperature was primarily due to the malfunction of a single unit. The best performing DHSU registered a return temperature of 29°C in summer. The 11 homes with IHEU, the average return temperature was 34.7°C in the weeks 26-47; in summer – weeks 26-38 – the average return temperature was 40.3°C. The high return temperature was primarily due to 2 substations, where the control valves were defected and allowed a relative large amount of water to flow uncooled to the return pipe. The best performing IHEU registered a return temperature of 26°C in summer. Observing the same weeks, a year later, showed improved results as seen in figure 9 for the 11 IHEU‟s, even though the supply temperature had been reduced in the meantime.

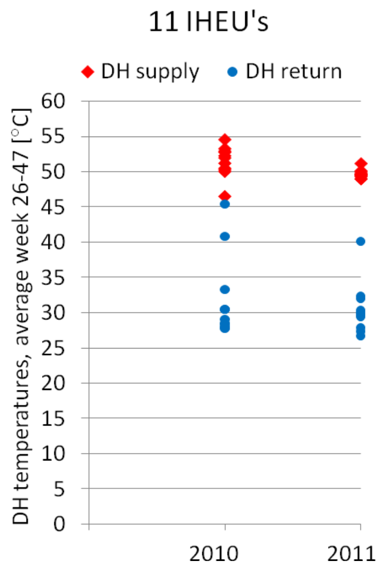

Figure 9: Supply and return temperatures for 11 IHEU‟s, average of week 26-47, 2010/2011.

In general, the return temperature in the heating season (week 39-47) was lower than during the summer, which confirms that the radiators delivers low return temperatures (28-33°C). This occurred although the indoor temperatures during operation were some degrees higher than the design conditions (20°C), which increased the minimum achievable return temperature from the radiators. Overall, the demonstration project has shown that the concept works, and that is further confirmed by the fact that there were no complaints from residents about the lack and quality of SH/DHW.

Simultaneity factors

In order to define design loads in areas with low-energy buildings, simultaneity curves were developed based on monitoring data sampled every 4 minutes during the summer weeks 24-38 in the year 2010. Totally 38,000 data sets, or time stamps, were recorded for each of 10 IHEU"s and 10 DHSU"s. The methodology used to develop the curves is: Data is sorted in the way that the combination of the highest group load E(N) is calculated for each time stamp. To avoid too high simultaneity curves, it is accepted to exceed the suggested design load pr. consumer e(N) in 1% of the tapping time. This is equal to shortcomings for a time period of 15 minutes if assumed the tapping is occurring all 24h/day. In practice the period will be quite shorter than 15 minutes. On the other hand the analysis assumes that the consumers with the highest DHW load by default are placed at the far end of the DH net. This will statistically not be the case, why this puts the suggested curves to the conservative side. The DHW heat power, e(N), of one consumer was determined to be 4.7 kW for the DHSU case and 24.3 kW for the consumers with IHEU. The e(1) value for the DHSU case is a bit higher than the expected design value of approx. 3 kW. The explanation is the accuracy of the setting of the flow controlled motor valve, which controls the charging flow to the storage tank. The real charging flow is thus higher than the design flow. By readjusting this, a lower e(1) can be obtained. The parameter e(1) for the case with IHEU is lower than what is usually used by the designers in similar conditions, e.g. 32.3 kW in Denmark. On one hand, this result must be seen in relation to the housing type and residents behaviours (mostly senior citizens and young families). On the other hand, the analysis points at the fact that the dimensioning of DH systems need a better basis for simultaneity factors, and that in future a greater consideration must be given to the installations types

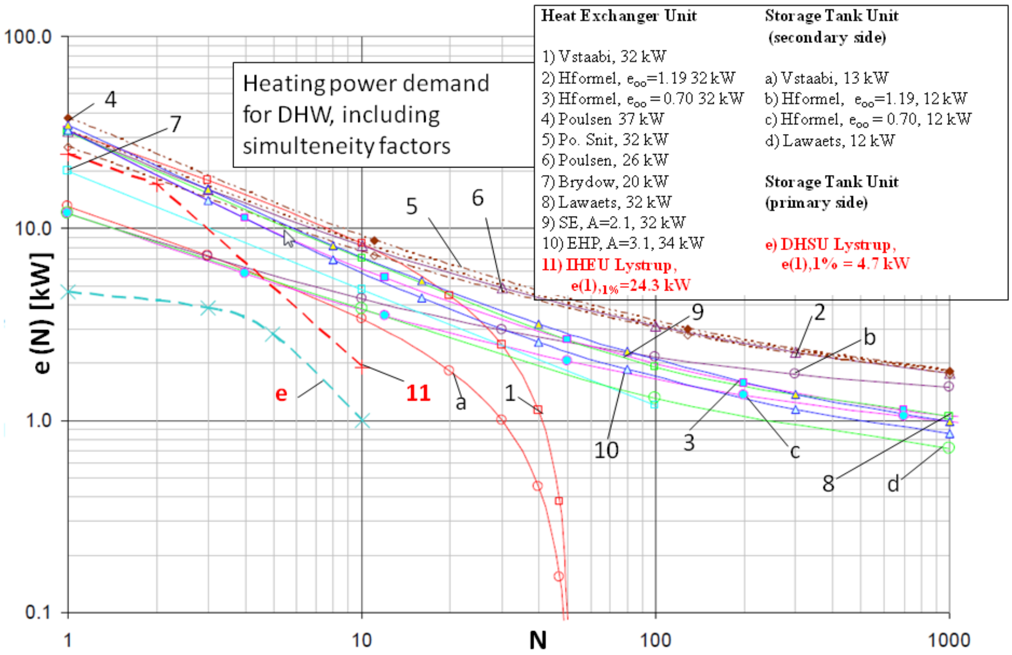

Figure 10: Comparison among simultaneity factors in the literature and the values derived from the measurements in Lystrup.

for the calculation of the optimal size of the heat distribution system. In figure 10, the developed simultaneity curves are compared with others in the literature. It can be seen for the IHEU tapping (curve 11) that simultaneity is evident for up to two consumers. For n higher than 2 the e(n) value drops by the slope of approx. -1/n, which means that the following consumers are not adding any simultaneous load to the network. The initial design of the DH network is thus over dimensioned when compared to the actual DHW load. The initial design simultaneity factor is similar to curve 1 in figure 10. Looking at the DHSU (curve e) then charging simultaneity is found up to approx. 5 consumers. For a higher number of consumers also here the slope is approx. -1/n, which again means that the following consumers are not adding any simultaneous load to the network. Also here the initial design assumption of e(n) = 1 is leading to an oversize of the DH net. Anyhow, since the smallest available DH branch pipe dimensions are installed, this has no practical impact on the branch pipes. Additional information"s for figure 10 can be found in [10].

Distribution heat losses and pump electricity consumption

For a Danish reference year DH demand, heat loss in the distribution network and the annual electricity use of the pump were calculated based on duration curves divided in 8 representative intervals combined with load vs. temperature curves derived for the first monitoring period of 2010 (as figure 6). In addition, a full year (2011) of measurements is available, see table 4.

Table 4: Key data of network operation

Year		DK ref (calc.)	2011 (meas.)
Total heat delivered to LTDH network	MWh	287.2	273.9
Heat demand	MWh	238.1	219.4
Distribution heat loss	MWh	49.1	54.5
Distribution heat loss	%	17.1	19.9
Heat power, yearly avg.	kW	-	31.3
Supply temperature, DH	°C	-	67.4
Supply temperature, LTDH	°C	55	52.7
Return temperature DH	°C	30	34.1
Electricity use, pumping station	kWh	2600	2556

The heat loss of the reference year for the entire network is in line with the expected heat loss calculated in the design phase and comparable with the present share of the heat loss in the existing city-wide distribution networks in Denmark. However, the measured heat loss for the full year 2011 is about 11% higher, which can be explained by a distance of unintended non-insulated pipes before the DH meter in each dwelling with IHEU. Considering these pipes insulated, the distribution heat loss for a network with 11 IHEU"s is only slightly above the corresponding distribution heat losses for the 11 DHSU"s. The total distribution heat loss in the low-temperature network are approx. ¼ of the estimated heat loss in the case of conventional medium-temperature network (single pipes, series 1, 80/40°C, 6 bar system, 1 m/s flow velocity). The electricity use for pumping was estimated to be 2,600 kWh/yr, equivalent to 9 kWh_{el}/MWh_{th}. This is comparable with the electricity demand for pumping purposes in existing well-established systems [4]. According to the design method, it was expected to measure a larger pumping demand; the lower electricity use for the pump is explained in practice by the fact that the pressure levels in the network were still well below the limits set. This points that there is room for optimizing the network design method even more, so that the heat loss can significantly decreased, at expenses of an additional, but less significant from the overall primary energy point of view, pumping demand. Hydraulic limitations and noise must not be forgotten, though.

Costs

The total investment of the system has been estimated to 346,900 € or approx. 8,460 € per house, see table 5 [4]. It is also seen from the table, that the DHSU is about 30% more expensive than the IHEU.

Table 5: Investment costs

Costs (2010)			
Item	**[€/m]**	**[€/unit]**	**Total [€]**
Pipes*	120		65,000
Pipe fittings*	32		17,000
Pipe laying**	131		100,500
DHSU substation*		3,700	41,000
IHEU substation*		2,600	78,000
Substation installation**		1,000	41,000
Pump + frequency controller*		2,400+2,000	4,400
Total Cost			**346,900**
Cost per house			**8,460**

* Cost in the current project
** Calculation cost from national average data

ONGOING R&D PROJECT

The investigations continue in an ongoing R&D project where low-temperature district heating is demonstrated in two existing single-family house neighbourhoods. The first area is in Tilst near Århus, where the low-temperature concept is being tested in a street with 8 houses with radiators. The focus is on strategies to prepare the end-users and their installations for low-temperature district heating; strategies than can be used in a nearby area with 1000 single family houses. The second area is in Høje Taastrup near Copenhagen, where a low-temperature DH system supplying 75 houses with floor heating has been built. This area is supplied with an alternative mixing system as described in [9]: a 3-pipe shunt arrangement is connected to the pumping station supplying mainly DH return water to the low-temperature area. When the return temperature is not sufficient, a portion of water from the supply pipe can be added into the mixing shunt. In this case the low-temperature network is supplied by water mixed from the supply pipe and the return pipe of the main district heating network. This solution can be installed in an existing district heating network at a location having a sufficient flow in the return pipe. In addition the monitoring continues in Lystrup with further analysis of substations and distribution network.

CONCLUSIONS

The demonstration project of a low-temperature DH network for low-energy buildings has shown that the concept works. The results show that it is possible to supply the customers with a supply temperature of approx. 50°C and satisfy both the SH requirements and the safe provision of DHW. This fact is confirmed by the fact that there were no complaints from residents about the lack of SH or DHW. The energy efficiency target was met, being the distribution heat loss equal to 17% of the total heat production for the Danish reference year. Even better real-life performance is expected when unintended non-insulated pipes are getting insulated.

In DH networks of this kind, serving low heat density areas with no possibilities for future expansion, the design should envisage the exploitation of the maximum pressure that can be withstood by the media pipes. The network design method can thus be optimized, so that the distribution heat loss can decrease even further, at expenses of an additional, but less significant, pumping demand.

The analysis points at the fact that the dimensioning of DH systems need a better basis for simultaneity factors and that a greater consideration must be given to the operation of the SH and DHW installations, for the calculation of the optimal size of the heat distribution system.

The results demonstrate that it is possible to guarantee an energy-efficient operation, but it is very important to obtain proper functioning of each substation, otherwise unacceptable return temperatures result.

In the case considered, the distribution heat loss for the area with DHSU‟s are slightly lower than in the area with IHEU‟s. The sum of the distribution heat loss and the standby heat loss from the substation is on the other hand larger in the DHSU case than in the case with IHEUs, because the additional heat loss due to the storage tanks more than counteracts the reduction of the distribution heat loss. However, in areas with hydraulic limitations, such as outer urban areas, DHSUs offer in turn some advantages, thanks to the lower peak pressure/load requirements. Moreover, the smallest media pipe diameters of the house connection pipes in the market have still a valuable water flow overcapacity and this suggest that smaller volume of the storage tank can be chosen, in case of DHSU, and this would reduce the substation heat loss, space occupation and costs somehow. The conclusion is that within the tested substations, the IHEU is a better solution in regards to energy performance, installation costs and space requirements. Anyhow there is no superior substation concept for all purposes, but the system should be chosen taking into account the specific characteristics of the site and of the demand.

AKNOWLEDGEMENT

The projects have received grants from the Danish EUDP-program making it possible to develop and demonstrate the low-temperature concept.

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Low Temperature District Heating Network Serving Experimental Zero Carbon Homes in Slough, UK

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Keywords: Low Temperature District Heating, Energy Performance, Heat Losses, Low Energy Homes

ABSTRACT

Development of new DH schemes becomes more challenging as new building regulations impose higher energy efficiency standards that reduce the heat demands of houses which are potentially new connections to DH schemes. Consequently, the income from energy sale is lower and the proportion of heat lost from DH network to heat taken by customers is increasing. Such a situation demands new solutions for design and construction of efficient DH networks. This paper presents the main characteristics and key design parameters of a small, low temperature DH network, along with its real operational parameters and energy performance. The DH network supplies heat for space heating (SH) and domestic hot water (DHW) systems to an experimental development of eight, mixed size, low energy homes and two apartments. The results of the analyses show noticeable differences between design parameters and the measured ones. Improvement work on the DH network components helped to reduce the average DH return temperature and the DH network heat losses. This had a positive effect on performance of ground source heat pumps housed in the Energy Centre. Furthermore, the DH network proved itself as a reliable and flexible way of supplying renewable heat to residential buildings.

1. INTRODUCTION

Utilisation of district heating networks for supply of energy for conditioning space and the provision of hot water in buildings is a well known concept. This way of heat supply has been explored in a number of countries, e.g. Sweden, Denmark, Germany, Poland and Russia. However, this technology has been utilised in UK only to a limited extent.

The European Commission and many governments, including the UK, developed policies and legal regulations requiring building developers (both domestic and non-domestic buildings) to reduce the energy requirements for newly constructed buildings. This is often achieved by limiting CO2 emissions allowed per m2. [1, 2].

Utilisation of waste heat from power production or other industrial processes, often serving hundreds of traditional dwellings via district heating network, is generally economically viable. However, building economically viable DH scheme utilising energy from dedicated heat plants using low carbon or renewable energy sources and serving low energy demand buildings becomes a much more challenging task. This is due to lower income from energy sales to fund the construction of new energy plants, heat networks or their extension and the heat losses on the network. These lower heat demands per DH connection present an opportunity to see if the required supply can be made at lower temperature and with small DH pipe. This situation encouraged the district heating industry and the research community to work on reducing the DH supply temperature to as low as possible, minimising the size of DH pipes and maximising the effectiveness of their insulation. All of these will reduce the heat losses, the DH installation cost and will additionally allow connection of lower temperature heat sources. This will help to improve the economics of DH installation and operation.

Different researchers started exploring concepts of low temperature district heating mainly through theoretical studies, mathematical modelling or equipment tests in laboratories. As the concept of low temperature DH is relatively new there is still very limited practical evidence to prove that district heating, for temperatures as low as 50-55°C, can still deliver sufficiently hot water and satisfy space heating requirements also in the UK climate [3, 4].

This paper presents the main characteristics and key design parameters of a small, low temperature district heating network, along with real operational parameters and energy performance of the district heating network. The DH network supplies heat for space heating and domestic hot water to an experimental development of eight, mixed size, low energy homes and two apartments. The key parameters analysed and presented in this paper are: predicted and measured total heat load curves, operating flow and return temperatures, average monthly heat loss parameter of DH pipework and linear density of the heat demand.

2. DISTRICT HEATING SYSTEM - GENERAL OVERVIEW

2.1. Low Energy Homes

The experimental development of a low temperature district heating system serving low energy, zero carbon homes is located in Slough, about 20 miles west of London and is featured in Figure 1. The site consists of ten dwellings; two 1 bed apartments (45 m2 each), a terrace of three 2 bed houses (80 m2 each), a terrace of three 3 bed houses and two 3 bed detached houses (94 m2 each), an information centre (45 m2) and Energy Centre. The summary of the development in numbers is presented in Tabel 1.

Four houses located on the western side of the development are built from timber frame panels manufactured offsite with the remaining buildings constructed with traditional masonry block. Both types of construction are typical for the UK but had to be insulated to a very high standard to reach a heat loss parameter (HLP) of around 0.8 W/m2K which is required for Code for Sustainable Homes Level 6[1]. The houses are also characterised by high level of air tightness of up to 2 m3/m2h. With such high level of airtightness the houses had to be equipped with a whole house mechanical ventilation system with heat recovery.

Tabel 1 Summary of information about experimental, low energy development in Slough.

Project initiator /leader:	SSE	Year of construction:	2010
Building units (residential):	10	Building units (tertiary):	1
Site area [ha]:	0.18	Area heat demand density [MWh/ha year]:	199
Heated area [m^2]:	845	Floor area heat demand density [kWh/m^2]:	42
Length of DH mains [m]:	165	Linear heat demand density [kWh/m year]:	217
Number of residents :	25	Plot ratio Built floor area/site area:	0.47

2.2. District Heating Network

Due to the layout of the houses in relation to the Energy Centre the network has two branches. The western branch serves 4 dwellings and eastern one serves 6 dwellings and the information centre. The branches are open ended which means that there is no connection between flow and return pipe at the end of a branch, which would allow for circulation of district hot water even if there is no demand. The variable speed DH circulation pumps located in Energy Centre are controlled to maintain constant differential pressure across the DH flow and return. Therefore, flow in DH pipes varies depending on the actual heat consumption.

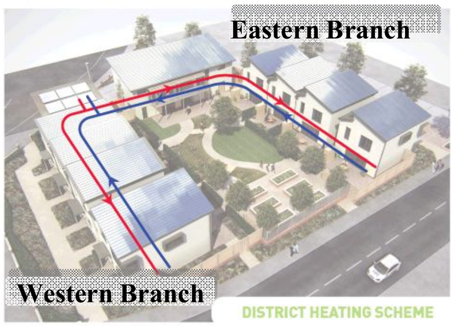

Fig 1 Layout of houses and district heating network at experimental development of low energy houses in Slough.

To assure the lowest possible heat losses from the network and to provide a long service period the heat network has been built mainly with a pre-insulated steel TwinPipe system. The system has both flow and return pipes of the same diameter.

The connection between DH mains and a house is made with AluFlex pipe, which is also a TwinPipe system, although not made of steel. The service pipe of the AluFlex is made of a multilayer system containing a plastic pipe (cross-linked polyethylene – PEX) and an aluminium membrane. Such construction provides advantages of a smooth internal surface of a plastic pipe with the durability and tightness of an aluminium pipe, protecting against cell gas diffusion into DH water and water vapour into insulation. The construction advantage of using Aluflex pipes is that the house connection can often be made using a single piece of pipe. This reduces the installation costs and a risk of joint leakage under houses. Selected characteristics of the pipes are presented in Tabel 2. The heat loss data in the table are valid for Tsupply/Treturn/Tground of 55/25/15°C.

Tabel 2 Characteristics of pipes used for district heating system.

Pipe Type	**Carrier Pipe/Casing Pipe Dimensions [mm/mm]**	**Heat Loss [W/m]**	**Installed Length [m]**	**Heat Loss [MWh /year]**
Twin Pipe Steel	25/160	4.5	13.8	0.5
	32/180	5.0	45.6	1.83
	40/180	5.8	46.3	2.13
	50/225	5.6	6.5	0.32
Twin Pipe AluFlex	26/125	4.1	52.8	1.75
Total			**165**	**6.53**

The available DH system drawings show that the main section of the DH network serving both branches of DH was constructed with 50 mm diameter service pipe. Another section serving western and the three furthest

[1] Code for Sustainable Homes is a sustainability rating tool officially adopted by the UK Government.

houses of eastern branch has been constructed with 32 mm service pipe. A service pipe of 40 mm diameter has been used to construct the middle section of the eastern branch with two flats, information centre and one three-bedroom house connected to it. All connections between the DH mains and the houses have been made with 26 mm service pipe (AluFlex) and 25 mm (steel pipe) in case of flats and information centre. Final connection between AluFlex pipes and the HIUs have been made with 22 mm copper pipes with insulation of either Aluflex (13 mm) or Climaflex (19 mm).

2.3. Energy Centre

The heat for the DH loads is provided from the site's Energy Centre. The centre consists of four renewable heating technologies:

- 30 kW biomass boiler with accompanying pellet storage silo,
- 2 x 17 kW ground source heat pumps (GSHP) with 7 boreholes of 100 m depth,
- 40 kW air source heat pump (ASHP),
- 20 m² evacuated tube solar thermal panels (STH).

The Energy centre is also equipped with 8 m3 stratifying thermal store with multiple connections for staged operation of heat pumps at different temperature levels in the store.

The energy centre was designed to demonstrate and evaluate that the Zero Carbon Homes standard could be reached by either the ASHP, the GSHP or the biomass boiler. The solar thermal system is an extra heat source to add to the other renewable technologies. The size of the heat load and size of the thermal store would have allowed the use of more solar thermal but the available roof space has limited the installed solar thermal capacity.

Operation of Energy Centre and district heating system is controlled by Trend BMS control system (BMS). The strategy implemented by the BMS aims to:

- maximise the operation of the heat pumps at lower temperatures,
- maximise the use of potential higher temperature solar heat to displace the requirement for the heat pumps to heat to 55°C,
- utilise the thermal store to smooth out peaks in DH which are significantly larger than heat output of each of the renewable technologies.

3. PEAK POWER AND DEMAND CURVE

<u>Design</u>

The heat demand for space heating and domestic hot water of buildings has been modelled using software package Virtual Environment initially with version 5.9 and later with version 6.4 [5]. The weather data used for modelling heat demand were based on data from Heathrow. Number of heating degree days (HDD) for base temperature of 15.5°C was 1745. To generate the DH network heat load the heat losses of DH network mains and connection pipes built with TwinPipe system have been added to the houses' heat demand. The corrected, ordered from the highest to the lowest, hourly heating load is presented in the Fig 2. Initially the peak heat demand has been estimated to be 44 kW (11 properties). Due to the fact that house no 2 was disconnected from the heat grid in December 2011 the predicted heat load duration curve had to be corrected to make it comparable with the heat load measured between May 2011 and April 2012. After correction the peak demand decreased to 40 kW. The annual heat demand of the whole development was calculated to be 37 MWh/year. With such a demand the linear heat density of DH network is 330 kWh/m,y or 1.2 GJ/m,y. If all the modelled heat losses we included, the heat demand on the supply of the DH network would increase to 49 MWh/y.

<u>Measured</u>

The real heat load of district heating network that combines both branches of the network was measured with a heat meter at the Energy Centre. The measurements of the heat demand were taken between 01/05/2011 and 30/04/2012. This period was characterised by relatively warm winter 2011/2012 with 1787 HDD for a base temperature of 15.5°C.

The measured heat load curve is presented in Fig 2. The measured peak load reached 34.4 kW, which is 14% lower than the modelled peak load.

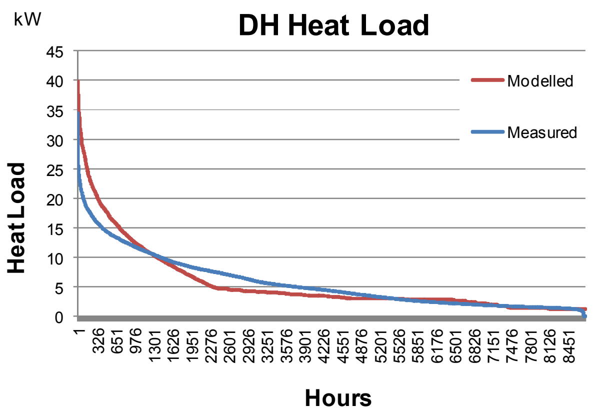

Fig 2 Modelled and measured district heating network hourly heat duration curve.

The measured annual heat demand of all the buildings connected to the DH network was 35.7 MWh/y and with DH heat losses 49.6 MWh. The linear heat density of DH network is 319 kWh/m,y or 1.1 GJ/m,y.

4. HEATING TEMPERATURES

<u>Design</u>

The district heating scheme is designed to operate at a flow temperature of 55°C. The DH circulation pumps are set to maintain 0.9 bar of the system differential pressure. The domestic hot water is supplied at 43°C via an on-demand heat exchanger in each house. The radiators and heater battery in all homes are connected to the DH network without any heat exchanger (direct system). The SH systems in houses were designed to achieve the lowest possible DH return temperature, to minimise heat loss and maximise the heat pumps' coefficient of performance. The expected return temperatures for DHW system is 20°C and for space heating is 35°C. The schematic of the hydraulic interface unit (HIU) connecting DH network and a house's heating system is presented in Fig 3.

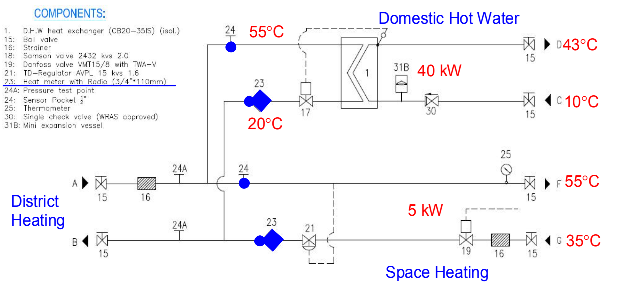

Fig 3 Schematic of a hydraulic interface unit connecting DH network with DHW and SH systems.

Measured

Monitoring of district heating network temperatures showed that the monthly volume weighted average DH flow temperature was well below the 55 °C design flow temperature and varied between 49.5 °C and 53.2 °C. The measured DH flow temperature together with DH return temperature for different months are presented in Fig 4 and Tabel 3.

The monthly volume weighted average return temperature was higher than the design return temperature and varied between 28.3 °C and 42.1 °C.

From March until June 2011 the return temperatures increased from 40.3 °C to 42.1 °C. Since July 2011 the average return temperature dropped and then stayed at a relatively stable level of around 36 °C. This is much lower compared to around 42 °C in previous period but still 11 °C higher compared to the expected value. Since October 2011, we can observe further decreases in return temperature to the lowest measured level of 28.3 °C in December 2011.

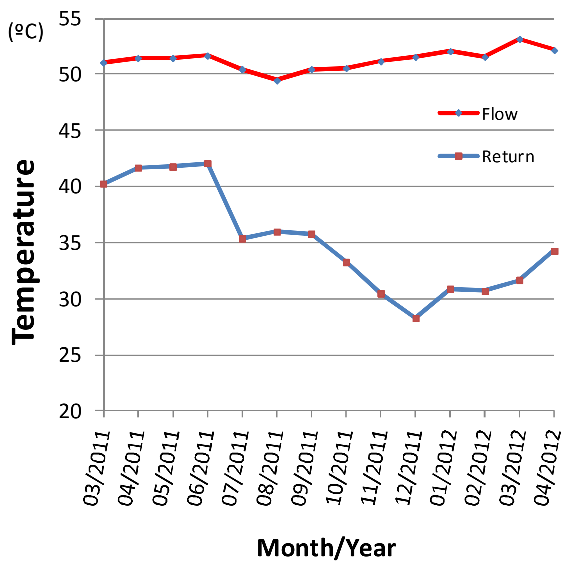

Fig 4 Measured flow and return temperature of the district heating network

Tabel 3 Measured operational temperatures and a heat loss of the district heating network.

Month/ Year	Average Flow Temperature (ºC)	Average Return Temperature (ºC)	Temperature Difference (ºC)
3/2011	51.1	40.3	10.8
4/2011	51.5	41.7	9.8
5/2011	51.5	41.8	9.7
6/2011	51.7	42.1	9.6
7/2011	50.5	35.4	15.1
8/2011	49.5	36	13.5
9/2011	50.5	35.8	14.7
10/2011	50.6	33.3	17.3
11/2011	51.2	30.5	20.7
12/2011	51.6	28.3	23.3
1/2012	52.1	30.9	21.2
2/2012	51.6	30.7	20.9
3/2012	53.2	31.7	21.5
4/2012	52.2	34.3	17.9

5. DISTRICT HEATING NETWORK HEAT LOSS

Design heat loss

Usually, district heating network losses are represented as a percentage of the total heat fed to DH network. For the modelled heat consumption such loses would be around 24%. However, as the network is expected to maintain a fairly constant flow and return temperature, it is useful to estimate the average heat loss expressed in kW. Tabel 4 presents the average seasonal and the annual heat loss parameters. The heat losses of district heating network mains and connection pipes built with TwinPipe system has been modelled using online calculation tool Logstor Calculator version 2.1 [6]. To calculate heat losses DH pipes the Logstor Calculator uses method from International Standard EN13941 [7].

Additional heat losses from internal connection pipes (insulated) have not been estimated during the design stage. However, heat loss calculations for this part of DH network have been conducted after construction. The heat loss from the copper connection pipes has been calculated using general equation for heat loss from insulated pipes, assuming constant temperatures of flow 55°C, return 25°C, heated space 20°C and unheated space 10°C.

According to the design calculations the average heat loss rate during winter months should not be much higher than 1.5 kW and 1.3 kW during summer months. Because the measured flow and return temperatures were different from the design assumption, the design heat loss has been adjusted using real temperatures. This adjusted heat loss is presented on Fig 5 with dotted blue line. The original calculations for heat loss separately for TwinPipe system and copper pipe connection is presented in the Tabel 4. It is worth noticing that much shorter and smaller, if compared to Twin Pipe system, the copper pipe connections account for almost half of the heat loss from DH network.

Tabel 4 Heat loss of the DH pipes and connections to houses

	Unit	Winter	Summer	Annual
Logstor TwinPipe system (165 m)				
Heat losses rate	kW	0.82	0.68	0.73
Copper pipes (52m)				
Heat loss rate	kW	0.71	0.63	0.68
Total average heat loss rate	kW	**1.53**	**1.31**	**1.41**

Measured heat loss

The average heat loss of the district heating pipes have been calculated as a difference between measured heat supplied to the DH network and heat consumption of all buildings connected to the network. The measured relative heat loss on the DH network was 28%. Fig 5 presents the average heat loss expressed in kW for each month, both expected and measured along with amount of heat supplied to the DH network and heat lost on the network.

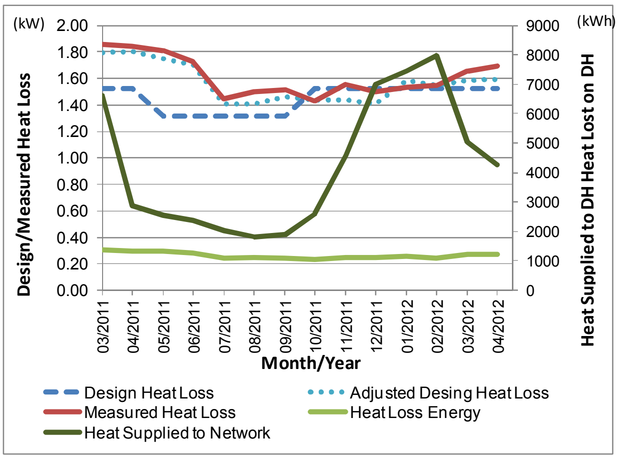

Fig 5 Expected and measured heat loss coefficient of the DH network along with heat supplied and lost on the network.

The heat loss of the DH network measured from March 2011 until June 2011 stayed at around 1.8 kW, which is about 18% higher than the initial design heat loss. A noticeable drop in heat loss has been observed from July 2011. From July on, heat loss maintained its level at around 1.5 kW until November 2011 when it increased to 1.55 kW. This is very close to the design heat loss for winter period. Nevertheless, there is further increase of DH heat losses during March and April 2012. This increase is correlated with the increase in DH return temperature during these months.

If we look at the heat loss from the monthly energy consumption view we can see that during the second heating season, starting from October 2011, the results show some improvements over the previous period. The correlation between heat loss and heat supplied to the DH network has been presented in Fig 6. For similar amounts of heat supplied in March 2011 (6600kWh) and in December 2011 (7000 kWh) the heat losses have been reduced from 1.86 kW (21%) to 1.5 kW (16%). This reduction in heat losses can be recognised as a results of the improvement works on insulation of pipes in Energy Centre and in HIUs in each house and optimisation of settings of DHW valves in HIUs.

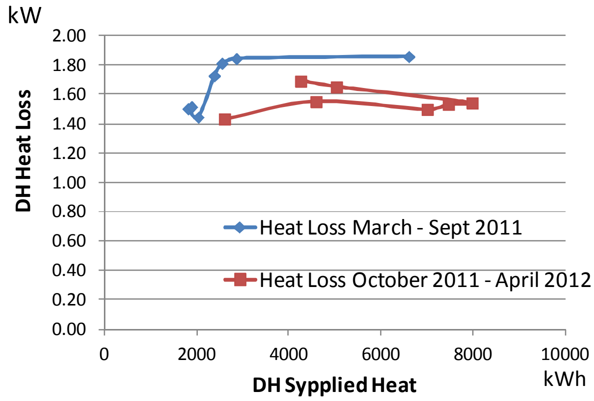

Fig 6 DH Heat Loss in 1st and 2nd year of network operation.

6. RELIABILITY OF DH SYSTEM

The district heating network built with TwinPipe system was relatively quick and simple to construct. No major problems have been noticed during construction or commissioning of the network or the HIU units. After the tenants moved into the houses, some of the HIUs' settings had to be adjusted and air released from the space heating distribution system. After that, only on two occasions the supply of heat to houses had been suspended for a short time. In the first case to allow replacement of a valve in Energy Centre allowing for connection of a new energy source. The second case shortly followed the first one and was a result of automatic shut down of Energy Centre, due to high pressure in the system caused by incorrect pressurisation of DH network after the valve replacement. On three other occasions the tenants reported problems with their individual heating system. Nevertheless, in all the cases cut off time was relatively short (up to few hours) and did not cause any significant thermal discomfort for tenants.

Moreover, operation of the DH at 50-55C has had no impact on the reliability of the DH supply or house heating systems. Despite the facet that the indirection connection of the house heating systems to the DH network is the norm in the UK, to date there have been no reliability issues related to the use of direct connection of DH. Indirection connection is the norm in the UK.

7. DISCUSSION OF RESULTS

7.1. Heat Demand

Taking into account the fact that the predicted heat demand comes from calculations using imperfect model of the buildings and the standard weather data slightly different from real weather occurring during the measurement period the difference of 14% between modelled and measured peak demand should be considered as relatively small. Furthermore, the modelled total annual heat demand was 49 MWh and the measured one was 49.6 MWh. This is surprisingly very close.

7.2. Operating temperature

Despite the intension of the designers of the DH network and Energy Centre to supply heat at relatively constant water temperature of 55ºC through the whole year, the measured supplied temperature varied between 50 ºC and 53 ºC. Investigation of possible causes of this situation revealed that the temperature of the top of the thermal store in Energy Centre was relatively constant around 54.5 ºC. The temperature loss between the top of the store and the DH heat meter was caused partly by uninsulated parts of the pipework in the Centre and by parallel circuit with DH water treatment unit. However, after insulating the exposed pipework in October 2011 the difference has been reduced to around 3 ºC. There is also a possibility that water from the return of the DH network had been mixed with the flow either through a biomass boiler or through a not fully closing mixing valve, connecting DH return with a flow pipe. This possible fault should be further investigated.

The DH network return temperatures are also noticeably different from the expected ones. Fig 4 shows evidence that lowering temperature settings for DHW system (July 2011), restricting water flow through radiators and increasing heat exchange area of the heater battery (October 2011) helped to reduce DH return temperature. Further investigation of return temperatures from individual houses shows that in one house the HIU malfunctioned, letting hot water to leak to the return pipe. This fault has not been rectified until May 2012. In March 2012, further checks of settings at HIUs revealed that, in three properties, DHW valve settings were different from the optimum ones set in July 2011. Both factors caused an increase in the overall DH return temperature. Further increase of the return temperature from March 2012 still has to be investigated.

The above analysis shows that for small development like the one in Slough the level of DH return temperature is very sensitive to faults or suboptimum settings of HIUs. Therefore, it is important to properly commission the HIUs and perform periodical checks of their operation. This should help to keep the DH return temperature low and reduce heating network losses.

7.3. Heat Loss

The measured DH network losses were only slightly higher than the corrected modelled losses of the network. The change of settings of the HIUs, in June 2011 helped to reduce the return water temperature which resulted in reduction of the network heat loss. The remedial works on the insulation of pipework in houses, in Energy Centre, reduction of the maximum flow rate in space heating system and doubling the heat exchange area in a heater battery located in a ventilation system in all the houses helped to further reduce the heat loss. However, further increases in the heat loss during March and April 2012 were probably a result of increased DH return temperature caused by a suspected malfunction of valves in DHW circuit at HIU in two properties.

It is also worth emphasising the importance of proper insulation of the copper connection pipes. Despite much shorter runs of these pipes (52 m compared to 165 m of TwinPipe system) they were responsible for almost half of the heat loss on the whole DH network. If designers had paid greater attention to it, they would possibly specify better insulation for copper pipes to prevent this heat loss. As a remedial measure, it might be worth to consider improving insulation of a connection to one of the flats where connection pipes run in unheated area.

Furthermore, the analysis showed that the performance of the district heating scheme is strongly depend upon the proper and reliable operation of the hydraulic interface units and heat distribution systems in houses. Malfunction of even one of them can cause increase of the return temperature resulting in higher heat losses on the network.

According to IEA DH|CHP report [8] on strategies to manage heat losses from district heating network, the losses above around 11% are recognised as avoidable. However, this figure is expected to be higher for networks serving low energy houses. This research shows that the annual heat lost on DH network was 13.8 MWh, which constituted about 28 % of energy feed into the DH network. If heat was generated with ground source heat pumps working with seasonal efficiency of just 2.5 and with a cost of electricity at £0.10 to run the pumps, its annual cost would be about £550. This constitutes about 23% of income from sale of the heat.

8. CONCLUSIONS

District heating networks have been implemented and operate with success in many countries. However, the new building construction standards and regulations impose significant reduction of heat demand in new buildings. Reduced demand makes heat supply via district heating networks more challenging due to lower income from heat sale and the heat losses associated with its transportation.

This paper presented results of a study of a small low temperature DH network, which supplies heat for space heating and domestic hot water to an experimental development of low energy homes.

The study showed that assuring the faultless and with the optimal settings operation of HIUs is crucial for maintaining the DH return temperature as low as possible. Increased DH return temperature has noticeable impact on the network heat losses. It might be worth to monitor return temperatures from individual houses to be able to quickly find malfunctioning HIU units.

Current heat loss from the DH network is higher than the design one and it might be difficult and expensive to reduce it significantly. However, reducing the return temperature by further optimisation of settings in HIUs should help to further reduce it.

To reduce the relative heat loss of the DH network designers of low energy homes that are planned to be connected to DH network should consider increasing use of domestic hot water by specifying hot fill appliances (dishwasher, washing machine).

The study showed also that low temperature DH networks operating at 50 ºC -55 ºC are capable to satisfy space heating and domestic hot water at acceptable level of thermal comfort in majority of connected low energy homes.

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DHC13, the 13th International Symposium on District Heating and Cooling
September 3rd to September 4th, 2012, Copenhagen, Denmark

INTEGRATION OF LOW ENERGY BUILDING AREAS INTO DISTRICT HEATING SYSTEMS USING SUBNET SOLUTIONS

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Space Heating, Passive House, LEB, Domestic Hot Water, Sequential charging

ABSTRACT

The purpose of this paper is to present a new approach on how to integrate low energy building areas into District Heating (DH) systems; it is a result of a research project investigating possibilities to increase the share of DH in Sweden.

The EU directive 2010/31/EU (EPBD recast) requiring that “all new buildings are nearly zero-energy buildings” by 2020 is posing a challenge on future district heating development.

At the same time that the energy demand in the building stock will decrease due to the gradual refurbishment of existing buildings, the heat density in newly developed areas will be much lower than it is in most areas with DH grids today. This will cause a relative increase of losses in DH systems and make them less efficient while the total heat demand is decreased. To compensate for a lower heat demand per customer, as many units as possible should be connected in areas with DH. Also, investment costs for newly developed areas will increase relative to heat sales making the development of DH networks unprofitable if traditional technology is used. It is therefore important to find new concepts for DH systems in low energy building (LEB) areas.

One possible solution to this challenge is presented in this paper: the connection of subnets to the DH system where many units with a low heat demand are bundled and connected to the DH system at a single connection point. The heat demand at this connection point is of a scale which makes it profitable for the DH provider and the subnet can be optimized in order to meet the specific demands of LEB areas. Integrating the planning of the subnet into the development of the area opens up new possibilities of system optimization. The subnet opens up the possibility to use different charging models since the low space heat demand makes traditional billing schemes unnecessary.

Splitting the DH system into a main grid and subnets gives the DH provider the opportunity to operate an efficient system while the subnet in the LEB area can be optimized to meet the requirements of the area while having access to a stable and environmentally friendly heat supply.

INTRODUCTION

European Climate Goals

The European countries committed to reducing greenhouse gas emissions by 20%, increasing the share of renewable energies by 20% and improving energy efficiency by 20% until 2020 [1]. The aims of minimizing the extent of climate change and of protecting the environment are incentives to commit to such challenging goals. In addition, increased energy security and competitiveness [1] on the global market convinced European leaders of the significance of such a target. Improving energy efficiency is pointed out as a key objective for Europe with a large future potential while, at the same time, being the most cost effective way of reducing greenhouse gas emissions [2]. Furthermore, all new buildings are required to be nearly zero-energy buildings by 2020 [3], with the definition of nearly zero-energy buildings left to the individual member states. Both district heating (DH) and low energy buildings (LEB) are suitable technologies for increasing energy efficiency– unfortunately it is not easy to combine the two of them using traditional DH technology. A different approach of combining these two environmentally sound technologies is analyzed in this paper.

District Heating

Increased district heating (DH) is seen as one opportunity for reducing greenhouse gas emissions, the dependence on fossil fuels and fostering the use of renewable resources. The development of DH has been very successful in Sweden since its introduction more than 50 years ago. More than 85% [4] of the apartment buildings are connected to the DH grid. The potential for further increase in DH can be met by connecting single-family homes to the grid, which is challenging since the heat density usually is much lower in single-family home areas than in areas with apartment buildings. A number of research projects have tackled this problem with the goal of reducing connection costs, which is the main obstacle to increasing connection rates [5]. In spite of these efforts connection rates for single-family homes are low and very few new houses are connected to DH. The recent decision of the EU to decrease the heat demand in the existing and future housing stock poses an additional challenge to the DH sector. New customers and an early entry into newly developed housing areas are needed. This demands solutions that are adapted to the changing pattern of energy consumption in the residential sector.

Swedish DH grids have large margins to connecting further consumers. The prevailing recommendations for dimensioning the DH system and its effect have resulted in over-dimensioned DH grids with large margins [6]. This excess capacity can be used to connect more consumers, such as LEB areas, to the existing grid without reducing the overall grid performance.

Line heat demand in Swedish grids is approximately 4,1MWh/m*a for large DH grids, 2,8MWh/m*a for medium sized grids and 2,3MWh/m*a for small grids [7].[1] Losses in small DH grids and areas with low heat densities can account for 40% and more, especially during summertime [17]. Sometimes losses even exceed the actual heat consumption.

Due to the low heat flow in small grids, relative losses increase; traditional DH is not being developed in areas with a line heat demand under 0,5MWh/m due to their poor efficiency.

Low energy buildings

Low energy buildings (LEB) are widespread over Europe and the number of units annually built and the market share are increasing. However, a generally accepted definition for LEB is missing and many different names, concepts and standards are used in Europe.

To connect LEB areas to DH has been shown to be challenging, as the annual heat demand for space heating (SH) is low. For this reason it is not viable to connect these areas to DH in a traditional way. Even the connection of single-family homes and single-family housing areas to DH has proven to be problematic due to high investment costs, long amortization periods [8] and low energy consumption.

Profitability of DH in areas of low heat densities requires low investment costs for local distribution networks and low heat production costs [9] as well as small losses in the grid. In many cases connecting single houses can be seen as environmentally or politically benevolent rather than a decision based on economic considerations.

Estimating a realistic annual heat demand for single houses with LEB standards is crucial for designing a valid model and for the capability to defining relevant system boundaries. Since no international or European definition of LEB or nearly zero-energy buildings exists, it is hard to make accurate assumptions about LEB areas. To build a realistic model, the international Passive House (PH) standard is used as a basis. From a model based on PH standards, general conclusions about LEB areas can be drawn. Another advantage of using PHs for the model is the amount of experience existing in this field, since the first PH was built in 1991 and a large number of buildings exist today. Many projects have been closely monitored and followed up by long-term measurements. Hence, it is certain that the PH concept works and a solid amount of data is available. The international PH standard defines a maximum space heat demand of 15kWh/m^2*a. Houses are planned using a standardized planning tool (PHPP) and are controlled and certified by the Passive House Institute. PH standard is based on some crucial concepts such as the use of solar and internal gains, extreme high thermal performance (including thermal bridges), high airtightness, mechanical ventilation and heat recovery. For further information see passiv.de [10].

SCOPE OF THE PAPER

Passive Houses and District Heating

Passive houses fundamentally differ from conventional buildings in terms of heat demand, which is about 88% [11] lower than the average of existing buildings in Sweden. The heating system needs to be adapted and optimized to fit the specific conditions with an extremely low annual heat demand, a very low heating load and a higher energy demand for hot water than for space heating during most of the year. While the building’s space heating in theory can be provided by using the air conditioning unit (HVAC, heating, ventilation and air conditioning), there are several advantages of hydraulic heating systems: the system is more flexible, can be steered on demand, peek demands can be met, it is easier to supply heat to rooms with a higher demand such as bathrooms and rooms in the outer corners of the building, etc..

Even though PHs differ from conventional buildings with regards to heat load and demand, many different heating systems can be a suitable choice. The concept and design of PHs does not limit the choice of heating systems by definition, but an efficient system with a low environmental impact should be a core interest of the investor for obvious reasons.

[1] It should be noted that the small size DH grid in average deliver 30GWh annually.

To include PHs in DH systems poses several challenges, with the greatest challenge of keeping distribution losses at an acceptable level. Due to the small heat demand of PHs, distribution losses increase relative to the heat consumption, making the DH system as a whole less efficient. It is regarded that DH is not competitive for single-family homes with current PH standards, though new technology most certainly will alter this fact [8]. The connection of apartment buildings built as PHs is only regarded as realistic in areas with an already established DH network and an existing building structure with a high heat density. Thus, it can be concluded that a conventional DH system is not an economic and efficient solution for newly established PH neighborhoods. An adaption of the system would without doubt be necessary, but simply increasing insulation will most definitely not solve the problem. The purpose of this paper is to present and discuss one possible technical solution to this problem, using an efficient subnet adapted to the specific requirements of LEB areas.

THE CONCEPT

Subnets

Connecting PH in an area with a low energy density is not efficient using traditional DH technology. An adapted concept of connecting newly developed residential PH areas to DH is presented and illustrated in this paper. Using subnets with decentralized storage tanks and sequential charging patterns, losses can be cut to a fraction of the losses of conventional DH. This idea is presented using a model of a PH area consisting of 40 single-family homes.

Subnets are used to supply the PH area with heat without having to connect every single house to the main DH grid. The subnet is connected to the DH grid at one point, acting as a single consumer with a consumption pattern differing from traditional consumers. The subnet can be regarded as a small DH system with adaptations made in order to minimize losses, working as a closed system that is designed to supply the heat demand of a defined area in the most efficient way. In contrast to DH systems, the subnet is designed and constructed for a specific area with a fixed number of houses. The subnet should not be over-dimensioned and does thus not give much room for further expansion and the connection of additional consumers.

Using a subnet opens up the possibility to connect areas to DH systems in an efficient way without having to alter the DH system as a whole.

The concept of connecting areas to DH via subnets could also be used for other areas with a low heat density, e.g. sparsely populated areas such as existing areas with single-family homes.

Who will develop and own the subnet is also significant to discuss. This could be done by the DH company, the developer of the area, or a local housing-owner association. The metering and billing could be assigned to any of these parties, allowing for an altered economic scheme for the subnet that has higher investments costs and lower running costs in contrast to traditional DH. In any case, a close cooperation between these parties is of high priority in order to guarantee a successful outcome.

Sequential charging

The core of the subnet is a stratified storage in each house. This installation allows for sequential charging in contrast to traditional DH, where hot water is pumped through the net around the clock with low degrees of utilization. During charging time the net is used to full capacity, while between charges the system is on standby. This pattern cuts transmission losses to a small fraction of what is common in DH areas with a low energy density. The energy needed to supply the heat demand of each unit per day is transmitted during one charging cycle during summer and two charging cycles during winter. On very cold days or other peak demands, e.g. increased hot water consumption due to visitors etc., an additional charging cycle can be triggered. Another advantage of sequential charging is that the subnet can be used to balance the DH system in times of overcapacity and thus reduce bottleneck situations.

THE MODEL

The area and its houses

The model area consists of 40 PH (according to international PH standards) designed as four-person households on 525m^2 properties. With a floor space of 150m^2 per house, the SH demand is 2250kWh/a. In 2010 the average annual heat demand (SH + Domestic Hot Water (DHW)) in single-family houses in Sweden was 126,5kWh/m^2 and 18,6MWh in total [11], providing an average floor space of 147m^2. SH demand on a cold day sums up to 36kWh/d per house while no heating is necessary during the summer months. Domestic hot water (DHW) consumption is assumed to be 100l/d at 50°C according to DIN V 4701-10 [12] but up to 150% more can be supplied within the regular operation schedule during the warmer months. In contrast to SH demand, DHW consumption per day is on a more or less constant level throughout the year. At the same time, DHW consumption varies much more from household to household due to individual behavior patterns, while space heating only shows a small variation in PH of the same type at the same location. The consumption pattern for DHW usually shows two peaks, one in the morning and one in the evening on weekdays, while the first peak usually occurs later in the morning on weekends and holidays.

In contrast to SH demand, the consumption profile of DHW is not as easily and clearly defined. Many studies have attempted to model DHW consumption. To dimension the heat demand for DHW, different concepts are used such as DHW use per area, per household or per inhabitant. These figures are always quite imprecise as consumption patterns vary to a great extent. To obtain an accurate number, a measurement of the hot water flow in the premises is necessary [13].

The values for DHW consumption per day that are given in the literature vary from 23l at 50°C per person and day (DIN V 4701-10) to 368l a day for a household without bathtub (DS439) [14]; measured figures from PHs are 18,8l at 50°C per person and day and 20,7l per person and day for LEB, with a mean variation of 10 in the PH and 5 in the LEB [15]. Also, an average of 90l/day per housing unit has been measured in PH and LEB [16]. An interesting observation is that the variation over time in the same households are small, so it can be concluded that individual behavior has a big influence on DHW consumption [13]. Another factor influencing DHW consumption is whether individual metering and billing is used or not, since consumers tend to be more conscious about their DHW use when they are billed for their actual DHW consumption.

Each house features a stratified storage with a volume of 250l that is charged from the subnet through a heat exchanger. In a stratified storage the water temperature increases from bottom to top and the tank with its connections are designed to maintain these vertical stratifications. This allows extracting more DHW than from a mixed tank of the same volume.

The storage is charged to a temperature of 90°C during winter and 70°C during summer, with two scheduled charging cycles during winter and one during summer. The main DH grid is assumed to distribute hot water with a temperature of 95°C during winter and 75°C during summer. Charging pattern can be adjusted to meet individual consumption patterns to some extent. If the heat demand occasionally exceeds the supply from the scheduled charges, additional charges can be performed. Software needs to be embedded into the system to manage demand and supply in the best way.

With a capacity of 19kWh, the tank needs to be well insulated to keep standby losses under 2kWh/day, 8,4-13,6kWh are available for DHW and 3,4-18,3kWh for space heating (Fig 1). Modern SH systems are able to work with low return temperatures of down to 20°C, which makes a greater portion of the energy stored in the hot water storage available for SH.

To minimize losses within the domestic system, the DHW system is designed as a continuous flow water heater (CFWH) without hot water circulation. In order for this system to work, the hot water pipes in the house have to be short and all hot water appliances need to be located close to each other, which is easily implemented in single-family homes. This has to be considered early on in the planning of the buildings.

DHW is heated in an external heat exchanger on the outside of the stratified storage on demand using the water from the upper part of the stratified storage, while the hydraulic SP system draws heat from its lower region.

CFWH eliminates the risk for Legionella without needing to apply hot water circulation, which implies significant losses. Also, the amount of water that can be heated from the storage is greater since the water temperature of the storage can decrease to 38°C instead of 55°C, which is necessary in systems with hot water circulation. All DHW installations are insulated, also within the house. Energy demand for DHW is dependent on the water temperature of cold water which is colder during wintertime than during summer; cold water is assumed to have a temperature of 5°C throughout the year.

The net and its dimensions

The net has been designed as a single loop of twin pipes with a length of 600m, where the diameter of the pipes is gradually reduced along with the decreasing heat demand for the remaining houses; the connections to the single-family houses are 15m apart from each other. The subnet is connected to the DH with 54mm pipes, reduced to 42mm after 17 houses, to 35mm after the next 8 houses and finally to 28mm after the following 6 houses. The connection pipes to each unit are 1,5m long and use twin pipes with 15mm in diameter. These dimensions allow for short charging times (1h27min twice a day during winter and 37min once a day during summer for layout conditions). In order to minimize losses and achieve good efficiency, the net is dimensioned to meet the demand of the area without excess capacity for possible future expansions, which might never happen. On the other hand, it is important not to underestimate the heat demand, since this would reduce the standard of living and comfort substantially. The tank size is chosen to meet the heat demand, including a reasonable margin and allows for a charging schedule with few and short charging times. Relative standby losses decrease with larger tanks.

In between charges, the water in the piping system stands still and the remaining hot water would cool down to ground temperature; this would result in significant heat losses. In order avoid these losses, an additional tank is integrated into the system and the hot water is pumped into this tank after each charging cycle while the pipes are filled with cold water. At the beginning of each cycle, the hot water from the storage is pumped back into the piping system. This procedure reduces losses significantly. This tank could be placed in the house closest to the main DH grid.

Limitations

DH grids are dimensioned to be able to cover the heat load even during the coldest days that occur once every 20 years, resulting in an overcapacity and higher transmission losses. To reduce losses in the DH grid, the grid temperature differs between the summer (off heating season) and winter (heating season) and in this model the temperature is reduced from 95°C to 75°C. Consequently, the subnet and the stratified storages have to be designed for both cases. Losses in the main DH grid are not studied and discussed since this is not within the scope of this study.

RESULTS

Using the concepts of subnets for areas with a line heat demand as low as 0,25MWh/m*a is shown to be a realistic option when the system is designed without margins. Losses within the subnet can be estimated to around 3.5% on average throughout the year.

Running the grid as a subnet with short charging cycles, twice a day during winter (heating season) and only once a day during summer (off heating season), the energy stored in the remaining water in the grid after the charging cycle has to be considered. Since the water cools down quickly when no heat is transported, especially in the smaller diameter pipes, these losses would decrease the efficiency of the net substantially. In total 117kWh are stored in the piping system. If this energy would not be recovered, losses would be around 60%. In order to avoid the losses connected with the cooling down of the water in the system, the hot water is pumped into an additional tank at the end of the charging cycle and back into the pipes at the beginning of the charging cycle. To avoid mixing of the water from the hot and return pipes, the tank needs to have separated chambers. Since the tank is much more compact, having a better volume surface ratio, and better insulation, losses from the tank are much smaller. Hence, the grid losses can be reduced to around 3-4%. It is convenient to place the additional tank in the house closes to the grid such that no additional building needs to be built; possibly it could be combined with the stratified storage in the first house.

This result is in line with the statement of the International Energy Agency (IEA) that areas with a line heat demand as low as 0,3MWh/m*a can be served economically [17].

In order to reach good efficiency, different charging scenarios have been tested. Systems with smaller pipe diameters and longer charging times reduce the heat stored in the pipes after charging, but the charging time increases. Nonetheless, overall losses are too high for the system to be efficient. Acceptable losses can only be reached with an additional tank to evacuate the hot water from the pipes in between charging cycles. For a system of this type, losses are smaller when pipes with larger diameters and shorter charging times are used, since shorter charging times reduce the time during which losses occur.

DHW consumption is hard to predict and model, as the highest possible consumption would result in over dimensioned systems. Individual behavior should be considered when optimizing the charging pattern of the area. An alternative could be to offer storages of two or three different volumes to meet the individual need of the different inhabitants in the area. Also, charging the storage to lower temperatures is an option for consumers with lower heat demands. During periods of vacancy, the temperature in the tank should be reduced until the return of the tenants. Balancing the heat demand for DHW is therefore an iterative process depending on the behavior of the tenant. The ability to adapt system parameters to the behavior of individual tenants can further reduce the energy demand of the area. Software is needed to allow for optimized and individually adaptable charging patterns.

Small grids with a low total heat demand will be more common in the future. It is therefore necessary to evaluate the possibilities of creating efficient solutions that are reliable and at the same time replicable. Modular subnets are one possibility to cover this demand. The model shows that it generally is possible to connect PH houses to DH with considerably low heat losses in the system.

During summer a total of 11,8kWh are stored in the stratified storage of which 8,4kWh can be used for DHW; the remaining 3,4kWh can only be used for SH (which is not necessary during summer). Due to the increased temperature of the system during winter, a total of 18,3kWh are stored in the tank of which 13,6kWh are available for DHW [Fig.1].

		Off heating season Summer	Heating season Winter
DHW (kWh)	min	-	-
	max	8.4	13.6
SH (kWh)	min	3.4	4.7
	max	11.8	18.3
Losses	%	4.0	2.3

Fig 1. Space Heating and Domestic Hot Water capacities

Subnets are not segments of the main DH grid, thus they do not cause the problem of a reduced line heat demand for the whole system which would make it less efficient.

CONCLUSIONS

The connection via subnets makes it possible to connect PH areas and other areas with low line heat demand to newly established and existing traditional DH grids.

Subnets can be used to substantially reduce the losses that account for up to 60% in traditional DH grids. Losses of around 3,5% may seem unrealistic, but a local heating network in the south of Germany, connected to a solar water heater and a pellet burner has similar losses (2,8%), [18] . Using decentralized heat storages allow for flexible charging times, which can be adapted to the needs of the DH company, e.g. charging during times of overcapacity in the grid. Improvements of energy efficiency and reducing losses decrease CO_2 emissions and environmental impact.

Planning and implementing subnets from scratch, specifically for each individual area, takes a lot of resources and is costly. Systems that can easily be replicated based on modules for fixed numbers of houses could cut costs and close the gap between traditional DH and the energy efficient buildings of the future.

As DHW consumption varies significantly, it is recommended to install meters and bill DHW accordingly. It has been shown that DHW consumption decreases when consumers have to account for their own consumption [13].

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SPACE HEATING IN DISTRICT HEATING-CONNECTED LOW-ENERGY BUILDINGS

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Keywords: space heating, district heating, low-energy buildings

ABSTRACT

In this paper, we have looked into experiences from low-energy buildings (LEB) regarding space heating (SH) and we have conducted simulations with the objective to compare different SH systems and their impact on the district heating (DH) network with regard to low return temperature and continuous load without substantial peaks.

At least in Sweden, it is from literature evident that there is yet not a clear direction towards radiators, underfloor heating or forced air heating in LEB. A simulation study, looking into the implications on the DH network from different SH systems in LEB, was carried out using the commercial software IDA-ICE.

Heat gains (from solar insolation and internal gains from humans and electrical appliances) make a much larger part of the total energy use in LEB and can during times cause significant over-heating and also cause larger variations in heat supply. Simulations have shown that a more realistic profile for heat gains, with an average vaule of 4.18 W/m^2 compared with a constant heat gain of 5 W/m^2 gives an increased heat demand and longer heating season (23 % and 1.5 months, respectively). A common situation in LEB is that the design indoor temperature of 20°C often is increased to 22°C, resulting in an increase of the heat demand with 75 % and of the heating season with 3.5 months.

Forced air heating (FAH) can give very low return temperature. However, FAH has problem maintaining a uniform indoor temperature and lack possibilities for room control. Radiator and underfloor heating systems can also give very low return temperatures in LEB. Underfloor heating is characterized, apart from radiators and FAH, by a more intermittent load profile, which is less favourable for the DH system.

INTRODUCTION

Heat demand is most certainly going to decrease in future buildings, encouraged by more strict building regulations regarding energy use and thanks to a general strive for energy efficient buildings. Traditionally, district heating (DH) has served building radiator space heating (SH) systems with relatively high temperatures, although temperature levels have been reduced over the years. In the various kinds of low-energy buildings (LEB) we have seen the past few years, the heat load is sometimes so low that the buildings require no conventional SH system at all, e.g., in the so-called passive houses.

However, with the cold climate in Sweden, and other countries with similar climate, there is still a need for space heat during times. In passive houses, this demand is commonly covered by additional heating of forced ventilation supply air flow.

In this paper, we have looked into experiences from existing LEB regarding SH and we have conducted a simulation study with the objective to compare different possibilities for SH and their impact on the DH network with regard to low return temperature and continuous load without substantial peaks.

The paper covers a part of a Swedish project called "Next generation DH", a project that mainly covers matters relating to network operation in a future situation with an increasing share of LEB. Due to the magnitude of the project, only the parts referring to SH are covered in this paper.

EXPERIENCES FROM EXISTING LOW-ENERGY BUILDINGS

The research area of LEB is substantial. Especially regarding passive houses there is a lot of literature, in Sweden and elsewhere, but perhaps mainly in Germany and Austria, who for a long time have been in the forefront of passive houses. Focus is mainly on building physics – how to build as tight and insulated buildings as possible with regard to aspects such as indoor comfort, moisture, economy etc. In this section, we aim to highlight the most relevant references on LEB that might be of interest for the DH business, i.e., aspects concerning energy use, thermal comfort and HVAC technology.

SP (Technical Research Institute of Sweden) (1) has conducted an evaluation of passive houses in Sweden. The experiences are in general positive, but a number of possible improvements are listed, that might be of interest from the perspective of the DH business. SH systems, no matter if radiators, underfloor heating or forced air heating (FAH), must be properly designed to provide thermal comfort even in dwellings with few occupants and low domestic electricity consumption. Measurements from the first passive house-area in Sweden (heated by FAH), Lindås, displayed a difference in temperature between first and second stories in each dwelling. The occupants sometimes reduce the air flow rate which causes reduced heat supply. They also request units that are easy to operate, e.g., with a “home” and “away” function mode. If the ventilation is reduced, however, heat supply must be guaranteed somehow. The residents in Lindås are generally satisfied. However, it is worth noting that 7 out of 10 houses in Lindås have additional heat sources and towel dryers (both electric) apart from the ventilation heat coil.

A previous report from SP (2) claims that, even if it is fully possible to build well-functioning LEB, there is still areas with lacking knowledge. These concern, among other things, thermal comfort during winter as well as during summertime and the users' influence on the energy performance of the building. Concerning demand-controlled ventilation operation, it is stated that even if it is necessary in order to minimize energy use, heat supply (as well as moisture and air contamination) must be considered if it is only supplied by air. A similar problem occurs for heat gains from humans and electric appliances: the indoor air temperature will decrease if the dwelling is not occupied. Especially, it is stated that the SH system must not be designed considering a mean value for heat gains but rather for a minimum value. This is especially important in case of a development towards more energy efficient appliances. Concerning downdraughts and “cold” radiation from windows, it is stated that more knowledge is required. The durability of the low heat demand in passive houses is also discussed. Even if it has turned out to be satisfactorily after 10 years in Lindås (1), there is reason to be observant what might happen in case of rebuilding, especially in case of DH-connection (the authors' remark).

Ventilation

From the perspective of primary energy efficiency, as well as from DH perspective, forced mechanical ventilations is preferable compared to a ventilation exhaust air heat pump, a solution that is sometimes used in Sweden. Pros and cons with the different ventilation techniques are dealt with by, e.g., Sikander and Ruud (3), except that the primary energy perspective is not discussed. In general, forced mechanical ventilation is considered to be the more attractive alternative. Some drawbacks are discussed. For example, air-to-air heat exchangers can have a thermal efficiency of more than 80 percent, which, however, to some part is offset by increased demand for fan power. Counter-flow heat exchangers have the drawback that they are sensitive to frost formation during cold weather and therefore need defrosting, a problem which increase in extent with more efficient heat exchange. Gustavsson and Joelsson (4) carried out a life cycle analysis of the primary energy use in residential buildings and found that the increased electricity use in forced mechanical ventilation systems can cause increased total primary energy use for a building in a DH system based on CHP.

Forced mechanical ventilation can provide a good indoor climate. Known problems relate to noise, and transfer of odour when rotating heat exchangers are used. Forced mechanical ventilation require slightly more maintenance, especially decentralized systems with individual flat units. Maintenance can be facilitated if units are placed in connection to stairwells. (3, 5)

Forced mechanical ventilation give possibilities for demand-controlled ventilation, meaning that the ventilation air flow rate is regulated based on parameters such as occupation of the premises, temperature, moisture and carbon dioxide concentration. Up until now, demand-controlled ventilation has mainly been used in bigger non-residential premises, but might be interesting for residential buildings with possibility to individually control ventilation. Previously, ventilation air flows below 0.35 L/s were not allowed in Sweden, but it is now possible to reduce the flow rate to 0.10 L/s when no one is at home (6). The purpose of reduced ventilation is obviously to save energy. As previously mentioned, it, however, might cause problem if, e.g., the residents go away for the winter and the dwelling is cooled down if FAH is being used. If the dwelling is a flat or row house or similar, the cooling will be slower at the expense of heat transfer from neighbouring flats.

Johansson et al (7) have studied the occupancy level of multi-residential buildings with the objective to estimate the potential for demand-control ventilation in residential buildings. The conclusion was that there is a potential for energy savings, but more research is required regarding the design of these systems and how proper levels of moist and thermal comfort is to be secured.

Space heating systems

Regarding SH systems, Sandberg (8), in a guide to energy efficient buildings, emphasize the need for rapid control, caused by the combination of small heat losses and large, but varying, heat gains from sun, humans and electric appliances. It is these variations that, to a much larger extent than the outdoor temperature, determine the indoor temperature. FAH systems are claimed to be the most fast-controlled. However, in order to limit heat losses, supply air heating should be situated in direct proximity to the flat, e.g., in the stairwell.

The first passive houses in Sweden used forced air heating for SH. This was possible thanks to low heat demand. What is attractive with this solution is the low installation cost and this is often mentioned as one of the benefits of passive houses – heat demand is so low, the ventilation system is enough to ensure proper thermal comfort. (9, 10) However, there is no demand or even recommendations to only use forced air supply for heating. Janson (10) as well as Sikander and Ruud (1) have shown that in Swedish climate it can be troublesome with only FAH. Although thermal comfort in general is good, it happens that property owners or tenants use additional (electrical) space heaters to increase thermal comfort. Gradually, several passive house projects have included waterborne heating, either by radiators or by underfloor heating.

In Denmark, there is scepticism regarding FAH with central supply temperature control because such a solution gives the same supply temperature to all rooms. This will lead to large differences in room temperature due to variations in solar insulation and internal heat gains. New building regulations (11) require individual room temperature control and disqualify such a system.

Radiator systems are a proven technology which also gives fast control but better possibilities for individual control (3). Energy efficient windows allows for a larger freedom regarding the placement of heat emitters.

Underfloor heating systems are sometimes claimed not to be suitable for LEB because they are slower and may increase heat losses via the floor to the ground. Besides, since the required heating power is very low it results in low surface temperature and users might be disappointed when they do not perceive the floor to be warm. Comfort floor heating, e.g., bathroom floor heating, is even more controversial (8, 12), but nevertheless used in some passive houses (13).

Sikander and Ruud (3) also bring up the drawback of low floor temperature. However, they also discuss the benefit – increased possibilities for self-control. As soon as the room air temperature exceeds the floor temperature (because of heat gains), heat transfer will seize (or actually reverse). More about this self-regulating mechanism can be found in, e.g., Karlsson (14). The potential to use the self-control in order to construct simple underfloor heating systems for LEB is further developed in Karlsson and Hagentoft (15), showing promising results.

A study from German Passivehausinstitut (16) claims that underfloorheating does not cause higher heat demand.

Finally, Sikander and Ruud (1, 3) emphasize the need among tenants to have a heat source they can control by themselves, see and touch and that is also simple and give instant feedback. Similar findings are reported in (10) and in (17).

At least in Sweden, there is yet not a clear direction towards radiators, underfloor heating or forced air heating in LEB. The DH business still has a possibility to influence the development towards a direction that is beneficial for the future of DH, regarding, e.g., temperature levels and heat load profiles.

Another topic that has caused some debate is whether LEB, in practice, actually has as low heat demand as was promised. In a doctoral thesis from 2011 from Lund University by Bagge (18), this subject was investigated. The author refers to a large number of Swedish and international studies showing that measured energy use turns out 50-100 % higher than predicted values. Important reasons for this are the influence of other parameters than outdoor temperature, such as climate-related factors (solar insulation and wind) and user-related factors (occupancy and electricity use). The DH industry in Sweden has also, among others, highlighted this matter (19).

SIMULATIONS

A simulation study, looking into the implications on the DH network from different SH systems in LEB, was carried out using the commercial software IDA-ICE. A single-family house of 159 m^2 and an energy performance of 36 kWh/m^2,a (according to the requirements for class 2015 in Denmark) (11) was simulated using radiators, underfloor heating and FAH, respectively. The ventilation system is of the forced mechanical type with an air flow of 60 L/s and heat recovery with an efficiency of 76 %. All heating systems are designed according to (20) with a design temperature of -12°C without taking heat gains into consideration.

Heat gains (from solar insolation and internal gains from humans and electrical appliances) make a much larger part of the total energy use in LEB and can during times cause significant over-heating and also cause larger variations in heat supply. A constant value of 5 W/m^2 is normally assumed for heat gains (11). For LEB, the level will probably be lowered in the future. The consequence of an overestimation of the heat gains is that the actual energy use becomes higher. Another reason to higher actual energy use than expected in Denmark, is that heat demand is calculated for an indoor temperature of 20°C, while new studies show that residents in general prefer 22°C (21).

The reason why a constant value for heat gains is used is that consideration of varying heat gains is more demanding in energy balance calculations and also because it has not been considered important enough. In order to study to influence of varying heat gains, we defined a schedule based on reasonable use of the dwelling and compared this with use of a constant heat gain. The mean value of the varying heat gain is 4.18 W/m^2.

From a DH perspective, it is beneficial if the SH system does not require a higher temperature than the domestic hot water system, which then becomes the lower design limit for the DH network supply temperature at a level around 55°C. A benefit with the lower LEB heat demand is that the SH system does not require such a high temperature level as traditionally. In this study, a constant supply temperature of 55°C in the radiator system has been assumed. The motive for using a constant supply temperature, instead of an outdoor-compensated, is that it is a method that gives possibilities for a return temperature as low as possible. It is also a method that has been tried out by Mälarenergi in Västerås, Sweden, in a new low-energy building area with promising results. Besides, because of the increased share of heat gains in LEB (in relation to the total heat demand), it is not sufficient with a feed-forward control of heat supply, but feedback from the indoor temperature is necessary.

Traditionally, SH systems have been substantially over-dimensioned. Therefore, it is relevant to question whether this will be the case in future LEB's. As the experiences from Denmark show, SH dimensioning for 20°C can still heat up a LEB to temperatures around 22°C, indicating a significant oversizing. All deviations will cause larger impact in LEB as they use less energy for heating. The increase from 20°C to 22°C means a relatively higher increase than in a conventional building. Simulations showed that a reduction of the heat gains, from constant value 5 W/m^2 to 4.18 W/m^2, but with a varying characteristic throughout the day, resulted in a 23 % higher energy use and a 1.5 month longer heating season. An increase from 20°C to 22°C increases the heat demand with 75 % and the heating season with 3.5 months.

In the following sections (Radiators, Underfloor heating and FAH) the simulation cases displayed in Table 1 are used.

Table 1 The simulation cases.

Case	**Heat gain (W/m2)**	**Type**
01 – design case	0	-
A1	5	constant
B1	4.18	constant
C1	4.18	varying

For the radiator system, a case D1 has also been used, assuming an increased indoor temperature, from 20 to 22°C.

Radiators

Radiators in LEB can give a very low return temperature, especially a low-flow system. Table 2 displays the results of the simulations.

Table 2 Results from simulations of radiator systems.

Case	01	A1	B1	C1	D1**
Heat gain [W/m^2]	0	5	4.18	4.18	4.18
Type	-	con-stant	con-stant	vary-ing	var-ying
Heat demand [kWh/a]	-	3 274	3 890	4 029	5 744
Difference [%]	-	0	19	23	75
Heating season [months]	-	6	7	7.5	9.5
Weighted primary return [°C]	25/29*	20.4	20.5	21.2	24.0

* Tsetpoint 20°C/22°C

** Case D - Tsetpoint 22°C

A few words on the radiator flow rate in LEB are motivated because they become very small. The Swedish company MMA produces radiator valves suitable for low-flow radiator circuits. The lowest controllable flow, according to laboratory test MMA performed within our project, is 0.02 L/min (Samuelsson, 2012). Figure 1 displays flows through two radiators, in living room (stue) and technical room (bryg), in the LEB during winter, hour 0-300 for three different cases (A, B, C). The flow in the living room is above 0.02 L/min, which is controllable, while the flow in the technical room is lower than 0.02 L/min the whole time. This also applies for most radiators in the house, why it is reasonable to question how this affects the radiator valves' operation. It is most likely to assume that they are working on/off the whole time, with a few minutes interval (Samuelsson, 2012). Due to the sensitivity in LEB for varying heat gains, it is motivated to look further into this and find out whether it might be a problem.

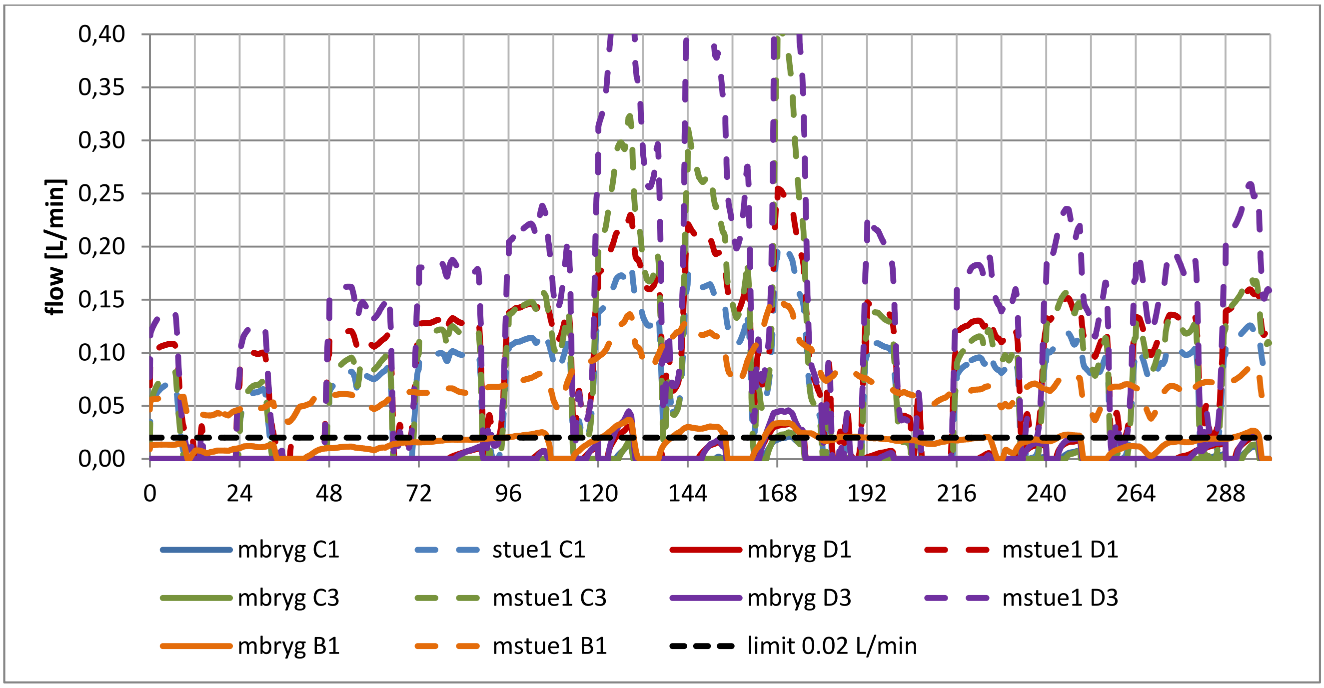

Figure 1 Variable water flows in different radiators.

Table 3 displays the maximum heat rate from radiators and the heat coil in the ventilation unit. As one can see, for 5 W/m^{2}heat gain, the maximum registered values from the radiators is 73 % of the design value. For case D1 (with temperature 22°C), the value is very close to the design value. A coincidence of various design parameters is the cause that the numbers match almost exactly, but the point here is that oversizing and consideration of heat gains result in possibility to heat up the room up to 22°C.

Table 3 Maximum heat rates in the SH system.

	P_{max} [W]		Degree of oversizing
Case	**Radiators**	**Ventilation heat coil**	**%**
01	2 967	607	0
A1	2 154	1 247	27
B1	2 298	1 251	23
C1	2 613	1 258	12
D1	2 972	1 117	0

In Table 4, two different supply temperatures in the air handling unit and two different heat recovery efficiencies for simulation case B1 are compared. The table reports consideration of the air supply temperature. An increase of the heat exchanger efficiency, from 76 % to 85 %, only reduces heat demand by 1 %. This is due to longer operational times with bypass. For 22°C, however, the decrease is 16 %.

Table 4 Influence of two different supply temperatures in the air handling unit and two different heat recovery efficiencies.

	Supply temperature 16°C		**Supply temperature 18°C**	
Efficiency heat recovery [%]	76	85	76	85
Heat demand [kWh/a]	3 276	3 246	2 918	2 511
%	100	99	89	77

Underfloor heating

A traditional underfloorheating system was simulated. Each room has an individual circuit with on/off control based on feedback from temperature sensors in the rooms. The supply temperature is controlled based on outdoor temperature. The system is designed to give 3°C temperature drop and a relatively high flow in order to ensure uniform distribution of heat. The simulation results are displayed in Table 5. Actually, the underfloor heating system gives higher return temperature than the other two tested systems, but still on a very low level. Cases A1 and D1 were omitted due to time constraints.

Table 5 Results for underfloor heating.

Case	01	B1	C1
Heat gain [W/m^2]	0	4.18	4.18
Type	-	constant	varying
Heat demand [kWh/a]	-	4 198	4 160
Difference [%]	-	28	27
Heating season [months]	-	7.2	7.9
Weighted primary return [°C]	26.2	22.9	23.3

Heat use becomes 8 and 3 % higher, respectively, than for corresponding cases with radiators. Underfloor heating is characterized, apart from radiators and FAH, by an intermittent load profile, which is discussed below.

Forced air heating

At first, the IDA-ICE built in air handling unit model, called Ashrae advanced model, was used. A drawback with this model is that it assumes turbulent flows, but for part-load operation, both water and air flows often become laminar which substantially decrease heat transfer. Therefore, an iterative model was developed in Excel, using manufacturer data (Veab.com) in order to calculate heat transfer and in turn, return temperature. The calculation, however, demands a lot of computer resources why only the first 1 100 hours of the year were simulated, and then only for constant heat gains. In total, the original model gives a primary return temperature of 19°C while the modified one results in 25.8°C. Because FAH cannot be controlled individually in each room, the simulations show highly varying temperatures in different rooms. Varying heat gains give even larger variations between rooms, and the model has problem with simulation of water borne heating coil and thus the case C was modelled with electric heating coil. The results are displayed in Table 6.

Table 6 Simulation results for FAH. Cases A1 and D1 are omitted.

Case	01	B1	C1
Heat gain [W/m^2]	0	4.18	4.18
Type	-	constant	varying
Heat demand [kWh/a]	-	4 446	4 670
Difference [%]	-	36	43
Heating season [months]	-	6.9	7.3
Weighted primary return [°C]	53.1	18.2	-

For the design case (01), the FAH system achieves a temperature in all rooms of 20±0.25°C. The heat coil operates at 9/49°C on the air side and at 55/53.1°C on the water side. When heat gains are introduced, the maximum supply temperature is reduced to 41.5°C. In average, the supply temperature is 30°C and the weighed primary return temperature is 18.2°C. Heat demand for FAH is 14 and 16 % higher than the corresponding cases with radiators, respectively. This is due to a higher ventilation flow rate (90 instead of 60 L/s) in order to supply enough heat based on the design case, 01.

The lowest room temperatures appear in rooms facing north during daytime, with 18.75°C as lowest value, see Figure 2. During this day, the insolation peaks at 600 W in the southern rooms which increases the room temperature over 22°C. Because the air handling unit's heat supply is controlled based on the average return temperature from all rooms, the supply temperature is reduced from 33°C to 20°C. Similar course of events appears often during simulations.

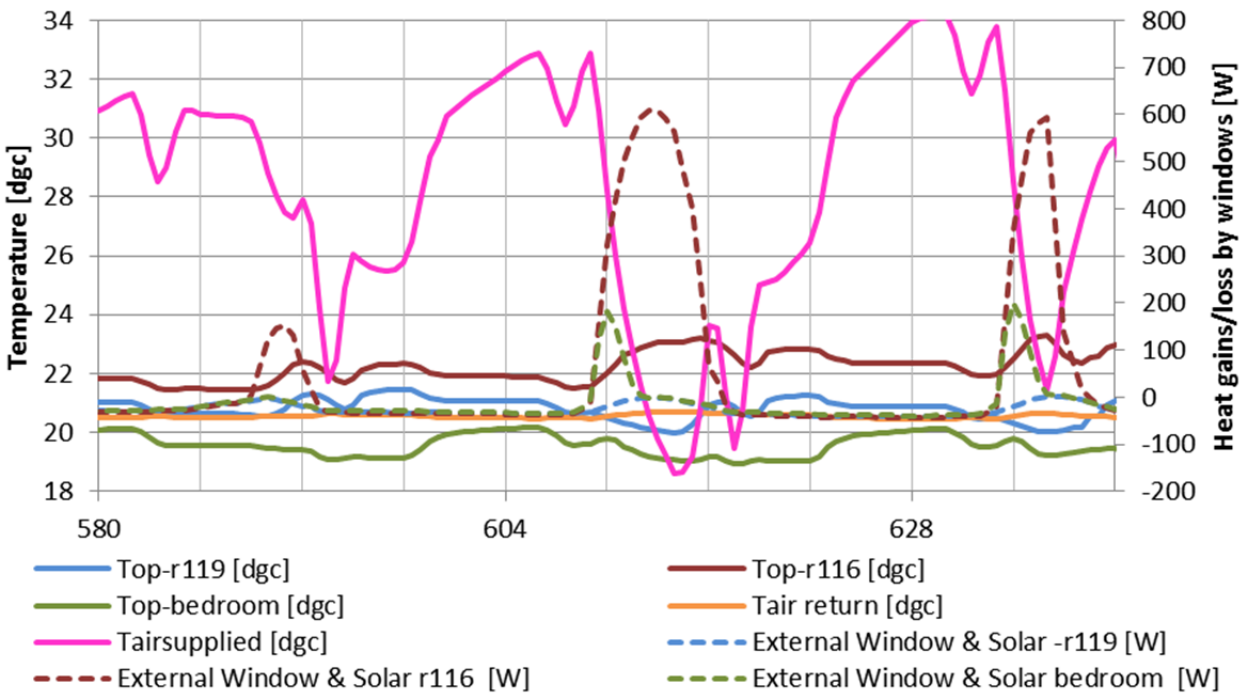

Figure 2 Temperatures during heavy insolation.

The situation is even worse when varying heat gains are assumed instead of constant. Another control method than the total return temperature from all room would fix the problem with cold rooms but the problem with lacking possibilities for individual room control remains

COMPARISON OF DH LOAD PROFILE

From a DH perspective, it is interesting to compare primary water flow needed to supply investigated SH systems and the return temperature from the systems for the critical period of the year, i.e. lowest outdoor temperature. This is displayed in Figure 3. The supply temperature of DH water is fixed to 55°C and the (rather low) flows needed for the ventilation heat coil with radiator and underfloor heating is ignored. While the radiator and FAH systems are operated more continuously, the underfloor heating system is operated in on/off mode, which results in more DH flow peaks. The return water temperature is quite similar for all cases, except the higher temperature and flow for FAH caused by very small temperature drop on water side of the heat coil in case of very high heat load. The radiator system has the lowest maximal flow 1.2 kg/s, followed by underfloor heating with 2 kg/s and FAH with 2.8 kg/s.

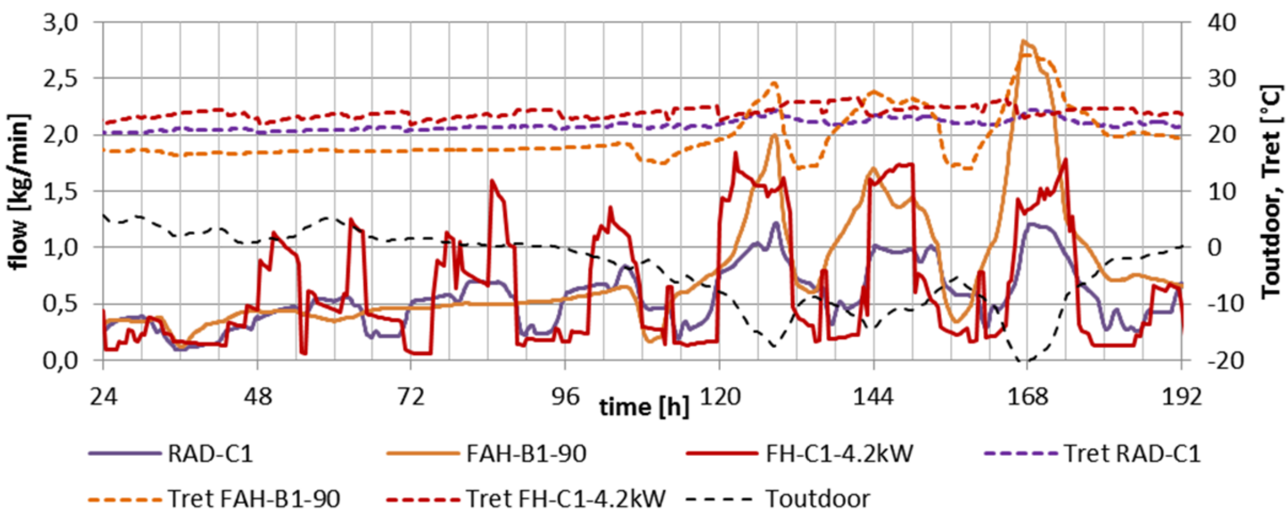

Figure 3 Primary water flow needed for the different SH systems at Tsupply=55°C

CONCLUDING REMARKS

A more realistic profile for heat gains, with an average value of 4.18 W/m^2 compared with a constant heat gain of 5 W/m^2 gives an increased heat demand and longer heating season (23 % and 1.5 months, respectively).

Influence of on/off control on thermal comfort and heat demand in LEB should be investigated more closely.

FAH can give very low return temperature. However, FAH has problem maintaining a uniform indoor temperature and lack possibilities for room control. Radiator and underfloor heating systems can also give very low return temperatures in LEB. Underfloor heating is characterized by a more intermittent load profile, which is less favourable for the DH system.

ACKNOWLEDGEMENT

This study is part of the project “Next generation DH”, financed by the Swedish DH association.

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THE EFFECTS OF LOWERING THE NETWORK TEMPERATURES IN EXISTING NETWORKS

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Keywords: Pressure, District heating, Low temperature, Heat loss

ABSTRACT

The trend in district heating (DH) is in the direction towards low temperature district heating (LTDH). There are numerous benefits of lowering the network temperatures, for example reduced heat losses, increased options of using alternative low grade heat sources and possible extra electricity production at the combined heat and power plants (CHP). However there are issues concerning lowering the temperatures in the system, for example existing houses may not have efficient heating (old radiator system rather than floor heating) systems to extract sufficient heat from LTDH and as the supply temperatures are decreased the more volumetric flow is needed to supply the same amount of heat to the consumers, which will result in increased pressure loss in the network. On the other hand new houses and buildings do not require the same amount of heat compared to old building. This paper will shed light on economic related issues concerning the increased volumetric flow needed in existing system if they are changed towards LTDH networks.

INTRODUCTION

In 1998 IEA issued a district heating and cooling report about district heating research projects, see [1], it stated that it would not be beneficiary to lower the supply temperatures below 90°C given increased network cost and cost at the consumer level. However the trend for the last decade has been more and more focusing on lowering the supply temperature in the DH systems. This trend has been driven by requirements of better energy use, environmental factors and by the fact that the energy prices have been and will increase in the near future. This interest has let too ambitious governmental goals, changed and more restrict regulations when it comes to energy usage and research in many different areas with the objective to realize the idea of low temperature DH systems.

In March 2007 the European Union (EU) set serious demanding climate and energy targets to be achieved in 2020, the policy is called climate and energy package 20-20-20. The goals of the climate and energy package are: 20% share of renewable energy sources of total energy consumption, 20% decrease of primary energy usage and 20% reduction of greenhouse gases. Some of the EU member states have set them self even higher goals, for example Denmark which aims at 30% greenhouse gas reduction by 2020 and 100% renewable energy supply in 2050.

To achieve these goals building regulations have been made stricter and high goals have been set regarding energy losses from buildings in the near future.

Another important part of achieving these goals could be to change existing DH networks from high temperature systems to low temperature systems and numerous papers have been written about the benefits and cost of lowering the supply temperatures. In [2] the quality of the energy is discussed in relation to exergy and cost of utilizing the low grade energy in buildings. In [3] the importance of evaluating the energy source in terms of exergy is investigated. However when low grade energy sources are used it can become more difficult to transfer the energy from its source to its intended usage place, this is where the benefits of DH come apparent. One of the key benefits of DH is its indifference of the energy source, however most of the DH networks today are dimensioned for high temperatures supply, which may not be achieved with low grade energy sources. It will therefore be needed to change those networks to low temperature networks.

One of the concerns in the transition from high temperature supply to low temperature supply networks is the foreseen increased flow rates that are needed to supply the same amount of heat energy from DH utility to the consumers. Increasing the flow rates in the network will increase the pressure loss in the network which will need to be compensated for. Traditionally the network pressure is maintained at the DH utility site. There are however limitations on the pressure level in the network and those limitations are partly due to the consumer installations, which have an operating pressure limitations. To solve this problem and hold up adequate pressure, booster pumps could be utilized in the network at different locations to increase the pressure to acceptable levels.

PRESSURE LOSS IN DH NETWORKS

To illustrate the system a case example is analyzed. The case consist a small network of 116 family houses with a living area of 159 m^2 each. The network could look like the network in Figure 1, see [4]. The white dots represent a branch loop connecting houses to the network. The consumers are directly connected to the network. In this study a network length of 3.588 meters is used and it is assumed that branch a) has equal network lengths as branches b) and c) combined.

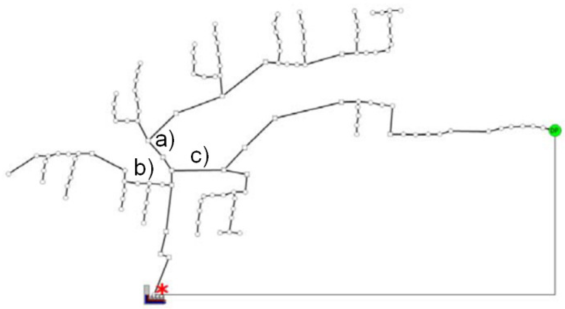

Figure 1. Example of a small DH network.

The network is dimensioned so that the critical consumer has at least 0.5 bar of pressure difference, this is even more than enough pressure difference for modern consumer installations.

The pressure loss is dependent on the pipes and components friction factors and the flow rate in second power, which can be expressed by the formula:

$$\Delta H = kQ^2 \tag{1}$$

In all DH operations it is necessary to maintain sufficient differential pressure for the consumer installations to operate. If an existing network is changed by increasing the flow rate the pressure loss will increase as mentioned above a measures will be needed to be taken to insure adequate differential pressure in the network.

Figure 2 shows pressure loss for traditional DH system (red and blue lines). The black lines are example of pressure losses if the flow rates are increased. From the black lines it becomes apparent that the situation may arise where additional pressure may be needed to operate the consumer installations, this could be solved by either increase the head at the heat plant or by adding distributed pumps in the network to increase the pressure in the network where needed. In case of distributed pumps the pressure along the system may become like shown by the black lines. If the pressure in the network becomes too high it is necessary to either have indirect connected substation and/or to include safety equipment such as pressure reducers or pressure relief valves that will open if the pressure becomes too high.

CHANGE FROM HIGH TO LOW NETWORK TEMPERATURES

The assumptions are:

- The network is designed for peak load performance.
- It is assumed that the houses have efficient radiators or floor heating (30-35°C is sufficient for heating) and instantaneous DHW preparation (55°C is sufficient for instantaneous DHW preparation).
- The ambient (soil?) temperature is 8°C when calculating heat losses.
- Existing DH network pipes are used.

Flow rate in the network

Figure 3 shows the heat demand for different kind of buildings in Sweden, for further information see [5]. Additionally it shows the design loads for the pumps under different load periods.

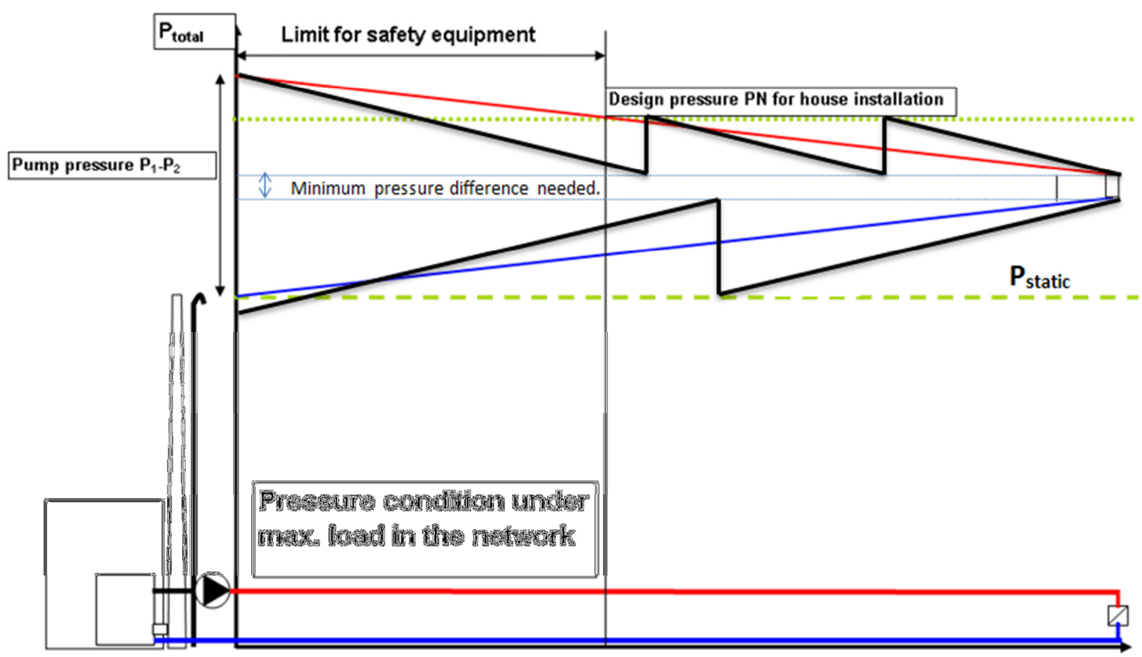

Figure 2. Pressure loss along a district heating network.

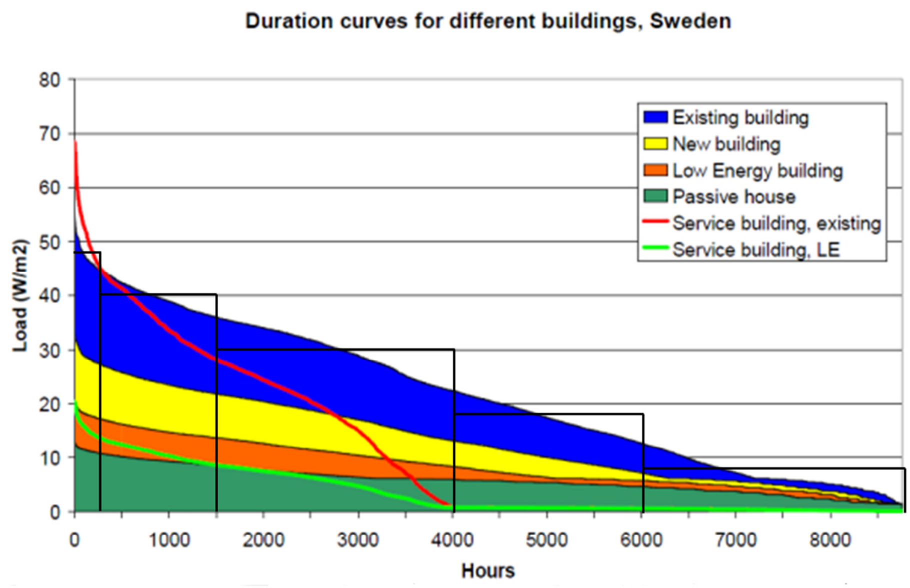

Figure 3. Duration curves for the heat load (space heating and DHW) for different kind of buildings, see [5].

From Figure 3 we can see that the maximum heat demand for an existing 159 m^2 building is approximately 8.6 kW. The necessary flow values to supply the demanded heat can be seen in Table 1 for two different network supply temperatures, 80℃ and 55℃ respectively. A ΔT of 40℃ and 30℃ have been used in the two cases respectively.

Table 1. Flow rate for each house during peak heating demand.

Peak heat demand	Energy need	80℃ supply	55℃ supply
Standard house	8.6 kW	0.051 l/s	0.069 l/s

Table 2**Error! Reference source not found.** shows the sum of flow rates in the system for all the 116 houses and the flow increase that is needed to supply the consumer their required heat if the network design temperatures are lowered.

Table 2. Net system flow rates.

Peak system flow rates	80℃ supply	55℃ supply	Flow increase
All 116 houses	6.00 l/s	8.00 l/s	33%

Typically DH networks are built with over capacity, however for simplicity it is assumed in this study that the system is perfectly dimensioned.

Heat loss in the network

Simple calculations for the average pipe temperature give the following heat loss reduction when going from high temperature system to low temperature system.

Table 3. Simple calculations for reduction of heat loss in the distribution system.

Network supply	T_{supply}	T_{return}	$T_{amb.}$	$T_{avg. pipe}$
Traditional 80℃	80	40	8	52
Low temperature 55℃	55	25	8	32
		Heat loss reduction	38%	

As can be seen in Table 3 the change from high temperature 80/40℃ to low temperature 55/25℃ DH network will reduce the heat loss in the network by 38%. At the same time the flow rates needs to be increased by 33% to supply the same amount of heat energy to the consumers.

PRESSURE LOSS IN THE NETWORK

The pressure loss through the main pipes in a parallel network is only related to the pressure loss in the main pipes (flow rate, pipe size, pipe roughness, pipe length, pipe elbows and turns and any components: valves, regulators and filters). The home installations will draw the flow from the main according to the available differential pressure between the inlet and outlet of the home installations, from Eq. (1) it can be seen that the flow is proportional to the square root of the differential pressure. According to this it becomes important to control the available differential pressure of the home installation to maintain good hydraulic balance in the system. If the system is not in hydraulic balance the far end consumers will not have sufficient flow to get the heat they need from the network. If the network pressure is constant a flow restrictors or limiters can be used to maintain hydraulic balance, if the network pressure is varying a differential pressure controller will be used to maintain constant differential pressure across the home installation and thus give high valve authority and consequently flow control, see [7] for more information on hydraulic balance in DH systems.

By using affinity laws we can predict the increased pressure loss by a factor:

$$\frac{H_1}{H_2} = \left(\frac{Q_1}{Q_2}\right)^2 = \left(\frac{1}{1.33}\right)^2 = \frac{1}{1.77} \qquad (2)$$

Similarly using affinity laws we can predict the increased electricity consumption need by a factor:

$$\frac{P_1}{P_2} = \left(\frac{Q_1}{Q_2}\right)^3 = \left(\frac{1}{1.33}\right)^3 = \frac{1}{2.35} \qquad (3)$$

In Euro heat & Power guidelines general guidelines are given for system design, see [6]. In this paper the following design limitations are used:

1. Absolute pressure in the network must be greater than 0.5 bar everywhere in the network to insure adequate working conditions for the consumer installations.
2. Absolute pressure in the network may not exceed 10 bar anywhere in the network.

Pressure loss in pipes

District heating networks are typically designed to have average pressure loss of 150-200 Pa/m. In this study it is assumed that the original network with 80/40℃ temperatures was designed to have average pressure loss of 150 Pa/m. If the flow rate in the pipes is increased the pressure drop will increase by the flow rate increase in second power, see Eq. (2). Traditional networks are typically designed for flow speeds of 1 m/s for the smallest pipes and up to 4-5 m/s for the transmission lines and low temperature networks are typically designed to have double flow speeds compared to the traditional networks.

LOCATIONS OF PUMPS IN THE NETWORK

There are commonly two ways to supply head pressure in networks, synchronous operation and distributed differential pressure regulating:

Synchronous operation

With a synchronous operation a central pump or a master pump will regulate the network pressure with the help of one or more slave pumps. The slave pumps are operated synchronously with the master pump. This method is robust but it does not take into account load differences in different branches in the network.

Distributed differential pressure regulating

With a distributed regulating the network pressure is regulated with pumps in various locations in the network. The various pumps ensure that the requirements for the proper differential pressure in the network are met between the pump pressure side and the next pump suction side. This steering-ring approach takes better account for load variations between different parts of the network, but is less robust to commuting.

In this study a distributed differential pressure regulating is used, that is a main pump is used at the utility and pumping stations are put in the network at critical locations to boost up the pressure to acceptable level.

SAVINGS AND COSTS

In the cost example it is assumed that renovation is being done on the network and the choice is between keeping the current network temperatures, 80/40℃, or go towards low temperatures, 55/25℃.

Increased pumping cost

The cost of increasing the flow rates includes both investment costs and operation costs.

The investment costs include the pumps and related components and installation in the network. The investment cost difference between the 80/40℃ network pump and the 55/25℃ network pumps are estimated to be about 2,300 EUR. Additional cost will be the pump installation cost, in this case it is assumed that the pump is installed in a network service house that already are in the network. The installation cost is estimated to be twice the pump investment cost. The pumps used are dry runner pumps, which typically have lifetime over 20 years.

The operation cost of the pumps can be divided between maintenance cost and electricity consumption, of the operation costs the electricity cost is the dominating factor. The first law of thermodynamics states: Energy can be changed from one form to another but cannot be created nor destroyed. Therefore not all the electricity consumption is lost, the hydraulic losses in the system will result in heating up the water. For dry running pumps the only real energy loss is from the motor.

In this though it is important to note that electricity price is typically higher than thermal heat price. In this study it is assumed that the electricity price is 130 €/MWh and the thermal heat price is 46.7 €/MWh, that is at maximum 36% of the electricity cost can be regained through heating of the DH water, this will further depend on the efficiency of the pumps used.

To estimate the pumping costs it is convenient to estimate the needed pressure for the network with flow temperatures of 80/40℃ and use the affinity law in Eq. (2) to predict the pressure losses when the flow rates are changed. By assuming that the average pressure loss during peak demand is 150 Pa/m and given the network length from above the pressure loss in the 80/40℃ network is estimated to be 5.38 bar during peak demand. Using the affinity law the pressure loss in the low temperature network is estimated to be

9.52 bar during peak demand, which is higher than the 6 bars Euro heat & Power guidelines recommend. However, if an existing network is designed for 80℃ it will be possible to increase the temperature level during peak days allowing more heat to be transferred.

When calculating the operating cost of the pumps in the system it is important to note that networks typically only run for limited hours per year on maximum load, therefore the duration curves in Figure 3 where divided in 5 intervals a) peak, b) high, c) medium, d) low and e) minimum heat demand and the pump cost estimated over each interval. These intervals chosen can be seen in Figure 3. In the calculations it is assumed that the energy prices will increase by 5% per year.

Table 4 shows the cost of operating the pumps to achieve desired pressures and the real cost when the heating of the DH water is taken in account.

The maintenance cost for pumps is commonly estimated to be 8% of energy usage.

From the table it can be seen that by decreasing the network temperatures from 80℃ to 55℃ it will be necessary to increase the pressure head from 5.9 bars to 10 bars to be able to supply the same amount of energy to the consumers. As mentioned above the design limitations above say that the network pressure should not exceed more than 10 bar anywhere in the network and supplying the required head by one pump located at the heat plant will touch the design limitation. If however a distributed pumps are used it is possible to achieve the necessary pressure head well under design limitations and in addition it is more economical than if only one pump is used, or approx. 530 € less expensive per year. As for distributed pumps the operational cost will be 1,070 € per year higher than for one pump in a 80℃ network, or approx. 9.24 € per consumer. The benefits of lowering the network temperatures have to compensate for this cost increase.

Increased cost of consumer installation

For the proposed change in network temperatures the consumer installations need to operate under lower ΔT. In this study it is assumed that all consumer installations are separated from the primary network via heat exchanger to maintain highest network and operational safety for the district heating company and to maintain higher secondary network safety for the consumer.

The low ΔT puts more requirements on the heat exchanger than the traditional ΔT does. This requirement has let to new developments in heat exchanger material and flow handling, for example the MPHE pattern developed at Danfoss which needs less material and gives better heat transfer per pressure drop unit than traditional heat exchangers, see [8].

Savings and benefits

In the paper [8], where the same network was analyzed, it was estimated that the heat loss for the network to be 164.4 MWh/y, that is 7,671 €/y for given energy prices. As mentioned above the heat loss reduction is estimated to be about 38% for the 55/25℃ network temperature, this amounts to savings of approximately 2,915 €/y.

In the paper [8] it was estimated that low temperature DH allows for better primary fuel efficiency in the magnitude of 5-10% which results in similar savings for the annual heat production costs. This was estimated to be around 20 €/house/y.

Additional benefits of using low temperature DH are a) increased option of using alternative low grade energy sources such as solar panels and low temperature geothermal, b) possible extra electricity production at combined heat and power (CHP) plants, c) reduction of CO2 emissions and many others benefits not mentioned here.

None of those additional benefits are given a value in this study but they certainly add to the value of going towards low temperature DH networks.

Other aspects

Another option in an existing network is to operate part of the network or a branch of the network under low district heating conditions (LTDH) supplied from the return line, which normally is at 40-50℃ and then boost the temperature to say 55-60℃ by mean of a heat pump. Such a measure not only increases the capacity of the existing network, it also improves the conditions for the connected CHP plant.

Cost balance

Table 5 includes a cost balance example for the studied network. The main findings in the table is that the investment cost increase is 270 € per consumer and the savings minus operational costs are 35 € per

Table 4. The electricity consumption to provide sufficient pressure and the real operating costs.

	Pump motor	Average pump efficiency	Pressure needed [bar]	Electricity usage [MWh/y]	Electricity cost [€/y]	Energy transformed to heat [MWh/y]	Real cost [€/y]	Cost per consumer
80℃	One pump	0.49	5.9	13.0	1,690	6.4	1,390	12.0
55℃	One pump	0.54	10.0	28.5	3.710	15.3	2,990	25.8
55℃ distributed	Pump 1	0.50	5.3	15.0	1,950	7.5	1,600	
	Pump 2	0.45	4.8	8.0	1040	3.6	860	
	Total for distributed pumps:			**23.0**	**2,999**	**11.1**	**2,460**	**21.3**
						Cost difference from 80℃:	**1,070**	**9.24**

consumer. In terms of simple payback time it will only take 7.7 years to get the investment back.

Table 5. Simple payback time.

Cost increase	Amount
- Increased pump Investment and installation cost.	60 €/Cons
- Operation cost, energy and maintenance cost	10 €/Cons./year
- Increased inv. cost for heat exchangers at consumer installations	250 €/Cons.
Savings	Amount
- Heat loss savings (DH temp. reduced from 80/40℃ to 55/25℃)	25 €/Cons.
- Increased heat generation efficiency (DH temp. reduced from 80/40℃ to 55/25℃)	20 €/Cons.
Simple payback time:	**8.9** years

The payback time of 8.9 years should be seen in the light of the lifetime of the components which is more than 20 years. All additional benefits of low temperature district heating, for example reduced dependency on particular energy source, cheaper equipment, easy operation of consumers consumer installations and etc. will decrease the payback time of the investment.

CONCLUSION

Given the assumptions stated in this paper it can be considered economical to change existing DH networks from traditional high temperature networks towards low temperature networks with supply temperature of 55℃ and return temperature of 25℃. It is inevitable that as the flow rates are increased the pressure loss in the system will increase and in some cases the needed pressure will become too high for the consumer installations, the solution for this is to have pumps distributed along the network and boost the pressure up where needed. Additional benefits of having distributed pumps are that they have lower operating costs then one main pump.

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ASSESSMENT OF HEAT LOSS REDUCTION IN TWO PIPELINE DISTRICT HEATING SYSTEM WITH INDIVIDUAL HOUSEHOLD SUBSTATION

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Keywords: District heating, Secondary connection system, Heat loss reduction, Individual substation

ABSTRACT

In this study we evaluate the secondary connection district heating system in terms of reducing heat loss and optimizing supply temperature. Our previous study showed that employing the two pipeline system with individual household substation could provide better energy efficiency than the conventional four pipeline systems with central substation. As a preliminary study before demonstration, conducting more detailed modeling and analysis has been made. A multivariable model was constructed to simulate the energy usage and heat loss through the district heating system of apartment building complex (total 204 households) for 365 days. It included the factors associating with the experimental test results of individual substation such as heating, hot water usage and indoor/outdoor temperature of each season. The numerical simulation showed that heat usage prediction became more realistic, so that more heat loss reduction could be achievable.

INTRODUCTION

Integrated energy supply is a centralized system for distributing heat to cover the large number of customer. It can take the advantage of the economy of scale that comes with managing a large amount of heat. In South Korea, district heating result in rapidly growing along with the government support and particular residence type. When the town is newly planned, government drives to provide district heating system if the heat demand of residential and commercial sector is estimated above 5.8 MW. Also the residential sectors are usually designed to be the large apartment complex which it has high heat demand density. This is well suited for installing district heating network and heat loss is relatively smaller than other European countries.

Table 1 District heating market penetration in South Korea (Domestic and commercial sector) [1]

Year	2006	2007	2008	2009	2010
Market share [%]	11.0	11.5	12.2	13.0	13.5
Rate of Increase [%]	6.8	7.1	9.2	7.6	7.8

Table 2 Market share comparison with European countries [2]

Country	Market Share [%] at 2008
South Korea	12.2
Denmark	61
Sweden	55
Finland	49
Austria	18
Germany	13

As explained, government has worked as a driver of expanding district heating as for improving energy efficiency and reducing CO_2 emission. Since the economic developing several decades, development of satellite cities and industrial complex also promote district heating penetrating within a short period. So now the market share has been growing to cover 14% of total household as shown in Table 1 though it is still lower than the several European countries (Table 2).

Fig. 1 illustrates the present schematic of district heating network in South Korea. The district heating pipelines are comprised of two separate pipeline zones; primary and secondary connection. The primary connection is from power plant to apartment's central substation. The secondary connection covers the individual households. In between there are central substations exchange heat.

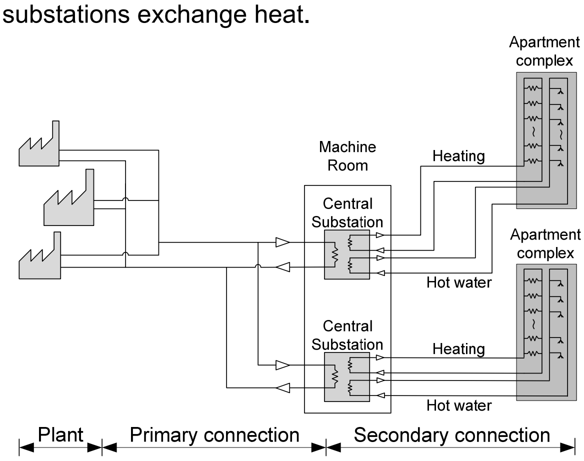


Fig. 1 The conventional district heating network in South Korea

The primary connection is not only well constructed and managed by the heat provider, but also maximum heat loss is regulated by government (Under 5% of heat loss). The secondary connection, however, accompanies substantial amount of heat loss due to the improper installation, inappropriate management and decayed pipelines since it is not under government regulation. For reducing heat loss and increasing overall efficiencies, heat loss in the secondary connection is necessary to be assessed by proper evaluating method. There have been several researches regarding reducing heat loss such as using smaller diameter pipeline [3], [4], supplying low temperature [5] and various pipe configurations [6], however, few researches were only made to investigate the effect of reducing the number of pipeline in terms of heat loss reduction [7], [8]. When district heating uses four pipes, the cumulative heat loss from hot water pipes exceeds than that of heating pipes even through one tenth of flow rate [7]. This is the reason why heating supply can be discontinued depending on the outdoor temperature, however, hot water supply is used to maintain the instantaneous use at all season.

This study focused on the assessment of heat loss reduction when the conventional secondary connection system is replaced with the two pipeline system with individual household substation (or Individual substation). The existing apartment complex was chosen for secondary connection network modeling coupled with various measurements throughout a year and experimental data. Numerical analysis provided the yearly overview of heat loss from the conventional four pipes secondary connection. In the following section, we introduce the new configurations for apartment complex and numerical model with experimental data. It predicts the heat loss reduction from the new configuration of secondary connection.

CASE DESCRIPTION

As a reference, an apartment complex, which is located near Daejeon, South Korea and serviced by district heating network, was chosen. It consists of 3 buildings and each building has 12 or 14 floors. Total number of household is 204. Current pipeline configuration is shown in Fig. 1. The primary connection is installed to the machine room of the apartment complex, The heat is delivered through the central substations for each building. At the secondary connection, four transverse pipelines (Two pipes for heating, two pipes for hot water) are distributed to each building through utility pipe conduit and then vertical risers and branched pipes are distributing heating and hot water to each household. Each household has 112 m^2 of residential area where heating is done by the radiant floor heating system. It circulates hot water (50 ^{o}C) through pipes beneath the living room and bath rooms. For an entire year, heat usage and indoor/outdoor temperatures had been monitored to make heat usage profile of apartment and individual households. It includes heating flow rate, hot water flow rate, multiple temperature of inside/outside of the buildings and monthly heating load of every household. Fig. 2 presents the measurement data of heating and hot water flow usage during a year. There was a large deviation in heating supply in each season, only a little amount of heating was supplied especially in summer. Hot water flow rate had maintained constant, however, because instantaneous demand of hot water was not much varied at all season. It can explain that considerable amount of heat loss could be taken place from the hot water pipes in conventional district heating system though the total amount of flow rate was not much.

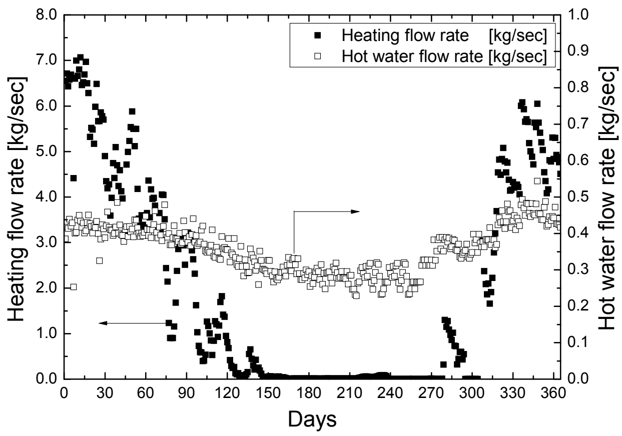


Fig. 2 Annual heating and hot water usage as flow rate

From our previous study [7], we compared the heat loss reduction according to the proposed configuration of secondary connection. Result showed that two pipes for secondary connection system can provide higher efficiencies than the four pipes one. Among the various two pipes configuration, this study limited to investigate the case of two pipes with individual substation as shown in Fig. 3. Pipeline is merged to supply heating and hot water by the two pipes, hot water is made by the individual substation. Comparing with the central substation type, individual substation uses city water to produce hot water on demand. It is commonly used in several European countries, however, there is no installation case in South Korea. It has advantages for reducing the number of pipes, heat loss reduction is followed by small heat transfer area.

There were limitations in the previous study due to a little information and operating parameters for the behavior of individual substation, it presumably resulted in overestimating the heat loss. In summer, flow rate of secondary connection was set as constant nevertheless it could be adjusted to have minimum when hot water demand is low.

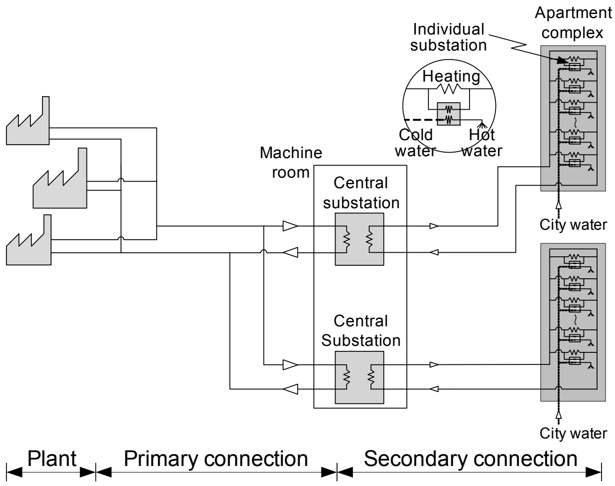


Fig. 3 Proposed district heating network schematic

NUMERICAL MODELING

Numerical model for secondary connection were constructed and solved with commercial thermo fluid dynamic software, Flowmaster V7 (Mentor Graphics Corporation). Fig. 4 represents the details of the pipe network in individual household.

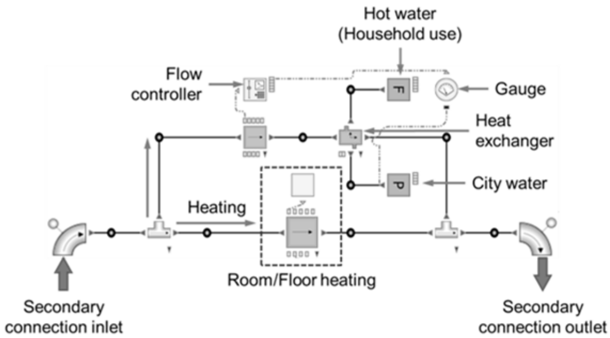


Fig. 4 Schematic of parallel type individual household pipe network and substation (Flowmaster modeling)

Individual substation is composed of heat exchanger and valve systems for supplying heat and hot water to the single house. Instead of using four pipes with central substation, two pipes (Supply and return of secondary connection) are enough to provide for heating and hot water. Heating directly brings the secondary connection flow to the radiant floor heating system. Room controller manages secondary connection flow rate to maintain the supplying temperature within the set points. For providing hot water, city water is heated on demand. Heat is transferred from the secondary connection flow to city water by internal heat exchanger. Substation has two types either serial or parallel connections depending on way to use the secondary connection flow. Serial connection uses the secondary connection flow that produces hot water and then making use of heating. Parallel connection is the most common, it is dividing incoming secondary connection flow into the heating and hot water side. There are pros and cons of each substation type. Serial type has more efficient use of secondary flow because of cascading use of heat for making hot water before supplying heating. Flow control, on the other hand, is more complicated by using active, electronics control. Parallel connection has rather simple control, however, dividing method can cause the shortage of heating supply if hot water demand is a lot. In this study, we limit the case of using parallel connection of household substation. Some types of individual substation can allow small amount of secondary connection flow to make heat exchanger stay warm while there is no hot water demand. When hot water is requested, valve opens secondary connection flow and city water to provide instant hot water. In the case that flow rate of hot water varies, flow rate of secondary connection is also proportionally changed for the hot water temperature to be maintained near the preset temperature.

Fig. 5 presents the proposed model of the entire secondary connection of apartment complex. There are 204 household in 3 buildings. There is one central substation that covers the entire apartment complex.

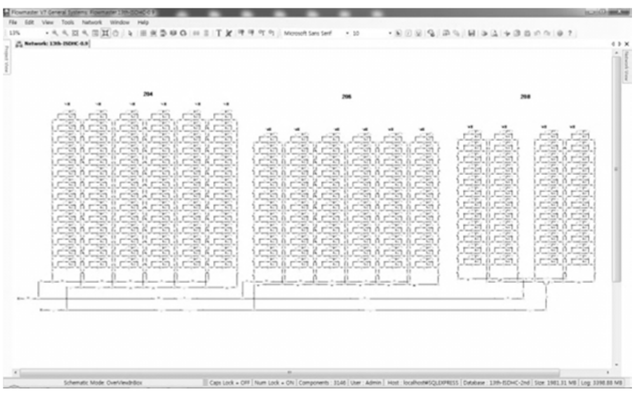


Fig. 5 Proposed secondary connection with two pipes model of apartment complex using Flowmaster

Boundary conditions were acquired from the reference apartment complex configuration and the annual operation data, such as heat and hot water usage, pipe dimension, insulation properties, annual temperatures and flow rate profiles. Since the operating data of individual substations was not available, the additional experiment was conducted to obtain the parameters for individual substation such as flow rate relationship and effectiveness of heat exchanger. Depending on the flow rate relationship, secondary connection can be changed when there is no hot water demand. It will be shown at the following section.

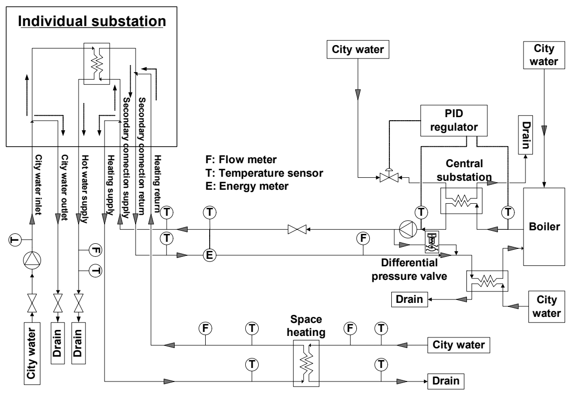
For the verification of numerical modeling for secondary connection, the numerical calculations were compared with the experiment data. Some sample months were chosen, loss/supply ratio was compared between measurement and numerical simulation. The four pipes secondary connection model was built and the loss/supply ratio was calculated. Experimental supply/loss profile was obtained from our existing research [8] and its boundary conditions were used as boundary conditions of numerical model. Comparing results were presented at Table 3. Data of two months (October and November 2010) were sampled for comparison because heating and hot water are used at those months. Difference of heat loss estimation between experimental and numerical was only 1.7 %. It shows that Numerical modeling can be used to estimate the arbitrary pipeline configurations for estimating the amount of supply and heat loss.

Table 3 Heat loss comparison between experimental and numerical simulation [Unit: MWh]

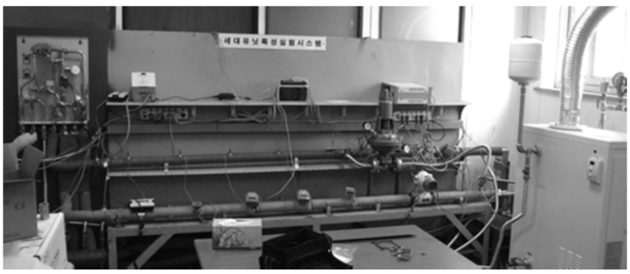
Heating and hot water supply at Oct. & Nov. 2010			
		Heating	Hot water
Measurement	Supply [MWh]	210.7	97.0
	Loss [MWh]	28.2	24.5
	Loss/Supply ratio [%]	17.1	
		Heating	Hot water
Numerical simulation	Supply [MWh]	195.1	110.2
	Loss [MWh]	23.2	23.9
	Loss/Supply ratio [%]	15.4	

EXPERIMENT

In the newly proposed two pipeline secondary connection, individual substation has an important role for the reduction of heat loss. For running the simulation and estimating accurate heat loss, understanding the behavior of individual substation is essential. Modeling requires two important parameters of individual substation that one is the proportional relationship of flow rate between hot water demand and secondary connection, the other is effectiveness of heat exchanger. Once hot water temperature is set, hot water demand make the flow rate of secondary connection varied with the usage of hot water in each household. In addition, effectiveness of heat exchanger is also necessary for estimating return temperature and heat loss. From these requirements, the experimental setup was established to evaluate the individual substation as shown in Fig. 6(a) and Fig. 6(b). The system was comprised of a boiler, heat exchangers, differential pressure regulator and an individual substation. There have been conducting the test of several types of individual substation for figuring out the behavior. In this paper, we chose the specific individual household substation (Cetetherm Micro, Alfa Laval AB). City water was heated to be provided in the primary connection side by gas boiler. Next to the boiler, there was a heat exchanger that worked as a central substation to heat up the secondary connection flow as 50°C. When there was heating load, secondary connection flow bypassed the individual substation to the other heat exchanger for consuming as heating load (as mentioned Space heating in Fig. 6(a)). In case that hot water demand made, city water and secondary connection flow supplied into the individual substation. Flow rates and temperatures were measured by data acquisition unit (midi Data Logger GL800, Graphtec Co.) for every second. Hot water temperature was set as 45 ± 0.8 °C, which was measured by 100 ohm Pt-RTD. Flow rate of secondary connection and hot water flow was ranged from 0 to 500 m^3/hr, it was measured by the electronic flow meter (KTM-800, Kometer Co.) respectively. These values were from the actual household usage of hot water. Flow rate was controlled by pump with current source inverter. In the secondary pipeline, there is differential pressure controller that regulates the secondary connection flow rate in order to maintain the differential pressure between inlet and outlet.



(a)



(b)

Fig. 6 Schematic of individual substation test setup
(a) System P&ID (b) Photographs of experimental setup

The test results of individual substation are shown in Fig. 7. When the average city water temperature was 23.3 °C and hot water temperature was 45 ± 0.8 °C, we found the flow rate relationship between secondary connection and hot water was almost one-to-one (1.05 times) at the current setting. In this figure, error bars represent standard error of the mean test data.

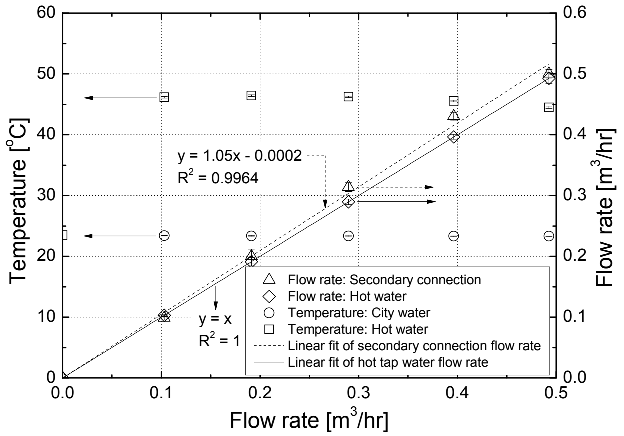


Fig. 7 Proportional flow rate relationship between secondary connection and hot water in individual substation

From the simple calculation, effectiveness of heat exchanger in the individual substation was also obtained. Following to the hot water flow, experimental results are presented at Fig. 8.

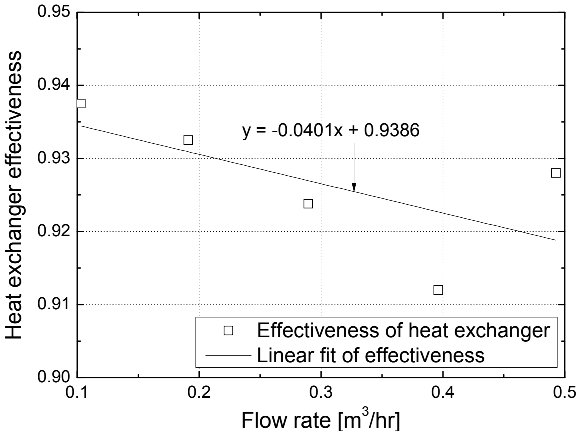


Fig. 8 Effectiveness of heat exchanger in individual substation

RESULT AND DISCUSSION

The newly proposed secondary connection configuration with various parameters was investigated by numerical simulation. Four pipes and two pipes system were compared in terms of heat loss reduction. In addition, two pipes system with different boundary conditions were considered regarding the flow control of individual substation. Comparison results are presented at Fig. 10 and Table 4.

There are three cases compared that conventional four pipes, two pipes with and without flow control. In case of the conventional secondary connection using four pipes, as shown in Fig. 1 and 2, heating pipe and hot water pipe are separated. Heating flow is discontinued in summer season due to no heating demand, whereas hot water pipeline should maintain constant flow rate for responding to instant usage. Two pipes with flow control also assumes different flow control scheme in summer due to hot water supply. If there is no heating demand, flow rate can also be cut only for hot water demand as four pipes system does. Moreover, the flow rate of secondary connection can be considerably reduced for solely warming up the heat exchanger of individual substation. When there is hot water demand, flow rate can be proportionally increased. Two pipes system with no flow control was referred from our previous study [7]. Due to the limitations in information of individual substation, assumptions were made that heat exchanger was always warmed up for responding the maximum amount of hot water demand even in summer. The flow rate of secondary connection resulted in setting as high covering the maximum usage of instant hot water demand all the time. Fig. 9 presents the total flow rate of secondary connection for each case. The two pipes without flow control had the largest flow rate because above-mentioned assumption.

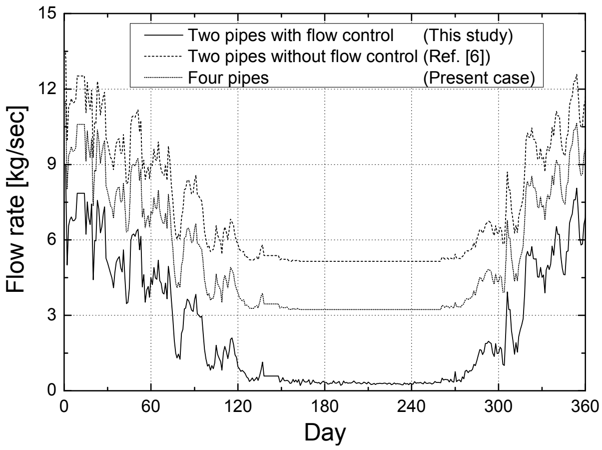


Fig. 9 The total flow rate of secondary connection for each case

Fig. 10 presents the heat supplied and heat loss of the various secondary connection systems. It shows that the case of two pipes with individual substation is superior to that of four pipes system in terms of heat loss reduction. It explains that heat loss mainly relies on the total surface area. In summer, however, two pipes system can be less effective than four pipes if not flow control is accompanied. When the flow rate of individual substation is properly controlled, heat loss is significantly reduced during all seasons, further more in summer. As explained, conventional four pipes system keep operating hot water pipeline in summer, so that the large amount of heat loss is inevitable. On the other hand, two pipes system needs only a small amount of flow which is enough for warming up the heat exchanger inside the individual substation so that it could have more heat loss reduction during summer.

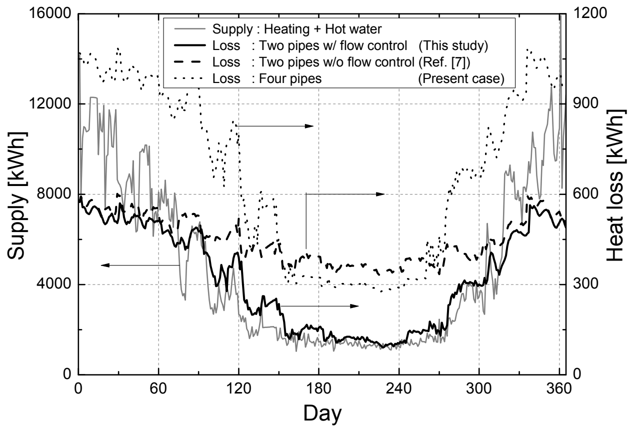


Fig. 10 The supply and loss of secondary connection comparison between four pipes, two pipes without flow control and two pipes with flow control

The effect of reducing the number of pipeline and controlling the flow rate in summer can be seen as annual heat loss at Table 4. Twenty six percent of heat loss can be cut only by reducing the number of pipes in secondary connection. Furthermore, forty six percent of heat loss can be achievable by using the two pipes with individual substation for secondary connection.

Table 4 Annual heating supply, loss and ratio of each scenario

Secondary connection method	Individual substation	Supply [MWh]	Loss [MWh]	Heat loss [%]
4 pipeline (Present case)	N/A	1736	243	14.0
2 pipeline (Ref. [6])	No flow control	1581	164	10.4
2 pipeline (This study)	Flow control	1537	117	7.6

For the purpose of reducing heat loss and achieving energy saving, low temperature district heating is current issues in many countries [10] – [12]. So we were investigating the relationship between secondary connection supply temperature and pipeline heat loss. Numerical simulations were made for two pipes system by changing the supply temperature. Hot water temperature was varied to have minimum heat loss while the secondary connection temperature was ranged from 40 to 70 °C. For example, hot water was calculated as 41 ± 1 °C when secondary connection temperature was 45 °C, hot water was supplied 48 ± 1 °C when secondary connection was 55 °C.

Results show that heat loss can be reduced down to 5.5 % when the supply temperature is 40 °C. By reducing supply temperature, it is obvious that one can accomplish more heat loss reduction with the lowered supplying temperature in secondary connection.

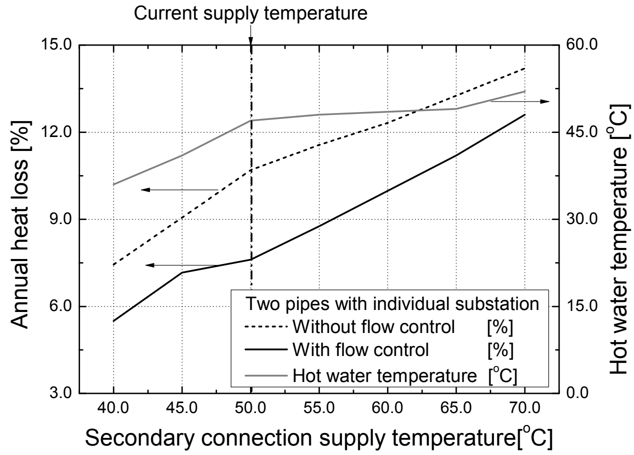


Fig. 11 Relationship between secondary connection supply temperature and annual heat loss

CONCLUSION

The primary aim of this paper is to assess the heat loss reduction when the two pipes with individual substation configuration is adopted at secondary connection. Based on an earlier paper [7], numerical model was improved by experimental supplement. Results showed that two pipes with individual substation could provide significant heat loss reduction comparing with four pipes if flow control and lowering supply temperature were properly followed. Further research are going to be made for demonstrating and assessing the effect of reducing the number of pipes and optimizing the usage of individual substations in terms of heat loss reduction.

ACKNOWLEDGEMENT

Support of this research was provided by KDHC (Korea District Heating Corporation). The content was solely the responsibility of the authors and does not necessarily represent the official views KDHC.

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ENERGY-EFFICIENT AND COST-EFFECTIVE USE OF DISTRICT HEATING BYPASS FOR IMPROVING THE THERMAL COMFORT IN BATHROOMS IN LOW-ENERGY BUILDINGS

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ABSTRACT

The bypass is cause of energy inefficiency in District Heating (DH) systems, particularly in low heat density building areas. This paper deals with: a) the modelling of bypass strategies in service pipes supplying low-energy buildings; b) the description of the use of the bypass flow in bathroom floor heating to increase the users' comfort; its techno-economic analysis, including the modelling of the in-house space heating system; the effect of the bypass to the DH network. Some conclusions were derived. First, the "continuous bypass" guarantees low heat losses in the service pipe, in the example considered 10-35% lower than in the traditional "intermittent bypass" case; secondly, it can be used to increase the thermal comfort outside the heating-season in bathrooms through floor heating, without causing overheating. It is important that the building design foresees the use of shading devices and the possibility of venting. Next, the "comfort bathroom" concept optimizes the operation of the whole network outside the heating season. In the case study the distribution heat losses are reduced by additional 13% during summer, in comparison to the "continuous bypass". Consequently, the utilization of the bypass in bathroom floor heating is a cost-effective solution, both for the DH utilities (reduced heat loss from the DH network and higher revenues), the end-users (improved thermal comfort) and the society (reduction of greenhouse gas emissions).

INTRODUCTION

The heat demand in buildings drops outside the heating season because the only need of heat the users have is in connection with Domestic Hot Water (DHW) use; this is particularly discontinuous and it is generally needed for less than 1 h/day in a typical single-family dwelling [1]. The lack of heat load would cause the undesirable cooling of the network to temperatures that would become insufficient to assure the prompt provision of heat when DHW preparation is required through instantaneous Heat Exchanger (HE) substations, if proper control strategies are not implemented [2]. That is the reason why bypass valves are installed at the in-house substations and/or at suitable locations in the network: their purpose is to direct ("bypass") a relatively low water flow from the supply media pipe to the return media pipe, so that the temperature at the DH substation inlet is maintained inside the required range of operation. The effect of the bypass is a certain flow achieved during low heat load periods, ensuring sufficient supply temperatures in the network. This operation, although necessary, is cause of heat loss and relatively higher return temperatures in the DH network, and are particular critical in case of low-energy demand building areas. The share of heat losses due to the bypass operation can exceed the heat demand of low-energy buildings outside the heating season, indeed; moreover, the duration of the non-heating season in low-energy buildings is longer than in traditional buildings; this accentuates the importance of an optimal bypass operation. In recent years, R&D and demonstration studies on low-temperature District Heating (DH) systems for energy-efficient buildings have demonstrated that the concept fits the vision of a sustainable building sector in Denmark, by integrating energy savings at the end-user' side, energy-efficient distribution networks, and low-grade sources and renewable energy at the supply side [1]-[8]. This paper deals with the modelling of bypass operation strategies in DH service pipes supplying low-energy buildings, the description of the use of the external bypass in bathroom Floor Heating (FH) to increase the users' thermal comfort, and its techno-economic analysis, including the modelling of the in-house Space Heating (SH) system and the effect of the bypass operation at the level of the DH distribution network. The questions which this paper tries to answer are:

- What is the most energy-efficient bypass strategy?
- Does the use of the bypass flow in FH of bathrooms cause overheating problems outside the heating season and/or not uniform temperature distribution on the floor surface?
- What is the effect of the bypass operation at network level?
- What are the socio-economic benefits involved?

TRANSIENT HEAT TRANSFER IN SERVICE PIPES

Bypass controls are generally operated by a thermostat and they are defined by the set-point temperature, $T_{bypass,set}$ and the amplitude of the "dead band", ΔT_{DB}, which also defines a "top temperature", $T_{bypass,top}= T_{bypass,set} + \Delta T_{DB}/2$, and a bottom temperature,

$T_{bypass,bottom}= T_{bypass,set} - \Delta T_{DB}/2$. The control ensures that the temperature is kept inside the range of operation set by the dead band.

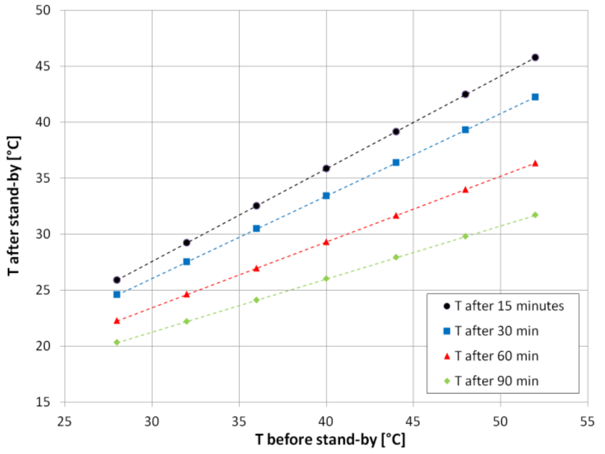


Figure 1: Examples of cooling-off curves, derived by 2D transient heat transfer simulations.

The investigations herein deal with the comparison of the energy performance of two theoretical bypass operations. The first case is the situation with an ideal thermostatic valve without dead band (ΔT_{DB}=0) where a continuous bypass flow is kept through the service pipe in order to maintain $T_{bypass,set}$ at the service pipe outlet (inlet to the in-house substation), where the bypass control is assumed to be located. The second one is the case of a perfectly "intermittent" bypass operation: the bypass during the intermittent operating mode is modelled as an ideal control that is acting like an on/off switch. When the temperature at the outlet of the service pipe reaches a specific value, $T_{bypass,top}$, the bypass flow instantaneously stops; the pipe is now in the "stand-by" mode, meaning that there is no flow in the media pipe and the water gradually cools down; after a certain time, the temperature at the service pipe outlet has decreased to the value of $T_{bypass,bottom}$, the bypass valve opens and the water flow develops again. A cycle of intermittent bypass consists of a period of water flow from the main distribution line to the service pipe outlet, the "bypass" period, and a period when there is no flow and the water inside the supply service pipe cools down, the so-called "stand-by" period; after that, another cycle starts, in a process that can be modelled as periodical. The Matlab® code modelling the DH service pipes, which had been developed in [6], [7], was applied to study the transient, coupled fluid-thermal phenomena during the bypass mode; the cooling of the water during the stand-by period was evaluated by regression curves derived by 2-D transient heat transfer simulations in Comsol Multyphysics®, see Figure 1. Given the geometry and the materials of the service pipe, a specific supply water temperature and certain boundary conditions, it is fact possible to calculate the transient temperature field in the pipe, see Figure 2. The model of the DH pipes in the heat transfer simulations were built according to the methodology explained in [8].

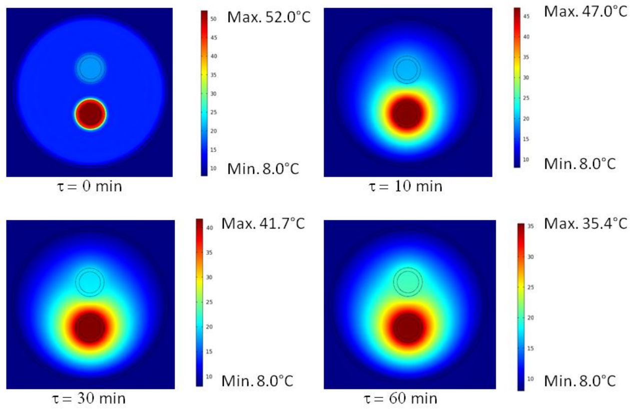


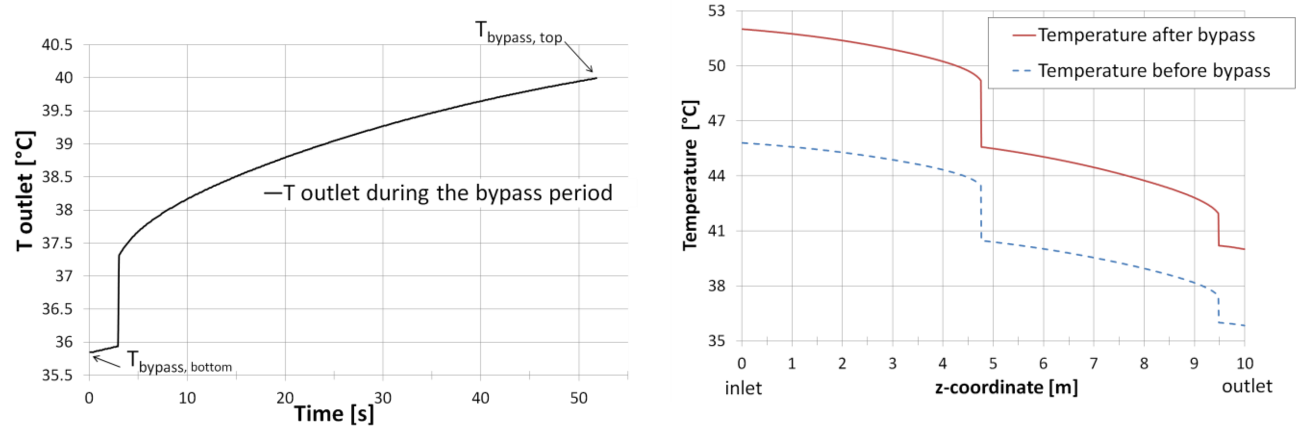
Figure 2: Cooling of the supply media pipe of the service pipe during the stand-by period. At τ=0: T_{soil}= 8°C, T_{PUR}= 15°C, T_{return}= 20°C. Service pipe: Aluflex 20-20/110.

This approach was applied to the service pipe type Aluflex 20-20/110 from the manufacturing company Logstor®. It is a typical product for connection of single-family buildings equipped with a DH HE unit. The reference pipe was 10-meter long; $T_{bypass,top}$ was set to 40°C and $T_{bypass,bottom}$ was set equal to the temperature at the service pipe outlet after either a 15-, 30- or 60-minute long stand-by period, that corresponds to either 35.9°C, 33.4°C, or 29.3°C. For the intermittent bypass case, various water flows were applied, defining a zone of laminar flow and a zone of transient/turbulent flow (see Figure 3 and Figure 4).

Different bypass flows lead to different water temperature profiles along the media pipes and consequently the heat loss varies, being the boundary conditions the same. Figure 4 groups the results of the study, taking a six-month period, i.e. a realistic duration of the bypass operation during a year.

In case of intermittent bypass, it is possible to see how higher $T_{bypass,bottom}$, due to shorter stand-by periods for the same $T_{bypass,top}$, brings along higher energy use. This is caused by the higher average temperature of the heat carrier in the service pipe during the standby period. On the other end, the more frequent use of the bypass ensures the faster provision of DHW and thus improves the users' comfort and reduces the use of water, thanks to the reduction of the waiting time for DHW at suitable temperature. Therefore, the proper bypass temperature must be carefully chosen. Based on the results, it can be concluded that the flow regime (laminar/turbulent) has no significant influence on the heat loss during bypass operation. The horizontal dashed lines of Figure 4 show the average energy use in the intermittent bypass operation. The most important conclusion is that the continuous bypass operation saves heat equivalent to up one third (for the case $T_{bypass,\ bottom}$=35.9°C) of the heat use for the intermittent bypass. It might be interesting to combine the use of the continuous bypass concept with an additional heat extraction, e.g. with the use of the bypass water in FH in rooms where it is desirable to have warm floor temperatures even outside the normal heating season, as it can be the case of bathroom FH in buildings situated in Nordic climate regions. The possibility is described and investigated in the following paragraphs with the name of Comfort Bathroom (CB).

a) Reynolds number: Re = 2100



b) Reynolds number: Re = 13300

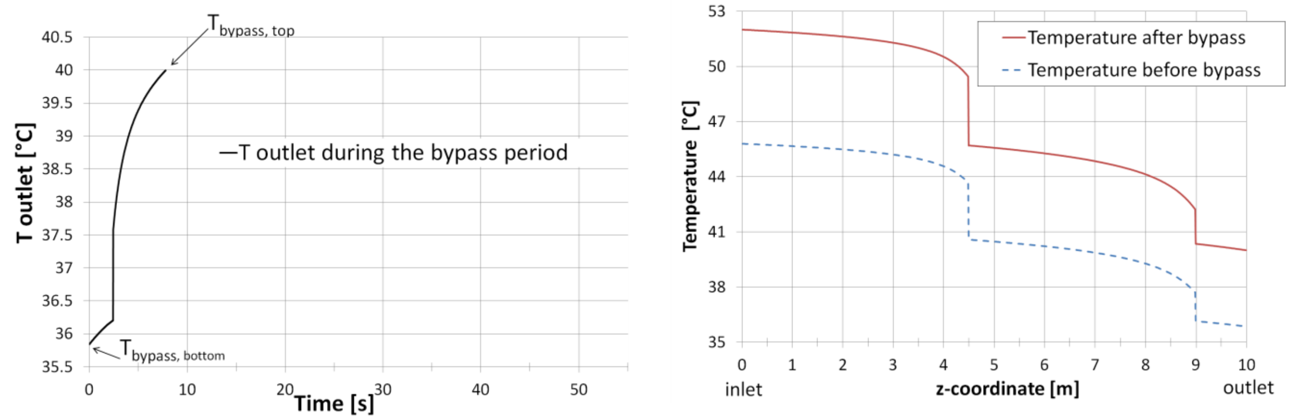


Figure 3: Intermittent bypass. Left: bypass period, outlet temperature vs. time. Right: stand-by period, heat carrier temperature vs. the longitudinal coordinate *z* of the pipe. Bypass flow: a) 0.96 kg/h; b) 6.0 kg/h.

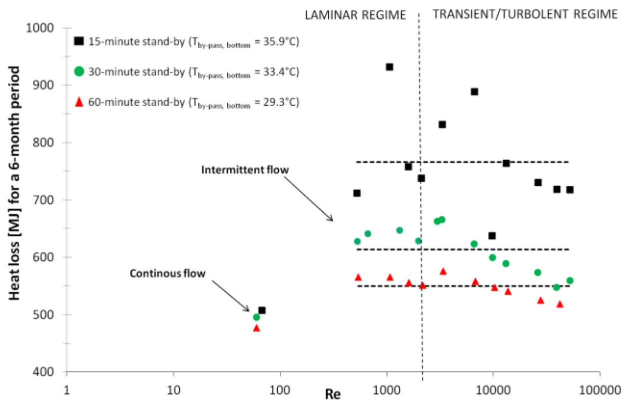


Figure 4: Heat loss from the service pipe for a 6-month operation of the bypass. Service pipe: Aluflex twin pipe 20-20/110, L = 10 m; $T_{bypass,\ top}$ = 40°C.

THE "COMFORT BATHROOM"

The CB concept was applied to a reference single family house fulfilling the requirements of the energy class 2015 in accordance with the Danish Building Regulation 2010 [9]. The house is described in **[10]** The house has two bathrooms, but we implemented the CB concept only in the larger one to make investigation valid also for houses with only one bathroom. The software used for the building energy simulations was IDA-ICE 4.2 [11] and the Danish Design Reference Year was applied. In the general cases (*a*, *c*), the FH in the bathroom was modelled with a constant flow of 1.8 kg/h or 4.7 kg/h and a constant supply temperature of 35°C.

Table 1: Description of the case studies.

Case	T_{supply} [1] [°C]	$T_{by\text{-}pass}$ [2] [°C]	Continous flow [kg/h]
a	50	35	1.77
c	40	35	4.68
d	50	50	4.68
e	40	50[3]-35	4.68

1 From the DH distribution network, at the supply service pipe inlet

2 At the supply service pipe outlet (inlet to the substation)

3 During periods with increased water temperature, due to DHW preparation

The flow rates used are the ones required to keep the water temperature at 35°C at the supply service pipe outlet; this is a typical set point temperature for the bypass in low-temperature DH systems. The differences in the flow rates are caused by the assumption of different water temperatures at the inlet of the supply service pipe, i.e. 50 or 40°. Nevertheless, the general cases do not reflect the effect of DHW tapping. After each DHW tapping period, the supply temperature to the CB increases for few minutes to 50°C (the supply media pipe is thus fully filled with hot water at 50°C) and decreases to 35°C in approx. 45 minutes. The influence of DHW tapping on the thermal comfort conditions in the bathroom is investigated by cases *d* and *e*. Case *d* is the extreme situation describing what happens if the FH is continuously supplied with 50°C water. Case *e* investigates the supply water temperature pattern including the effect of DHW tapping, i.e. there is a 5-minute period of DHW tap every 3 hours (daily between 6:00-21:00). Figure 5 shows the results for case *e* from an hourly dynamic simulation during a whole year. During the first part of the heating period (hours: 0–2714) the average heating power supplied to the bathroom is 60 W and it is 50-65 W during the second part of the heating period (hours: 7014-8640). The power emitted during the period in-between is lower, 38 W on average. This is caused by a self-regulation effect in the FH, meaning that the heat flow from the floor is reduced as a result of the decreased temperature difference between the pipe and the floor. Thus, a smaller amount of heat is transferred to the bathroom as it can be seen in Figure 5.

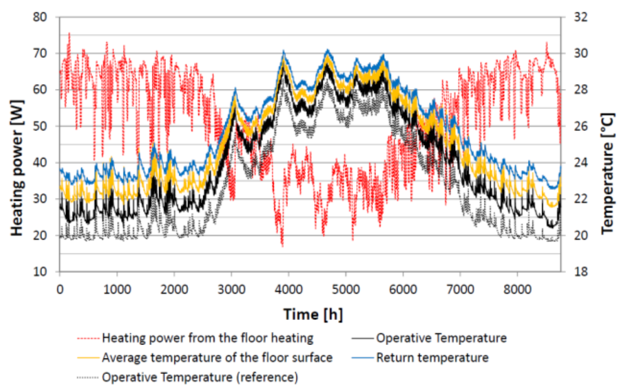


Figure 5: Case e. Annual simulation of the indoor operative temperature, floor surface temperature, return temperature and the FH heating power (time step: 0.1 h).

The consequent effect is the increase of the return temperature from the FH loop. The pattern of the FH heating power in Figure 5 is mainly caused by the effect of the solar radiation through the bathroom window as it is exemplified in Figure 6, for a very warm period in summer. It can be seen that when the solar radiation is at the highest level, both operative and surface temperatures increase. The consequence is the reduction of the heating power from the FH and the increase of the return temperature from the FH circuit during period with intensive solar radiation. Next, Figure 6 shows that the tapping of DHW – and the consequent increase of the supply temperature to the FH (not shown in the figure) – has a negligible influence on the thermal comfort and on the return temperature, as it is demonstrated by the relatively small temperature peaks in the blue curve representing the return temperature of the FH system. Moreover, a continuous flow of 4.68 kg/h is sufficient to keep satisfactory thermal comfort conditions also during the heating season without the need to increase the flow and/or the supply water temperature.

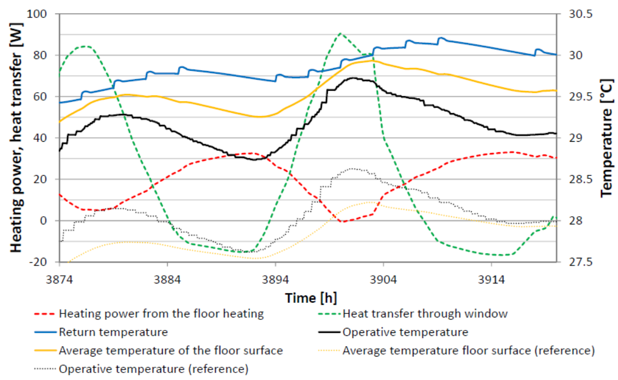


Figure 6: Case e. Simulation of the indoor operative temperature, floor surface temperature, return temperature, FH power and heat transfer through the window during the summer period with the highest operative temperature and average temperature of the floor surface (time step: 0.1 h).

Table 2 shows the average floor surface temperature, the operative temperature and the return temperature in the bathroom for the cases investigated and the reference case (no FH in the bathroom) during the period without space heating demand in the other rooms of the house (also called “summer period” or “non-heating season”). In the reference case the maximum floor surface temperature is 28.4°C, the maximum operative temperature is 28.6°C and the maximum return temperature is 37.5°C; the latter value is due to the continuous bypass operation strategy, but without CB. It is important to notice that the design of the house was not optimized to minimize overheating issues, for example by means of external shading devices. Therefore, overheating problems were likely even in the reference case without FH during the summer. Next, let’s consider the cases when the CB concept is applied. On one hand, the additional heating power supplied by the FH increases the average operative temperature by 0.5-1.2°C – thus contributing to create overheating in the room – and is cause of local thermal discomfort due to floor surface temperature higher than 29°C in certain periods of time (ISO Standard 7730, 1994; ANSI/ASHRAE Standard 55, 1992; [12]).

Table 3 summarizes the number of hours outside the heating period when the comfort operative and surface temperatures are exceeded.

Table 2: Thermal comfort and energy-related parameters outside the heating period (2700-7000).

Operative temperature [°C]					
	Reference	a	c	d	e
Average	25.4	25.8	26.4	28.1	26.6
Max.	28.6	29.1	29.6	31.2	29.7
Min.	20.7	21.3	22.1	23.7	22.3
Standard Dev.	1.7	1.7	1.6	1.6	1.6
Diff.	-	0.5	1.1	2.7	1.2
Avg. floor surface temperature [°C]					
	Reference	a	c	d	e
Average	25.4	26.3	27.6	31.0	27.3
Max.	28.4	28.9	29.8	33.3	30.0
Min.	20.7	22.1	23.9	27.3	23.3
Standard Dev.	1.7	1.5	1.3	1.3	1.4
Diff.	-	0.8	1.7	4.3	2.0
Return temperature [°C]					
	Reference	a	c	d	e
Average	35.0	26.1	27.1	29.6	27.9
Max.	37.5	29.0	29.7	32.3	30.3
Min.	32.5	21.7	23.1	25.5	24.2
Standard Dev.	-	1.6	1.4	1.4	1.3
Diff.	-	-8.9	-7.9	-5.4	-7.1
Additional heat demand [kWh/(house·yr)]					
	-	153	397	953	457
Cost [DKR/yr]	-	92	238	572	274

Table 3: Number of hours outside the heating period (2700 h – 7000 h) when the operative or the floor surface temperature in the bathroom exceed the desired values.

	Reference		**Case c**		**Case e**	
T_{op} > 26°C	1781	39%	2596	56%	2726	59%
T_{surf} > 29°C	-	-	288	6%	515	11%

On the other hand, there are sound advantages; they deal with the improved thermal comfort and the lower return temperature. In fact, the average surface temperature of the floor increases by 0.8-2.0°C, while the return temperature decreases on average by 7.1-8.9°C (the case *d* not being considered, because not interesting for the purpose of such analysis). Finally, two main conclusions can be derived from the discussion. The first is that the overheating problems are mostly caused by the intrinsic design of the building, including orientation and lack of solar shadings, and not by the FH system. The second is that the CB concept improves significantly the thermal comfort (sensation of warm floor) in the bathroom, while ensuring the proper cooling of the DH water and thus enhancing the energy-efficiency at the supply/distribution side. It could be therefore successfully implemented in low-energy buildings connected to low-temperature DH network. It is important that the building energy design is optimally integrated with the requirements of the energy supply system and that it envisages the use of shading devices and the possibility of venting.

Floor surface temperature

The results presented so far were based on the modelling of the FH as a "single element". Since the flow rates in the CB are particularly low, it is necessary to investigate the temperature distribution on the floor for a set of possible layouts of FH piping, as described in Figure 7. In this paper we investigated models of piping layouts with 8 segments, where the pipes are either in "series" or in "parallel". Figure 8 and Figure 9 show the average surface temperature of the parts of the floor that corresponds to a specific FH pipe segment and the temperature of the water leaving the segment and entering the next one. The serial connection case is the most critical in regard to the difference in temperature distribution on the floor surface. The results of the simulations show that the surface temperature corresponding to the first pipe segment is in the summer case 29.6°C, while the surface temperature of the last element is 27.2°C, giving a temperature difference of 2.4°C. The surface temperature difference in the winter case is 3.7°C (25.5°C - 21.8°C), that is not desirable from the thermal comfort point of view.

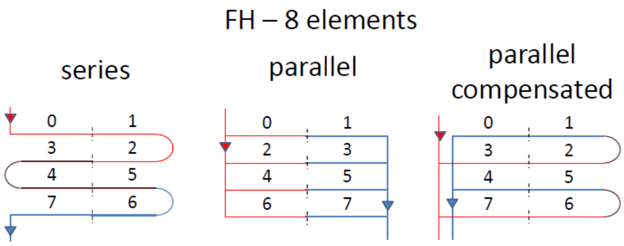


Figure 7: Principles of FH piping layouts.

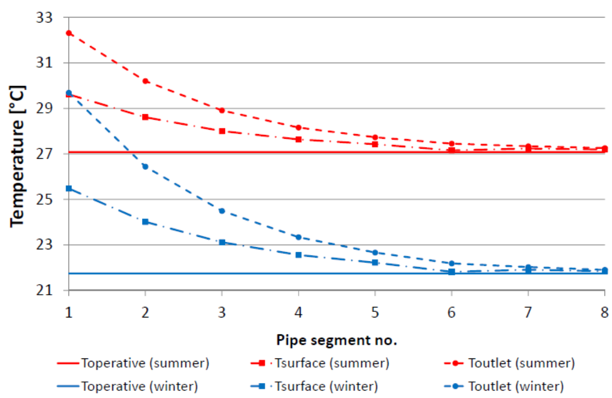


Figure 8: Distribution of the surface temperature on the floor and the outlet temperature in the serial layout; typical day in winter (time of the year: 3 h) and the warmest time during summer (time of the year: 4200 h).

If the pipes in FH are laid out in parallel, the surface temperature distribution on the FH will be more uniform, as it is shown in Figure 9. The maximal surface temperature difference will be 0.8°C and 1.4°C for the summer and the winter case, respectively. Table 4 summarizes the results of the annual temperature difference in the layout designs.

Table 4: Annual simulation; max. and min. surface temperature difference for serial and parallel pipe layout.

Layout type	$\Delta T_{surface}$ [°C]			
	max.	min.	Average	Stand. Dev.
Series	4.2	1.7	3.1	0.7
Parallel	1.5	0.5	1.1	0.3

The parallel layout guarantees a more uniform floor temperature distribution. It can be predicted that the most uniform distribution of the surface temperature are obtained by the application of the "compensated parallel layout", because the pipe segment with the warmest water is place next to the pipe segment with the coldest water.

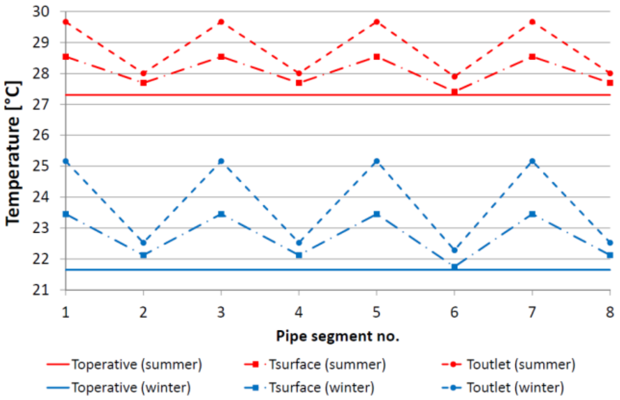


Figure 9: Distribution of the surface temperature in the floor and the outlet temperature in the parallel layout; typical day in winter (time of the year: 3 h) and the warmest time during summer (time of the year: 4200 h).

Moreover, the simulations demonstrated that the FH supply temperature oscillations due to DHW tapping cause the continuous sincrease of the average surface temperature by 0.2°C (max. 0.6°C, comparison between case c and e), and therefore they are not critical at all.

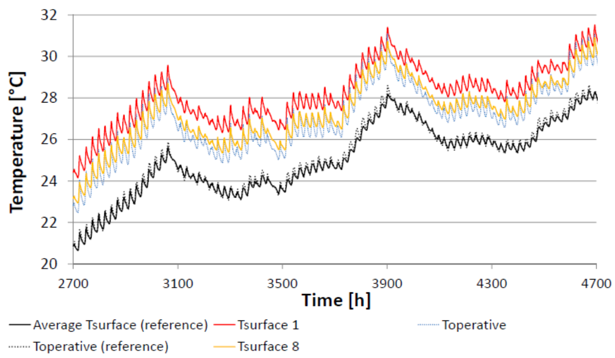


Figure 10: Average surface temperature of the floor during the operation of the CB is during the summer.

Figure 10 shows that the average surface temperature of the floor during the operation of the CB is during the summer period in average 2.1±0.3°C higher than in case without FH. The designer should pay attention to the fact that the surface temperature of part of the floor is in some periods during summer over 29°C, which is the suggested upper limit for thermal comfort reasons. The increase of operative temperature is in average 1.3 ±0.2°C.

Effect on heat production and distribution

It can be foreseen that the continuous bypass has additional advantages than the ones explained above. In fact, as the lower average temperature of the heat carrier in the supply media pipe guarantees heat loss reduction from the service pipe in comparison to the intermittent bypass case, the heat loss from the return media pipe similarly decreased. The same concept similarly applies to the main distribution pipes too: this is investigated by simulating the network energy performance when the continuous bypass is applied. The implementation of the CB concept gives a valuable advantage at network level too, thanks to the lower return temperature. The existing low-temperature DH network design and layout described in [4] was chosen as case study and the results are reported in Figure 11 and in Table 5.

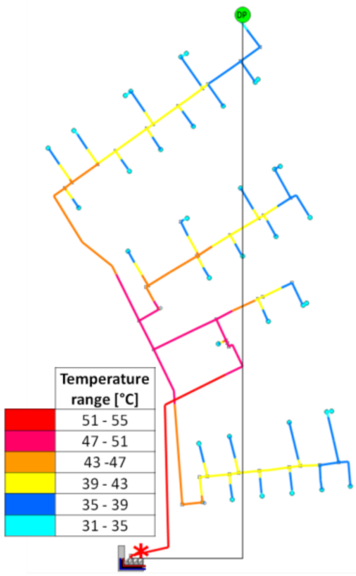


Figure 11: Plot of supply temperature in the network during application of the continuous bypass and "CB concept" in the summer season. The $\Delta T_{supply\text{-}return}$ in the FH was set to 8°C.

The network was modelled in the software Termis® and steady-state simulations were carried out, in which it was ensured that the supply water temperature at the entry point of each in-house substation was kept at 35°C±2°C by a continuous bypass flow that was then delivered to the bathroom FH system. The heat load in each bathroom due to the radiant FH was set to 30 W (average value during summer, see Figure 5). As consequence, the DH water was further cooled down in each house by 7.5°C in average (max.: 8.0°C, min.: 4.0°C, standard deviation 0.8°C). The lower return temperature along the distribution pipelines decreases the heat loss from the return pipe by 35%; it is possible to notice from Table 5 that the distribution heat loss from the supply pipe slightly increased. This phenomenon is due to the twin pipe configuration: a slightly greater heat transfer from the supply media pipe towards the surrounding ambient derived from the lower return temperature, being the media pipes embedded in the same insulation and thus "thermally coupled". As overall effect, the heat loss reduction thanks to the CB concept is approximately 13% and it is therefore possible to conclude that 40% of the heat used by the CB is "free" heat, thanks to the lower distribution heat loss (in the example, 0.5 kW heat loss reduction with a heat load of 1.2 kW). Moreover, there is a possible improvement at the heat generation side thanks to the lower return temperature: outside the heating season the return temperature to the plant is 23.8°C on average, instead of 27.7°C in case of no SH demand.

Table 5: Results from the network simulation with application of only the "continuous bypass" (A) or "CB concept" in the summer season (B).

	Case A	**Case B**	**Difference**
Heating Power [kW] (plant)	3.8	4.5	18%
Tsupply [°C] (from the plant)	55	55	-
Treturn [°C] (to the plant)	27.7	23.8	-3.9
Heating Load [kW]	-	1.2	-
Total Heat Loss [kW]	3.8	3.3	-13%
Heat Loss Supply [kW]	2.25	2.3	2%
Heat Loss Return [kW]	1.55	1	-35%
Heat loss/production [%]	100	72.4	

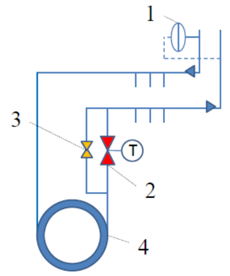
ECONOMY

There are no additional investment costs for the proposed bypass/FH systems if it is applied during the design phase, because the only change in in-house substation design is in "moving" the bypass valve to the bathroom FH loop. The cost figures difference (see Table 2) among the cases is caused by the different flow rates which are needed to keep the constant temperature of 35°C at the substation inlet. The further the end-user is located from the heat production plant, the higher the bypass flow rate that is required, because of the lower supply temperature. At the same time the surface and operative temperature in the bathroom are higher, thus making the magnitude of the heat transfer vary from case to case.

The cost for the additional heat supplied to the FH in the bathroom during summer is minimal: between 92 and 274 DKK/(house·yr), assuming a heat price of 600 DKK/MWh (currency exchange rate 1 DKK = 0.1345 EUR). Moreover, and with regards to the operational costs, the example in the paper demonstrated that a significant part of the additional heat demand for the FH of the bathrooms is counteracted by the lower distribution heat losses and by the benefit of lower return temperatures to the heating plants. In Denmark, district heating distribution companies are non-profit, generally municipal companies and therefore the diseconomies caused by the heat losses are anyway hidden in the final users' heat price. Finally, most end-users could be willing to pay the limited extra investments and operational costs, given the improvement of the thermal comfort in their homes.

Technical solution for practical applications

We here propose a practical method to implement the concept in real-life situations. The general case deals with buildings with direct SH system with radiators equipped with individual thermostatic valves, FH in the bathroom and no-weather compensated control strategy (see Figure 12).



1- Differential pressure controller
2- Thermostatic valve
3- Needle valve (constant flow)
4- FH circuit

Figure 12: FH in the bathroom and radiators in the other rooms. Installation of a needle valve.

The constant continuous flow of bypassed water is assured by installing a proper needle-valve, to be placed in parallel to the thermostatic valve. The SH loop must be equipped with a differential pressure controller which assures a constant differential pressure in the loop and consequently a constant flow rate through the needle valve. The additional heating power during winter (i.e. when higher flow through the FH is needed) is controlled by a thermostatic valve placed on the FH return pipe. The thermostatic valve must be turned to the close position during summer operation. The drawback of the solution is the absence of a mixing loop for FH and thus the FH supply temperature is up to 50°C in periods with preparation of DHW (or even higher if the low-temperature DH network envisages a temperature boost during peak load periods in winter): the simulation proved that this is not a real issue concerning the indoor operative temperature, but it can result in non-uniform surface temperature distribution, depending on the FH pipes layout. The CB concept can be similarly applied to indirect systems and systems with weather compensation.

CONCLUSIONS

The conclusions of this study are summarized here below:

a) The "continuous bypass" for the reference case without FH in the bathroom [2] reduces the time needed by the in-house substation with HE to prepare DHW with 40°C by 2 s in average, (16%) in comparison to the "intermittent bypass".

b) The "continuous bypass" guarantees lower heat losses from the service pipe, in the example considered between 10-35% in comparison to the "intermittent bypass".

c) The "continuous bypass" can be used to increase the thermal comfort outside the heating season in bathrooms through radiant FH, with very limited overheating problems. Nevertheless, it is important that the building design foresee the use of shading devices and the possibility of venting. This proves that a methodology based on the integrated energy design must be applied when designing low-energy buildings that are optimally combined with energy-efficient and sustainable energy supply systems.

d) In the case study of a low-temperature DH network serving 41 low-energy buildings in Denmark, the CB concept reduces the distribution heat losses by approximately 13%, in comparison to the bypass with "continuous" flow. That corresponds to 40% of the SH demand in the bathrooms during summer.

e) The use of the bypass water via bathroom FH is a cost-effective solution, both for the DH utilities, the end-users and the society as a whole: the first could "monetize" supply of heat that otherwise would be wasted in distribution heat losses and benefits from lower return temperatures; the second can increase the comfort standard in their houses in an economical way; the latter would benefit from the opportunity of including larger share of low-grade heat and renewable energy into the heating system, thus decreasing the greenhouse gas emissions and contributing to the country energy security.

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LOW TEMPERATURE DISTRICT HEATING CONSUMER UNIT WITH MICRO HEAT PUMP FOR DOMESTIC HOT WATER PREPARATION

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Keywords: Low temperature District Heating, DH consumer unit, Domestic hot water, Micro booster heat pump

ABSTRACT

In this paper we present and analyse the feasibility of a district heating (DH) consumer unit with micro heat pump for domestic hot water (DHW) preparation in a low temperature (40 °C) DH network.

We propose a micro booster heat pump of high efficiency (COP equal to 5,3) in a consumer DH unit in order to boost the temperature of the district heating water for heating the DHW. The paper presents the main designs of the suggested system and different alternative micro booster heat pump concepts. Energy efficiency and thermodynamic performance of these concepts are calculated and compared. The results show that the proposed system has the highest efficiency. Furthermore, we compare thermodynamic and economic performance of the suggested heat pump-based concept with different solutions, using electric water heater. The micro booster heat pump system has the highest annualised investment (390 EUR/year) and the lowest operation (320 EUR/year) expenditures. Electric heater-based concepts consume 5-14 times more electricity, which leads to relatively high annual operation costs (530-970 EUR/year); while investment costs are lower (326-76 EUR/year). The suggested DHW heat pump-based system is cost-efficient for private consumers already today. Furthermore, application of the micro booster heat pump in low energy houses complies with the energy consumption requirements, set by the recent Danish Building Regulations. The use of electrical heater variants would exceed this limit.

INTRODUCTION

District heat in Denmark is mainly produced in heat boilers or combined heat and power plants [1]. The average yearly district heating supply and return temperatures in distribution networks are 80 °C and 40 °C respectively [2]. Clearly, lower DH temperatures are desired in order to reduce energy losses in the district heating networks. Reducing district heating supply temperature becomes possible with increasing focus on energy efficiency improvements in energy supply systems and in the buildings. In Denmark energy performance requirements for new buildings set progressively lower limits on energy consumption for space heating and hot water preparation. At the same time renovations of the existing buildings are required to include certain minimum energy saving measures, such as insulation of roofs and walls and replacement of windows with more efficient ones etc. Consequently, with decreasing heat demand, low temperature heating becomes feasible in the increasing share of the building stock.

According to the proposal by the Danish Government [3] for future energy, heat and power supply and transport systems should solely rely on renewable energy (RE) resources by 2050. An important milestone is in 2035 where the entire heat and power supply should be 100 % renewable. Clearly, energy efficiency plays an important role in achieving these targets – reducing energy resource consumption and additional capacity investments. In the district heating sector biomass will play an important role in the 100 % renewable energy system. However, both national and global biomass resources are scarce. Therefore, other energy resources and technologies will have to be used in addition to biomass plants. For district heating production alternative sources are solar, geothermal, ambient and waste heat resources. The utilisation efficiency of energy resources depends on the required district heating water temperature and increases with decreasing DH temperatures

In this context the benefits of low temperature district heating (LTDH) are multiple. First, heat losses from the district heating network can be reduced. For example, by reducing DH supply temperature from 80 to 40-45 °C, heat losses in a DH system can be lowered by approximately 37 % or even more [4]. Second, low temperature DH in local networks opens for possibilities to connect new users to existing DH systems without necessarily requiring additional capacity investments[1]. Moreover, LTDH enables efficient use of low temperature renewable energy resources, such as solar, geothermal, industrial waste heat.

[1] Depends on a specific DH system and generation technology

The viability of a LTDH consumer substation with DH supply at just above 50 °C has been proven and demonstrated in Denmark [7]. Here it is possible to prepare domestic hot water of 45 °C without any additional energy source. Further lowering DH supply temperature could for example enable use of the DH return water (40 °C) in the traditional networks (and connect more consumers without significant increase in capacity). However, while district heating supply at 40-45 °C is in principle sufficient for space heating, it cannot be used for domestic hot water preparation.

In this paper possibilities for preparation of domestic hot water, when DH supply temperature is as low as 40 °C are discussed. We analyse different heat pump and electric heater concepts for utilising additional energy source – electricity for heating DHW. The concepts are compared on the basis of thermodynamic and economic calculations, described in the article. We recommend using a small heat pump for boosting DH water to 53 °C. As it was mentioned earlier, such temperature is sufficient for DHW preparation.

ENERGY CONSUMPTION FOR SPACE HEATING AND DOMESTIC HOT WATER

We assume that low temperature district heating is supplied to a low energy detached single family house. The house is built according to the requirements of the recent Danish Building Regulations (BR10) for low energy buildings of class 2015. The total yearly energy demand for space heating, domestic hot water preparation, operation of ventilators and pumps should not exceed the maximum annual energy demand set by the BR10 – the energy frame (E_{frame}, kWh/m^2), calculated by the following equation (1):

$$E_{frame} = 30 + \frac{1000}{A} \tag{1}$$

Here A is gross heated floor area (m^2).

Different weight coefficients are applied for consumed district heat and electricity – 0,8 and 2,5 respectively – when comparing the calculated energy consumption of a designed building with the energy frame.

Table 1 Energy consumption in the low energy house

Space heating demand, kWh/year	2570
DHW demand (250l/m2 per year at 55 °C (BR10)), kWh/year	2083
Electricity in pumps and ventilators, kWh/year	525
Total energy consumption, kWh/year	5178
Total allowed energy consumption by energy frame, kWh/year	5771

The analysed single family house has a heated area of 159 m^2, thus the energy frame is 36,3 kWh/m^2. The calculated energy demand is presented in Table 1. The energy consumption for domestic hot water heating accounts for a considerable share (40 %) of the total energy demand in the low energy house according to Table 1.

The single family house is heated by under floor heating. Consequently, with low energy demand and under floor heating systems the house is well suited for low temperature (40°C) district heating supply.

Different hot water consumption rates are assumed by various literature sources. For comparison of energy consumption in the building when different domestic hot water preparation alternatives are applied with the energy frame, hot water consumption calculated according to BR10 (Table 1), is used. For energy and economic cost calculations a more conservative and higher DHW [4] demand of 3200 kWh/year has been assumed (800 kWh per person per year and 4 occupants), which is 54 % higher than according to BR10.

DOMESTIC HOT WATER SYSTEM AND LOW TEMPERATURE DISTRICT HEATING

When considering domestic hot water preparation systems, three main aspects/requirements need to be taken into account:

- The required temperature of DHW is 40 - 45 °C, depending on the tapping place (kitchen or bathroom);
- The risk of bacterium ‘Legionella’ (especially if storing the hot tap water), which can be avoided either by increasing temperature of the DHW to around 55 °C or by avoiding storing it;
- The Danish water standard DS 439, which includes hot water tapping profile, has to be met when dimensioning DHW system, meaning that the peak load of 32,3 kW has to be satisfied and the hot water storage tank has to be large enough to cover the most critical DHW tapping profile during morning hours.

Previously a low temperature DH network and consumer substations have been developed and demonstrated, when district heating supply temperature was lowered to around 50 °C [7]. The Danish full-scale demonstration project of the low-temperature DH supply to low-energy buildings has proven that the concept works – both space heating and hot water demand can be satisfied.

In this article we take a step further and reduce DH supply temperature to 40 °C. Clearly this temperature is too low for heating the tap water up to 45 °C, thus additional energy is needed for domestic hot water preparation. This energy could come from electricity – in a heat pump or electric heater. For evaluation of energy systems with multiple fuels and products, the thermodynamic quantity *Exergy* is commonly used [5]. The exergy level of a stream expresses the availability to do technical work, as temperature, pressure and chemical composition of the stream reaches equilibrium with the ambient. Electricity has a very high availability to do work, normally considered to be 100 %. If the ambient is represented by the cold tap water, the exergy of district heating water at 40 °C is very low (10 %) compared to electricity. Exergy expresses the minimum demand of primary energy supply theoretically needed to fulfil the DHW demand and should thus be minimized. The total energy demand for DHW supply may thus be quantified by the total exergy consumption of electricity and DH. From this viewpoint it will be advantageous to substitute one unit of electricity by up to ten units of DH. The further lowering of the district heating supply temperature is from a thermodynamic point of view more beneficial if the share of electricity in total energy, consumed for DHW, is small. Compared to an electric heater, where one unit (kW) of electricity input results in one unit (kW) of heat output, heat pumps can reduce this consumption by several units. To optimise the DHW production we have designed a small heat pump-based unit for hot tap water preparation in the low temperature DH system – a *microbooster heat pump unit*. Clearly, such DHW unit has to fulfil also the 2 latter requirements regarding legionella and sufficient capacity. This has been also taking into account when designing different DHW system concepts.

CONSUMER DHW UNIT WITH MICROBOOSTER HEAT PUMP

The additional energy, needed for DHW can be added either on the secondary side, directly to the tap water, or to the district heating water on the primary side, which is then used to heat the tap water. Different system configurations regarding hot source for the heat pump (DH supply or return water), pre-heating of tap or return water, configuration of the heat pump and storage tank type are possible for the two options. We have selected the three most promising concepts for further analysis (see Figure 1).

In variant **A** the district heating water entering the hot water system is divided into two flows. The temperature of the first flow is boosted from 40 °C to 53 °C as it flows through the condenser of the heat pump. The second DH flow runs through the evaporator and is the heat source for the heat pump (and is cooled down to around 25 °C). The heated DH water is stored in a stratified accumulator tank and instantaneously heats tap water in a micro plate heat exchanger [10], when the tapping starts. Here the district heating storage tank is used in order to lower DH flow, heat pump capacity and investment cost.

Variant **B** resembles **A** - the only difference is that return water from hot water heat exchanger (and possibly space heating) is used as hot source in the heat pump. This variant has a reduced DH flow when compared to **A**.

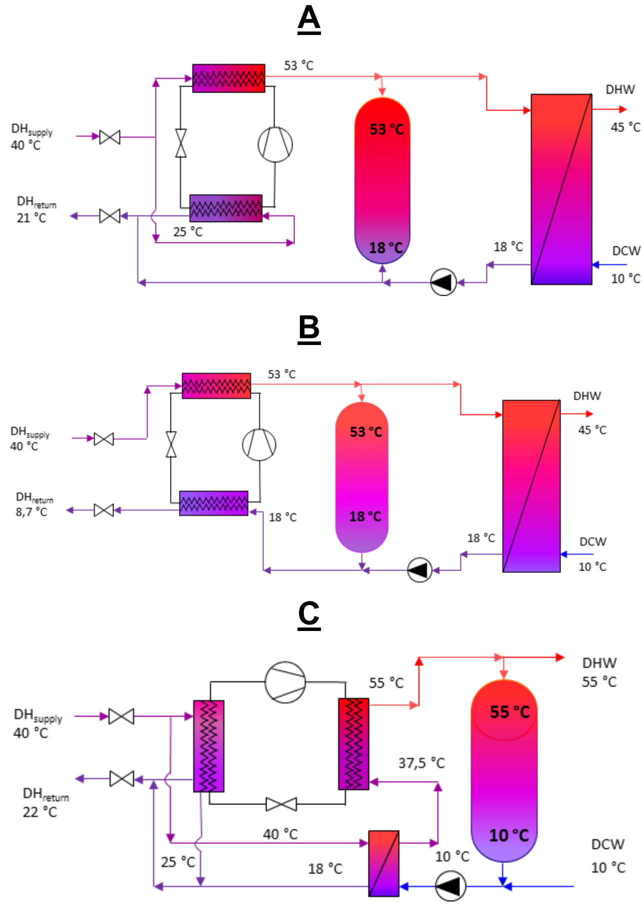

Figure 1 Analysed microbooster heat pump DHW concepts

In Variant **C** cold tap water is heated to 55 °C in the heat pump. DHW is stored at higher temperature than DH water in order to avoid formation of 'legionella' bacterium. In order to reduce required heat pump capacity, the cold water is preheated in a heat exchanger by using district heating water. The heat source of the heat pump is, as in variant **A**, district heating supply water.

For each micro booster heat pump variant, a numerical model has been implemented in Engineering Equation Solver (EES) using the assumptions presented in Table 2. More details on the numerical models and some results has been published previously [6]. In this paper some assumptions have been changed for the heat pump, to better represent the actual working conditions in the considered system. The heat pump is switched on from the start of the tapping sequence until the re-filling of the stratified tank is completed. Steady state operation can be assumed for the heat pump, as fluctuations from the hot water tapping profile are managed in the stratified tank. The storage volume of all the considered solutions has been calculated individually to allow similar operation patterns and operation time for all the heat pumps.

Table 2 Assumptions used in modelling DHW systems with micro booster heat pump

Variable	Assumption
Refrigerant	R600a
Isentropic efficiency of compressor, /	0.5
HEX pinch temperature difference in both Condenser and Evaporator, K	2.5
Pinch temperature in Tap-water HEX (Q_{MAX}=32 kW), K	8
Temperature of DH return from the evaporator (variants A & C) , °C	25

The main results of the calculations are summarised in Table 3. The flow of DH water, electricity consumption and exergetic efficiency are averaged values, which is possible due to steady state operation in the heat pump units.

Table 3 The results of three micro booster heat pump-based DHW system calculations

	Microbooster Heat Pump variants		
	A	B	C
DH flow, l/h	85	50	75
Power, W	142	214	155
Coefficient of performance (COP)	5,3	3,5	5,0
Exergetic efficiency	0,43	0,41	0,42
Storage size required, l	128	128	100

From the table it can be seen that variant A has the lowest required power capacity and the highest district heat flow. When DH flow is reduced and the return water is used in the evaporator in variant B, more power is needed to boost the DH water temperature. The reason is low temperature of the return water (around 18 °C), entering the evaporator. As a consequence the heat pump in variant B has low COP. In variant C more energy has to be used to heat the DHW. Here domestic hot water is heated to 55 °C, i.e. 2 °C higher than in the case of primary DH water. Furthermore, even though the cold tap water is pre-heated to 37,5 °C before entering the heat pump it is still lower than the temperature of the DH water entering the heat pump in variants A and B.

The differences in district heating water flow in the three analysed hot water systems will not have any effect on the size of service pipes, since they are already oversized due to low energy consumption of the house and the fact that the smallest DH pipe size available on the market has been assumed.

The relation between the required heat (DH flow) from the district heating network and the additional electricity needed is of primary interest, as both are needed to produce hot water with the micro booster heat pump unit. Heat and electricity are in many cases produced as main products in the Combined Heat and Power (CHP) plant, and in this way the interaction becomes important. As exergetic efficiency is a measure of both the inputs and products (the product is in this case the constant amount of domestic hot water) the objective is to minimize the amount of heat and power required as the energy source for the heat pump. As the DH supply water has lower exergy content than electricity [5], the heat pump configuration with the lower power consumption and the higher heat consumption has the highest exergetic efficiency. With the highest exergetic efficiency the lowest amount of exergy (or available work) is used to complete the process, and thereby the highest fuel efficiency is reached. It is observed that due to the differences in heat pump configuration the significant differences in COP are not reflected equally significant in the exergetic efficiency. Thus, it is of importance to take both measures into account to do a consistent evaluation.

In variants A and B district heating and not domestic hot water is stored in the tank (Figure 1), which eliminates the risk of legionella formation in the DHW. The content of hot water after the heat exchanger on its secondary side, in DHW pipes, is possible to be kept under 3 litres. This is the maximum permissible hot water amount in the DHW system in order to avoid legionella if no additional treatment is applied, according to the German guidelines (DVGW, W551) for hot water systems [7]. In variant C the possibility of bacteria formation increases, as DHW is stored in the tank. In order to reduce the risk additional energy is needed to occasionally increase the temperature in the tank to 60 °C.

When comparing the required storage tank size (Table 3) variant C has an advantage of smaller hot water storage requirement. Usually smaller storage tanks are desired due to practical reasons, such as available space for the consumer DH station at the households. A smaller tank could also lead to lower heat losses. On the other hand DHW is stored at higher temperature (variant C) than the heated DH water in variants A and B, which would lead to higher heat losses. Heat losses are neglected in the calculations, as they are assumed of similar magnitude when considering the total installation.

When comparing A and B concepts, it seems that heat pump in variant A will have more stable operation conditions, as district heating supply water flows through both, condenser and evaporator. Whereas in case of variant B, temperature of the return water, flowing through evaporator, can vary, depending on e.g. cold tap water temperature.

Based on the lowest electricity consumption as well as other advantages and disadvantages variant A has been chosen for further development.

CONSUMER DHW UNIT WITH ELECTRIC HEATER AND COMPARISON WITH MICRO BOOSTER HEAT PUMP

Even though the micro booster heat pump is expected to use significantly less additional electricity than electric water heaters, the latter solution can be expected to have lower investment costs and more simple design (Figure 2). In order to compare the costs and benefits of micro-booster heat pump and electric water heater DHW concepts for low temperature district heating, three electric heating alternatives have been calculated. The chosen micro-booster variant A is then compared with the 3 electric heater alternatives.

In the first electric heating alternative (D) the heat pump is replaced by an instantaneous electric heater, which boosts DH temperature from 40 °C to 53 °C. The design is more simple when compared to the variant A and only one DH flow is used for hot water preparation. In the alternative E district heating water flows through a coil, which is mounted in a hot water tank. Cold tap water in the tank is pre-heated to 35 °C by the coil and further heated up to the required 55 °C by an electrical heater, also installed in the tank. Finally, in the alternative F only electricity is used to heat domestic hot water in the tank with the installed electric heater.

The microbooster heat pump and the electric heating alternatives are compared, based on energy (e.g. increased electricity) consumption, exergetic efficiency, CO_2 emissions, as well as annualised investment and operation costs. Thermodynamic analysis has been performed using the same tool and assumptions as described in the previous section. The yearly costs have been calculated for assumed hot water consumption of 3200 kWh.

Cost calculations are performed for private consumers, assuming low temperature district heating supply to the single family houses. Additionally, socioeconomic costs of hot water preparation are compared based on the projected future energy costs in order to include the expected development of the Danish energy system into the analysis [9]. Investment costs of different alternatives include only costs, related to hot water installations of a consumer substation in a low energy single family house with low temperature district heating supply. The heating part of the substation is assumed to be the same for the analysed house, regardless of the hot water installation. All hot water units are assumed to have 15 years economic lifetime. A 6 % discount rate has been used for the private consumer and 3 % in the socioeconomic calculations.

District heating and electricity prices for private consumers are based on the latest data by the Danish Energy Regulatory Authority [8] (see Table 4). District heating prices for households include only variable heat costs, since the house is connected to a DH network and the fixed yearly fees have to be paid anyway. District heating prices in Denmark vary depending on the DH company and span between 3 and 21 ¢/kWh. For the calculations average and minimum DH price has been used. Electricity prices are based on the price level for consumers with yearly consumption of 4000 kWh and include energy and CO_2 taxes. Private investment costs and energy prices also include VAT, which in Denmark reaches 25 %. Socioeconomic district heating and electricity costs (Table 4) as well as CO_2 emission rates (kg/GJ) of district heat and electricity are based on the estimations by the Danish Energy Agency [9].

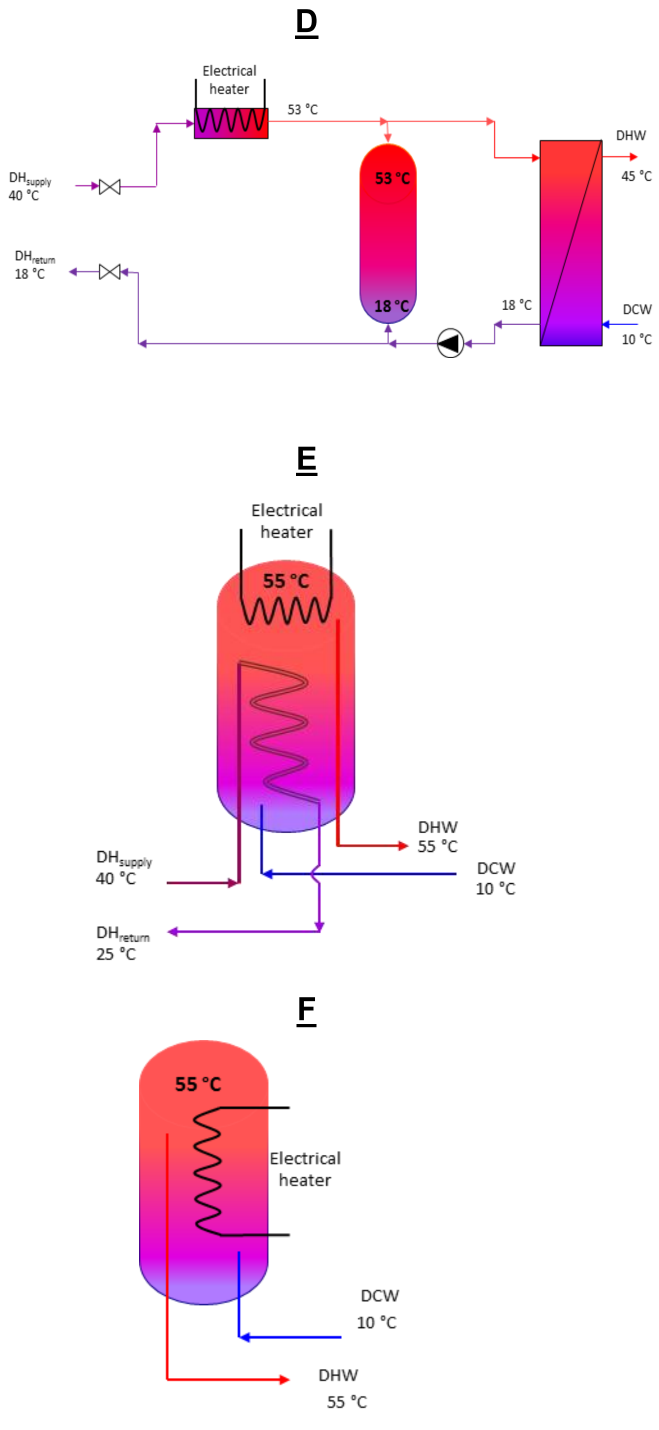

Figure 2 Analysed electric heater DHW concepts

CO_2 emissions are based on district heating and electricity production in 2011, while socioeconomic energy prices reflect DH and electricity costs in 2030.

Table 4 District heating and electricity prices

¢/kWh	Average	Min
DH price, private	8,4	3,0
DH price, socioeconomic, 2030	3,5	
EL price, private	30,3	
EL price, socioeconomic, 2030	11,2	

The main calculation results regarding DH and electricity capacities needed and system efficiencies are summarised in Table 5.

Table 5 The results of micro booster heat pump- and electric heater- based DHW system calculations

	Microbooster heat pump and electric heater variants			
	A	D	E	F
DH flow, l/h	85	50	65	0
Power, W	142	749	896	2017
Coefficient of performance (COP)	5,3	1,0	1,0	1,0
Exergetic efficiency	0,43	0,14	0,12	0,06
Storage size required, l	128	128	100	100

The highest exergetic efficiency of the system is achieved in variant A, where the heat pump is used for boosting the DH water temperature. At the same time the highest share of the total energy for hot water heating comes from district heating in this alternative (93 %), see Figure 3. Other variants (D, E and F) have considerably higher electricity consumption, which is not desired. When electricity consumption increases, exergetic efficiency decreases. Thus, the advantage of micro booster heat pump – only moderate increase in electricity consumption – is clearly illustrated here. If a large share of electricity is produced in wind power plants and other non-dispatchable renewable energy technologies, higher electricity consumption can be acceptable, also due to the possibility for providing balancing services for the electricity grid (since the boosted DH or domestic hot water is stored in the tank making electricity consumption flexible). However, increased power consumption might require reinforcements of electricity distribution networks if considerable share of consumers would choose e.g. variant F.

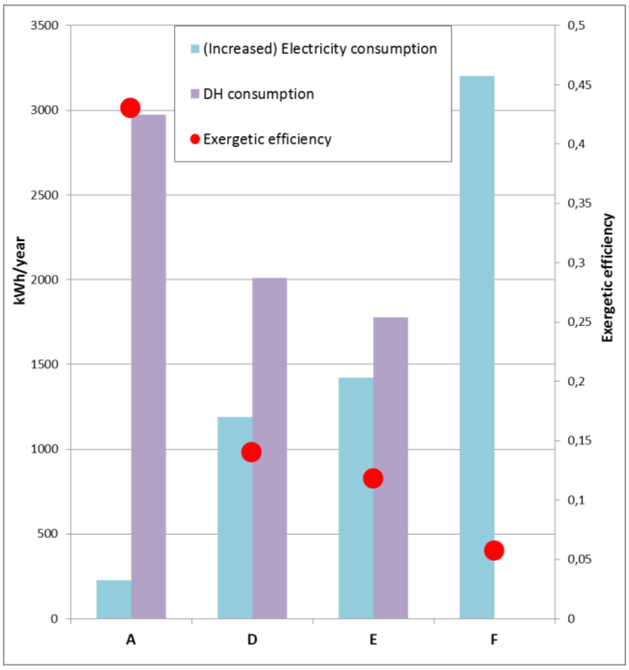

Figure 3 Energy consumption in DHW system and exergetic efficiency

From Figure 4 it can be seen that, based on the fuel mix in production of district heat and electricity today, the microbooster heat pump alternative causes the lowest yearly CO_2 emissions. Clearly, the emissions from DH production can be significantly lower if low temperature and renewable energy sources, such as solar, geothermal energy or biomass, are used. For electricity it also depends on whether fossil fuel-based production will be repalced by renewable energy ressources (e.g. wind or biomass).

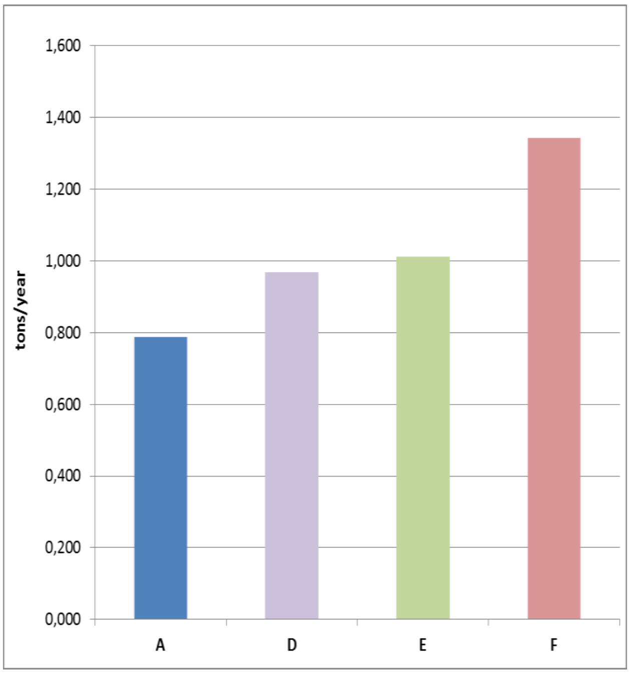

Figure 4 CO_2 emissions, caused by different hot water heating alternatives

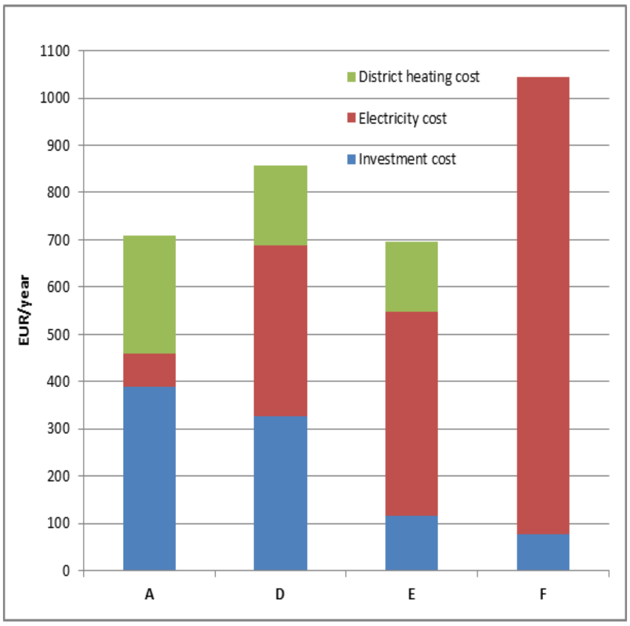

Figure 5 Yearly costs for private consumers, average DH price and 6 % interest rate

Figure 5 and Figure 6 include yearly costs of different hot water heating alternatives for private consumers with average and lowest variable district heating prices respectively.

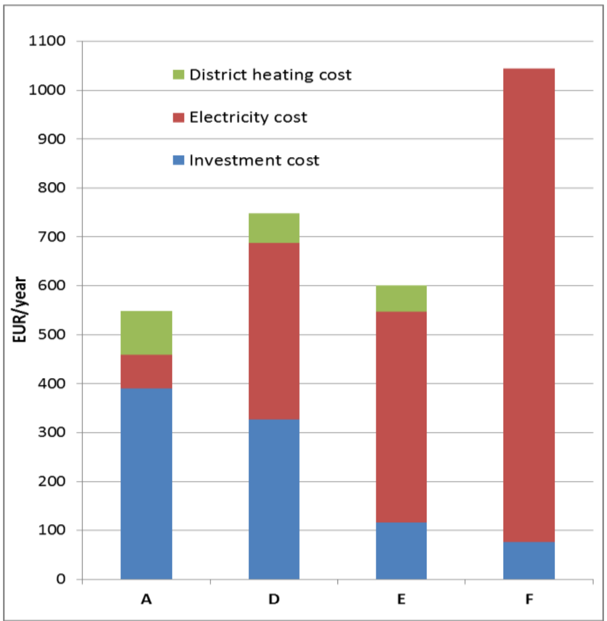

Figure 6 Yearly costs for private consumers, minimum DH price and 6 % interest rate

Investment costs account for the largest share (55 %) of the yearly expenditures when the micro booster heat pump alternative is chosen. At the same time yearly operation costs are high when electric water heaters are installed – between 62 % and 93 % of the total yearly costs. From the figures it can be seen that the least cost alternatives are A and E. With average DH price (Figure 5) variant E has the lowest yearly cost, which is only marginally lower than for variant A. Low DH price (Figure 6) leads to reduced operation costs for all hot water installations (except for variant F) – but most significantly when the micro booster heat pump is used. Hence, variant A is the least cost alternative in this case.

If hot water consumption is lower (e.g. 1240 kWh/year) than the one, used in the calculations (3200 kWh/year), operation costs decrease and the electric heating alternatives become more cost efficient than heat pump-based system. While the investment in a micro booster heat pump is more beneficial with high DHW consumption.

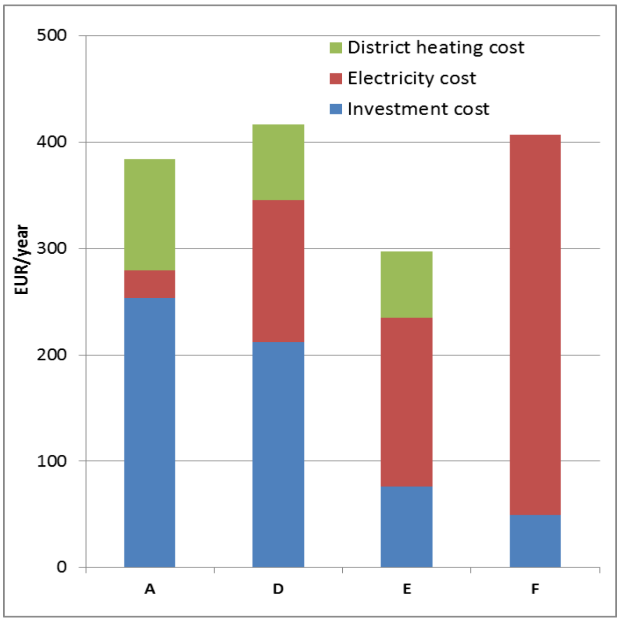

Figure 7 Yearly socioeconomic costs (2030 prices), 3 % interest rate

In general, the conclusion can be made that it is critical to reduce investment costs of the micro booster heat pump. Clearly, use of heat pump in the low temperature DH consumer substation can already today be cost-efficient for private consumers with hot water consumption of around 3200 kWh/year. When looking at the results of the socioeconomic calculations with 2030 energy prices (Figure 7) it is obvious that the cost of the micro booster unit has to be reduced by approximately one third for this concept to be more cost efficient than variant E from the socioeconomic point of view. The micro booster heat pump hot water unit is at the prototype stage today, thus a certain cost reduction might be expected.

Figure 8 compares the total energy consumption in the low energy single family house with different hot water installations. Here hot water demand is calculated according to the guidelines in the recent Danish Building Regulations (Table 1) and is lower than the demand, used for cost calculations.

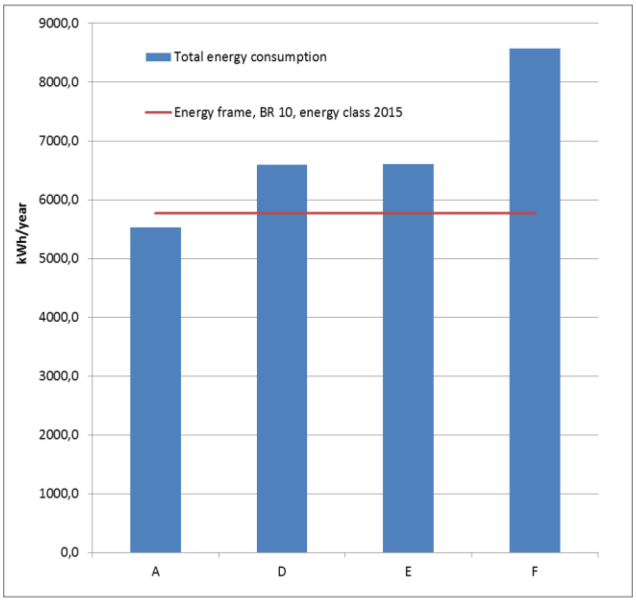

Figure 8 Comparison of total energy consumption in a building with energy frame, according to BR 10

Only variant A complies with the energy frame for buildings of low energy class 2015. The reason is high electricity consumption of electric heating alternatives, which is in this calculation weighted by a factor 3 when compared to the district heating consumption. Thus, energy policy of today encourages district heating consumption and promotes electricity savings in building installations. Consequently, a micro booster heat pump-based hot water installation is the most suitable concept, with low temperature (~40 °C) district heating supply according to the Danish Building Regulations.

CONCLUSION

Different concepts for domestic hot water preparation when district heating supply temperature is reduced to 40 °C have been presented and compared in the article. The reduction of DH temperature implies the use of an additional energy source (electricity) for DHW preparation. Two main concepts of utilising the additional energy have been compared – based on heat pump and electric heater technologies.

Based on the performed calculations several main conclusions can be drawn. From the cost perspective it is not obvious that heat pump use in DHW system (variant A) is the most beneficial concept under current technology and energy prices for the private consumers or based on future socioeconomic costs. Combined electric and DH water heater in the DHW tank (variant E) is the competing technology. On the other hand, heat pump alternative reduces electricity consumption by more than 6 times, which is an important advantage in the light of the expected more rapid increase in electricity prices, when compared to the prices of the district heat. The benefits of reduced electricity consumption are reflected in the calculated exergetic efficiencies of the two alternatives (0,43 and 0,12 for variant A and E respectively), which reflect consumption of primary energy. According to the recent Danish Building Regulations the DHW system with the micro heat pump is the best alternative, due to the lowest electricity consumption.

FUTURE WORK

As a part of the Danish Energy Technology Development and Demonstration project (EUDP 11-I, J. nr. 64011-0076) the first prototype of the DHW system with micro booster heat pump has been built according to the design of the variant A. The laboratory tests have shown that it is possible to achieve high heat pump COP and prepare the domestic hot water at the required temperature. Five consumer DH stations with the micro booster heat pump will be installed in single family houses, supplied with 40 °C district heating, for demonstration of the technology during the heating season 2012/2013.

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Details of DHC- design

FACTORS INFLUENCING SOIL FRICTION FORCES ON BURIED PIPES USED FOR DISTRICT HEATING

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Keywords: buried pipe design, pipe soil interaction, friction force

ABSTRACT

This paper identifies several approaches to account for different factors that influence the soil friction forces on buried pipes for district heating. Much of the current understanding of soil-pipe interaction have been based on investigations conducted on pipes buried in cohesionless soil backfill. In practice, due to economic reasons, trench excavation spoil typically with a significant fine-grained fraction is often reused as trench backfill; hence, there is a need to better understand the soil-pipe interaction in pipes buried in fine-grained soil backfill. It is clear that research work on a number of additional fronts is needed to obtain a better understanding of the soil loads on buried pipes while taking into account real operating conditions and modern pipe laying technologies.

INTRODUCTION

Over the last 40 years, pipeline design has been based largely on the assumption that simple Coulomb friction law would be sufficient for the calculation of axial friction forces around the perimeter of pipes. According to this approach, the friction forces are assumed proportional to the radial contact pressure around the pipe. The ratio between the contact pressure and friction force is defined as the soil-pipe interface coefficient of friction (μ), or $\tan\delta$, where δ is the interface angle of friction between soil and pipe surface. 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.

For buried pipelines, the radial soil stress (earth pressure) that acts normal to the perimetric surface of the pipe is the other parameter that controls the axial soil resistance. For an average contact pressure (σ_{avg}) acting on DH pipes equation 1 is commonly used.

$$\sigma_{avg} = \gamma' * \left(\frac{1+K_0}{2}\right) * \left(H + \frac{D}{2}\right) \qquad (1)$$

where: γ' = average effective unit weight of soil; K_0 = coefficient of lateral earth pressure at rest for the soil; H = depth from ground surface to the top (crown) of the pipe; D = external pipeline diameter. This formula can be found and is used in many applications for determination of axial loads on pipes buried in cohesionless soils including regulations and standards [3]. Nevertheless, it is important to note that a numerous other methodologies are available for the calculation of earth pressure on pipes. The most common design methods are known from Marston [5], Spangler [4], Leonhardt [6], ATV 127 [21,10].

SOIL STRESSES FROM INSTALLATION PROCESS

In addition to significant deviation in the results due to different assumptions in the calculation methods, it has also been observed that the radial soil stresses on the pipe from the installation process is not well represented by the earth pressure coefficient at rest [7]. For example, in standard trench conditions very good compaction of backfill soil is needed to avoid settlements. It has been observed that the radial earth pressures on pipes buried in trenches with compacted backfills are significantly higher than the earth pressure at rest. In engineering practice this can be accounted by increasing the earth pressure coefficient K. Several recommendations for an increased coefficient of earth pressure exists. Some of them are shown in table 1.

Table 1 – Earth pressure coefficients for compacted backfill

Earthpresure coefficient K	Reference	Soil Conditions in the trench
K=1	ALA, ASCE USA, 2001 [20]	Compacted backfill
K≥1	TRFL 2003 [19]	Medium dense to dense sand
K=0.3 – 3.0	Mackey 1967 [7]	Compacted backfill
K=0.88	Netzer 1998 [17]	Compacted crushed gravel
K=0.9	Achmus 1995 [16]	Dense to very dense sand
K=0.7-0.85	Gramm 1983 [18]	Dense Sand

From Table 1, it is obvious that assuming K to be 1.0 for compacted backfill in pipe trenches will simplify Equation 1. σ_{avg} remains only dependent on overburden height, the outer diameter of the pipe and, of course, the weight of the soil.

SOIL-POLYETHYLENE INTERFACE FRICTION IN DISTRIC HEATING (DH) PIPES

Three different materials are combined in the manufacturing of typically used pre-insulated, bonded DH pipes. These include: steel pipe for the hot water, surrounding insulation foam made of polyurethane, and an outer pipe coating made of polyethylene. Consequently, the interface between the pipe and the surrounding soil is polyethylene. Investigations by O'Rourke et al. [2] have shown that the coefficient of interface friction angle of cohesionless soil and polyethylene depends on the hardness of the used polyethylene material. The tendency for impregnation of soil on the pipe surface will increase with increasing softness of the pipe material, in turn, affecting the soil-pipe interface frictional behaviour. Equation 2 had been derived describing this dependence for different Shore-D hardness.

$$\delta / \varphi' = -0.0088 * H_D + 1.15 \qquad (2)$$

Where δ = interface angle of friction between soil and pipeline, φ' is the internal friction angle of the soil and HD is the Shore D hardness of the coating. Several tests have shown that the Shore-D hardness of the coating of DH-pipes usually ranges between HD=58-62 [9]. This leads to δ/φ = 0.64 – 0.60 according to O'Rourke et al [2]. Since μ is usually set equal to *tan* δ, the value μ would range from 0.41 to 0.38 for a sand with φ'=35°. The coefficient of friction μ can be applied to compute the soil-pipe friction force (F_R) using the formula given in Equation 3.

$$F_R = \mu * D * \pi * \sigma_{avg} \qquad (3)$$

Where F_R=friction force, μ=coefficient of friction between pipe and soil backfill, D=pipe diameter; σ_{avg}=average contact pressure.

It should be noted, that the pipe coating and the interface is heated up to approximately 40° C during the operation of a conventional district heating pipe. The influence of temperature on the behaviour of the interface is not well understood at present.

EFFECT OF SOIL DILATANCY

As mentioned earlier, there is potential for significant pipe-soil interaction due to the movement of DH pipes in the ground due to thermal expansion. The friction forces acting on the pipes during movements are most relevant for the straight pipe sections. Another well-known phenomenon at the initiation of axial pipe movement is the increase of soil contact pressures on the pipe due to shear-induced dilation of soil. This increase in soil contact pressures during axial movements has been observed by many researchers for a wide range of cases involving buried structural components such as pipes, piles, anchors, etc. For pipelines, the effect is schematically shown in Fig. 1.

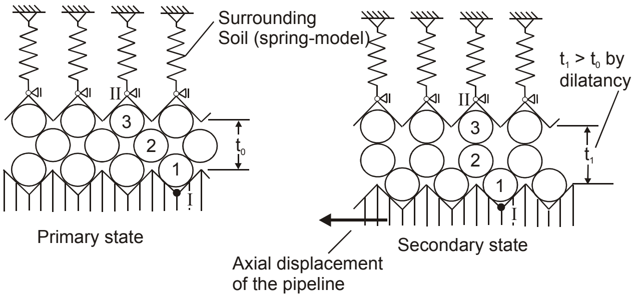

Fig. 1 Schematic expression of the soil dilation effect on pipelines [9]

This effect of soil dilatancy has also been noted by Wijewickreme et al. [3] during their research involving steel pipes. In full-scale testing of steel pipes (D=460 mm, H/D=2.5) having lengths of 3.8 m and 5.0 m embedded in a chamber with dense sand , significant increase of the contact pressure was observed during axial pull out.

The test results from Wijewickreme et al. [3], as reproduced in Figure 2, show that soil loads observed during axial pullout are significantly higher than those computed based on the expected contact pressure under at-rest soil conditions. As may be noted from Figure 2, steel pipe buried in sand backfill that was allowed to rest (or age) for a certain period displayed even larger axial pullout loads. This effect of ageing is addressed in a separate section below. In an overall sense, it appears that the axial pullout soil loads increased by a factor having a bandwidth of 1.75 to 2.5 due to the effect of soil dilation at the soil-pipe interface. Based on this, the authors believe that it is reasonable to expect similar effects for the polyethylene-sand interfaces encountered in buried DH pipelines.

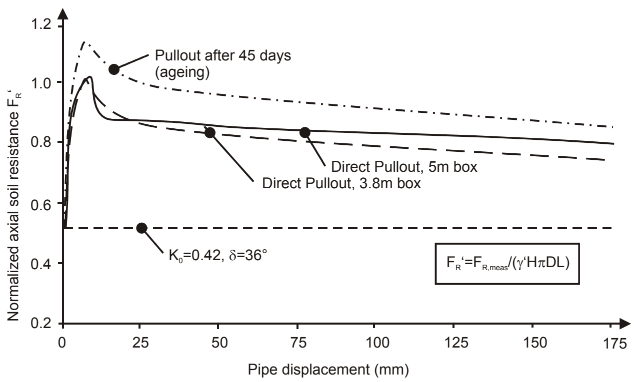

Fig. 2 Force – displacement curves during axial pullout testing demonstrating the effect of soil dilation on steel pipe – sand interaction [3]

LOADS ON PIPES DURING RELATIVE LATERAL SOIL DISPLACEMENT

It is also important to note that bow and U-sections of DH-pipes also interact laterally with the surrounding soil during normal operating conditions. This interaction could also affect the contact soil pressures on the pipes during lateral displacements. For example, the lateral movement at a bow would decrease axial stresses in the straight product pipe sections and increase bending moments in the bows. Some movement is generally wanted during normal operations, and this can be accommodated by installing safety cushions made of polyethylene foam around the pipes. This general approach used for bow and U-sections is schematically shown in Figure 3.

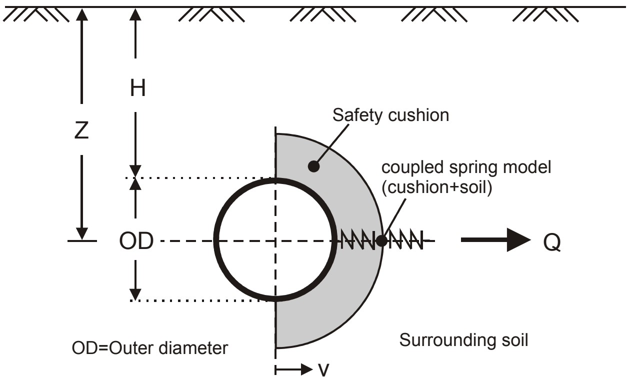

Fig. 3 Schematic cross-view of a embedded pipe with a lateral safety cushion

The soil normal stresses during initial lateral soil movement (bedding pressure) can be calculated according to Audibert and Nyman and others [12, 11]. For standardization, a three spring model was derived according to EN13941 [13]. The behaviour of safety cushions is discussed in a paper published by Wolf et al. [14]. The amount of bedding pressure will impact the expected friction forces. The coupling of the material behaviour for the soil and the safety cushion and the resulting friction forces are shown in Figure 4.

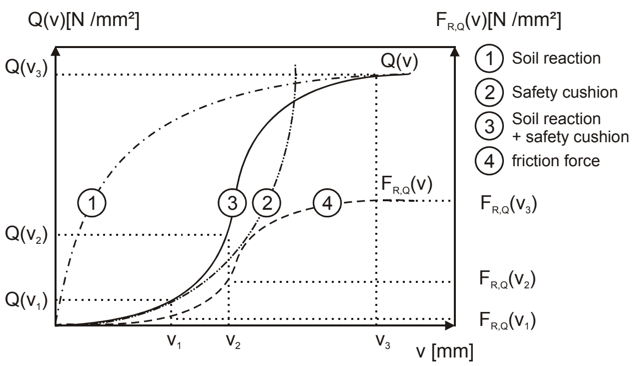

Fig. 4 Coupling of bedding pressure and friction force.

It has to be noted that a gap might occur between the pipe and the soil during pipe displacement. This would reduce the contact pressure on the trailing side. However, it is considered that neglecting the gap formation and simply adding the friction force from lateral displacements to the friction force in the initial state would lead to a safe analysis. This dependency only applies for the bow and U-sections and is not present for the whole pipe system.

RADIAL EXPANSION OF DH PIPES DUE TO THERMAL LOADING

Different investigations have shown that the friction forces on district heating pipelines are not constant, but considerably dependent on the operating temperature. One reason for this is the increase of radial stresses σ_r, due to the temperature-induced increase in the pipe diameter. Achmus calculated 1995 the soil reaction stresses due to the radial expansion of a cylindrical cavity (pipe) by numerical investigations with the finite element method [16]. Typical parameter combinations for sand with different relative densities were used in the calculations. The experimentally established friction force increase with increasing operating temperature was confirmed by the numerical model. As a measure of temperature dependence, the factor κ_l, was defined as follows:

$$\kappa_l = \frac{\sigma_{r,avg}(\Delta T = 100K)}{\sigma_{r,avg}^{(0)}} = \frac{F_{r,u}(\Delta T = 100K)}{F_{r,u}^{(0)}} \qquad (4)$$

where: κ_l = factor for the relationship between initial stress state and subsequent stress state, $\sigma_{r,avg}$ = average contact pressure on the pipe perimeter, $F_{r,u}$ = ultimate friction force, ΔT = temperature increment.

The above investigation led to the conclusion that the factor κ_l is almost independent of the nominal pipe diameter (DN), for the range of DN 100 to DN 500. However, the results indicated that this factor is significantly dependent on the relative density of the sand, and the overburden height h. Achmus derived equation 5 given below for the calculation of κ_l from the results (valid for ΔT=100K).

$$\kappa_l = 1.18 - 0.1 * h[m] + 1.22 * D_r \qquad (5)$$

where: κ_l = factor for the relationship between initial stress state and secondary stress state, h = depth of overburden to the top of the pipe, D_r = relative density of soil bedding.

EFFECT OF SOIL AGEING

Even when the DH pipes are not subject to movement, because of maintenance activities and/or other supply breaks, there is a possibility of certain time durations that would allow the soil bedding around DH pipes to experience “ageing”. This, in turn, could lead to time-dependency of soil contact pressures on the pipes. The second author, through his research work at the University of British Columbia, Canada, has observed increase in axial soil loads on pipes that have been kept still for significant durations [3]. For example, as shown in Figure 2, the axial pullout load was increased by about 10% in when the soil around the pipe was allowed to age for 45 days compared to those from pipe that were tested immediately after backfilling. While further studies are needed for firm determination, it appears that soil ageing has led to an increase of the contact pressures and/or an increase in the friction coefficient at the soil-pipe interface. This suggests that there is a potential need to account for ageing effects, leading to increased axial friction forces, for district heating pipes that are taken out of service for several days.

CYCLIC RESPONSE

When continuous cyclic thermal loading is present, it has been noted that the soil contact pressure could decrease due to stress redistribution in the surrounding soil due to cyclic axial movement of pipe. The reduction of contact pressure, in turn, leads to a reduction of friction, where this effect has also been shown to be significantly dependent on the overburden height and the relative density of the soil [8].

In present practice, the halving of the initial friction force is assumed for simulating the residual state upon cyclic loading. According to EN13941 [13], the recommended coefficient of friction (μ_0) for the initial movement of the pipes is 0.4. Considering long-term effects (arching-effect), the recommended residual (μ_{res}) coefficient of friction is a value between 0 and 0.2. For example, the low values should be used when designing for the cases of pipe expansion. For loadings with very high numbers of cycles, no further changes in the residual friction force are expected. But it must be noted, that changing μ is only an equivalent way of accounting for the cyclic loading effect. The surface of the pipe coating is hardly affected by the axial movement of the pipe. As shown by Weidlich in [9], the reduction of friction is caused by a changing contact pressure σ_r. For the sake of simplicity, the changing of μ is still used in the current calculation methods [13].

In the accounting of cyclic loading, a degradation factor D_F as given in Equation 6 can be defined according to Poulos [15].

$$D_F = \frac{F_{res}}{F_0} \tag{6}$$

Where D_F = degradation factor, F_{res} = residual friction force, F_0 = friction force for the case corresponding to initial movement

Using the ration μ_{res}/μ_0 with the figures given in EN13941 for the calculation of D_F this will lead to a bandwidth of D_F from 0 to 0.5. For dense cohesionless backfill and small pipe diameters (DN40 – DN80) Weidlich, based on experimental results, demonstrated that D_F can be estimated according to Eq. 7.

$$D_F = -0.0388 * \frac{H}{D} + 0.73 \tag{7}$$

To account for the first ten cycles, Equ.8 was derived by Weidlich from experimental and numerical results. After the first ten cycles, F_{res} is valid for all subsequent residual stress states.

$$F(N) = \frac{F_0 * (1 - D_F)}{100} * N^2 + \frac{F_0 * (D_F - 1)}{5} * N + F_0 \tag{8}$$

Where F(N) = friction force for cycle N; F_0 = initial friction force; D_F = degradation factor; and N=number of cycles.

Unlike for axial loads, the effect cyclic lateral loading on soil-pipe interaction is currently not well understood. The calculations of lateral bedding pressures on pipelines are presently based only considering data laboratory tests with monotonic loading [12,11]. As such, cyclic lateral soil response effects are not explicitly accounted in the current standards for district heating pipes.

CONCLUSIONS

This paper identifies several approaches that have been developed to account different key factors influencing the soil friction forces on buried pipes for district heating. In spite of the findings from numerous research investigations carried out over the last century, the effects of some of these factors are rarely known and not well accounted in current calculation procedures adopted in engineering practice. In particular, there is an opportunity to extract from important results that have been obtained in the last decade, in developing current design procedures of district heating pipelines. For example, consideration should be given to applying and integrating the new equations and findings, as those presented in this paper, in the existing design procedures.

It is also of interest to note that almost all investigations with respect to soil-pipe interaction seem to have focused mainly on pipes buried in cohesionless soil. In practice, due to convenience and economic reasons, trench spoil is often reused for the backfill; as such, soils with significant fine-grained fraction end up in becoming the backfill that would interact with the pipe coating. However, at present, there is no well-established calculation method for the determination of the contact pressure on pipelines in fine-grained soils under undrained loading.

The temperature-dependent interface behavior for polyethylene-sand interfaces is another factor that is not well understood and require further investigation.

In essence, additional research work on a number of fronts is needed to obtain a better picture of the friction between buried district heating pipes and surrounding soil taking into account real operating conditions and modern pipe laying technologies.

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ON THE RADIAL CONTACT PRESSURE OF PIGGY-BACK LAID BURIED PIPES FOR DISTRICT HEATING

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ABSTRACT

For expansion of district heating networks the focus for construction today is economic pipe laying. Cost reduction potential is still seen in earth works. Accurate and safe design must be coupled with economic, flexible and innovative pipe laying methodologies. Putting supply pipe and return pipe vertically on top of each other in one trench is a promising pipe laying technology that can lead to a cost reduction. However, only a few investigations are available for the design of district heating pipes in such type of trenches. This paper deals with the contact pressure acting on such "piggy-back" laid buried district heating pipes. The contact pressure from the overburden earth loads is an important parameter, since it affects the friction forces which may be mobilized. It is generally expected that interaction between the pipes themselves and the trench walls increases with a decrease of the distance between the pipes and the trench width, respectively. The present investigation compares radial stresses according to current design directives for buried single pipes with numerically calculated stresses for buried pipes laid side by side and on top of each other.

INTRODUCTION

Today's ambitious targets of the European Union for energy efficiency, CO_2-reduction and share of renewable energy resources are an economical and technical challenge. One way for efficient energy consumption is the use of chp-generated power and heat mixed with available renewable and recycled sources. The delivery of efficient renewable heat to the consumer requires a powerful infrastructure, that connects consumer to source. Wide district heating networks are one key measure to achieve this goal. The potential for the expansion of these networks is great in several European countries as for instance in Germany. However, the construction of big heating grids is cost intensive and one of the highest cost-reduction potential lies in the earth works.

In trenches for district heating a supply pipe and a return pipe is being installed. Because of the necessary work space in trenches between the trench walls and the pipes the trench's cross sectional area may be shrunk considerably by putting one pipe at the top of the other one (Piggy-Back pipe laying). Realizing narrow trenches means a reduction in trench spoil, reduction in emissions for transport, reduction of deposit costs and a smaller impact to the environment.

DESCRIPTION OF THE SYSTEM

The so called Piggy-Back pipe laying method requires a slightly deeper trench, but the trench width can be significantly smaller than for the side by side laying. It can be applied for all pipe diameters. Today Piggy-Back systems are known for nominal pipe diameters up to DN400. In urban areas in Central Europe trenches are constructed with vertical walls. Northern European trenches are usually built with sloped walls. Vertical walls are necessary due to heavy traffic or limited space next to the trenches. In Germany strutting is necessary for trenches with vertical walls that are deeper than 1.25m below surface [1]. Piggy-Back trenches with a depth of 1.25m or less can only be realized for DN150 pipes and smaller pipes.

Fig. 1 shows the standard side by side laying technology in comparison with the Piggy-Back laying technology.

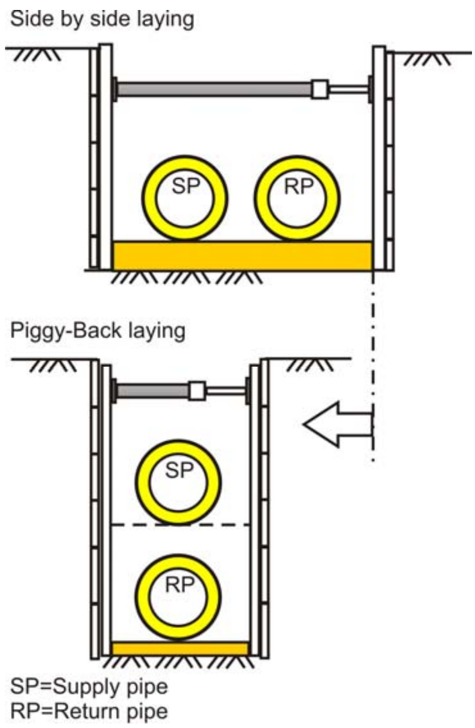


Fig. 1. Comparison between standard side by side pipe laying and Piggy-Back laying technology.

There is no rule of thumb, whether the return or the supply pipe should be put on top. This question has to be answered dependent on the particular situation. It may be advantageous to put one or the other on top. If the pipe is prewarmed the supply pipe should be put on top, since the top pipe is easier to reach than the bottom one. For cold installation economical reasons suggest an arrangement where the supply pipe is the bottom one. The pipe has then a higher coverage, which might increase friction and reduce the necessary efforts for compensation.

Obeying the experience that leakage usually occurs at the supply pipe, it is advantageous to put the supply pipe on top, since repair works are then easier. Considering network operation, other suggestions arise. The pipe is less prone to buckling under compression when it's deeper laid into the soil. Furthermore heat losses are reduced when the warmer supply pipe is put deeper into the ground.

Carefully balancing the above mentioned arguments must be the base for the decision which pipe to be put on top. However, Piggy-Back laid pipelines provide also a higher degree of flexibility, for instance to route around buried obstacles. The change from standard side by side laying to Piggy-Back laying is shown in Fig. 2. Obviously Piggy-Back laying can also be applied only for a limited section of the network.

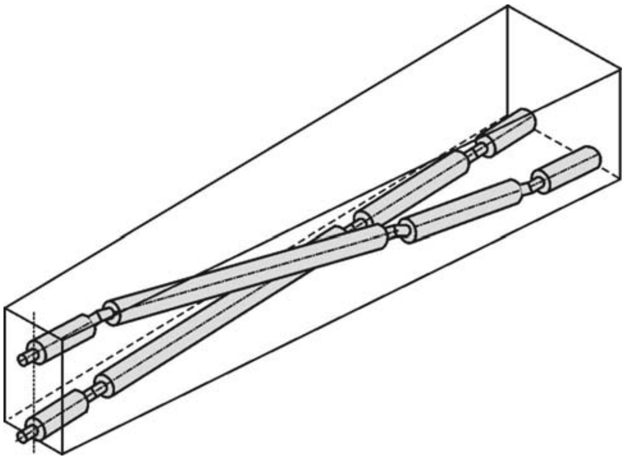


Fig. 2. Change from side by side to Piggy-Back.

PIPE DESIGN

Vertically installed pipes can be designed independently of each other according to [2]. It is usually assumed that the bottom pipe experiences higher friction forces because of higher coverage, which would reduce the displacements occurring at the open pipe ends.

Anyway, the acting friction forces are linked to the temperature loads and the earth pressure on the pipe after installation and during operation. The axial deflections of the pipe and the distribution of normal stresses, which are induced by the temperature loading of the pipe, are determined by the friction. The friction on the pipe coating is calculated for single pipe trench conditions by multiplying the normal contact pressure with the coefficient of friction. The normal contact pressure is dependent on the overburden weight of the soil, the diameter, the pipe weight and an earth pressure coefficient [1].

Since an interaction between the supply pipe and the return pipe was observed for the side by side laying technology [3], an interaction for Piggy-Back laid district heating pipelines must be assumed to be also very likely. Nevertheless, today there are no investigations available that proof an independency of the two pipes for vertical Piggy-Back pipe laying.

NUMERICAL INVESTIGATIONS

Numerical calculations were carried out with two dimensional finite element models. The program PLAXIS version 8.6 was used for the calculation. Two standard situations with different outer pipe diameters D (DN65, D=140 mm; DN250, D= 400 mm) of vertically buried district heating pipes were investigated. The distance between the pipes was chosen to be A=20 cm (see Fig. 1), which is marginally greater than the today's recommended minimum distance of 0.15 m. The overburden height of the backfill material of the trench was H=0.5m for both diameters. The finite element mesh used for the DN250 pipe is shown in Fig. 3 as an example. The trench width was set to 2,0m as maximum dimension (DN250, 60cm distance & 30cm on each side). All models and variations were calculated with the same trench width in order to exclude influences on the results by varying geometry making it difficult to interpret the results. The trench walls were modeled as ideally rigid with a friction angle of $\delta = 2/3\varphi'$ as for standard trench walls.

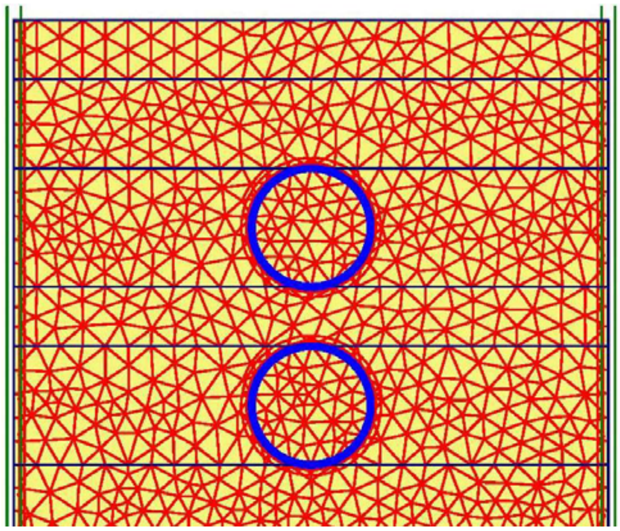


Fig. 3. Finite element mesh for the case DN250, H=0.5m (to the top of the upper pipe).

The installation process was simulated by a "staged construction" process, considering a retained trench and the backfilling procedure with several layers. The compaction process was accounted for by loading and unloading with a static distributed load of p=10 kN/m² on each of the layers. Ground water was not considered in this investigation.

Sand in a medium dense to dense state was assumed as backfill material. The mechanical behavior of the soil was modeled with the HARDENING-SOIL constitutive law. This material model considers realistic non-linear elasto-plastic material behavior and also an elastic unloading and reloading stiffness modulus in order to better simulate the resulting deformation in the respective construction stages. The parameters used for the model are shown in Table I.

Table I. – Soil parameters used for sand in the HARDENING-SOIL material model.

Definition and Unit	Value
Unit weight γ [kN/m³]	19
Oedometric Elasticity Modulus E_{oed} [MPa]	30
Elastic Modulus E_{50} [MPa]	30
Parameter m	0.0
Un- and Reloading Modulus $E_{oed,ur}$ [MPa]	90
Poisson's ratio ν	0.3
Internal angle of friction φ' [°]	37.5
Angle of dilatancy ψ [°]	7.5
Interface friction R_{inter} [1]	0.536
Equivalent μ-factor (tan δ_i)	0.41

Between pipe and soil, the COULOMB friction law with a soil dependent interface friction angle δ_i was established. The interface friction angle δ_i is defined according to Eq. (1).

$$\tan\delta_i = R_{\text{inter}} * \tan\varphi' \quad (1)$$

In order to keep the model as simple as possible the pipes were assumed to be rigid. The weight of the pipe was calculated for DH-pipes filled with water according to FW401 [4]. The used values are shown in Table II.

Table II. – Weight of water-filled pipes.

Pipe	Pipe weight [kN/m]
DN65	0.10
DN250	2.04

In a first simulation the radial contact stresses were calculated for a single pipe with overburden heights of 50 and 100 cm. Once the soil and the initial stresses were generated first and the pipe was then considered by a "wished-in-place" procedure, i.e. the installation process was not taken into account, and once the layer-wise installation of the soil backfill was simulated. Disregarding the installation process, the results for both diameters were accurately matching with the regulation from the EN 13941 [5] where the average radial pressure on a single buried pipe can be derived for the investigated trench condition according to Eq. (2).

$$\sigma_{r,avg,13941} = \gamma * \left(H + \frac{D}{2}\right) * \left(\frac{1+k}{2}\right) \quad (2)$$

The simulation of the installation process led to an increase in the average radial pressure depending on the overburden depth. The results of both simulations are compared in Table III. The overall increase in percent is at about 8% to 10% at 50cm depth and 18% to 20% in 100cm depth.
As the installation process is obviously affecting the average radial contact pressure, this has to be taken into account when considering the interaction of two buried pipes at small distances.

Table III. – Average contact pressure $\sigma_{r,avg}$ under consideration of the installation process in layers.

DN	Depth	Single pipe according to DIN EN 13941	Single pipe according to numerical simulation with layers (Diff. in %)
65	50 cm	7.53 kN/m²	8.10 kN/m² (7.5%)
65	100cm	14.14 kN/m²	17.00 kN/m² (20.2%)
250	50 cm	9.15 kN/m²	10.18 kN/m² (10.1%)
250	100cm	15.86 kN/m²	18.84 kN/m² (18.8%)

Fig. 4 shows the distribution of radial stresses for the case in which the construction sequence was taken into account. The stress distribution around the pipe shows slight variation from the expected ideal "egg-shaped" form owing to the stress redistribution by layer-wise construction from the loading/unloading process. The effect decreases with greater depth due to higher overburden pressure.

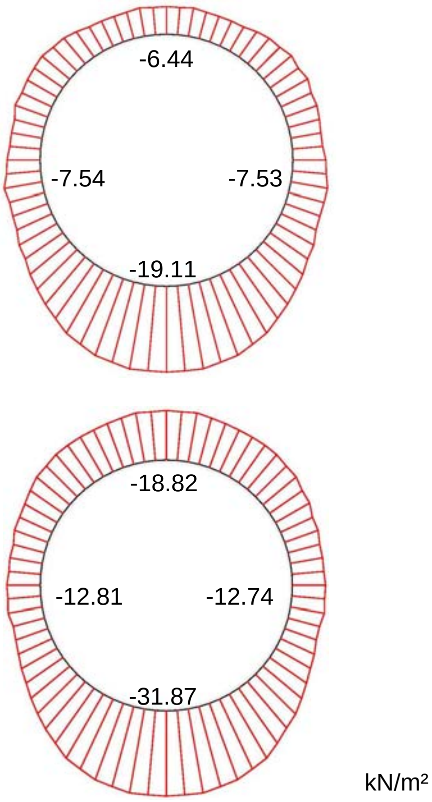


Fig. 4. Contact pressure distribution for a single pipe with DN250, H=0.5m (top) and H=1.0m (bottom).

In a next step the mutual influence of two adjacent pipes of the same diameter laid side by side was analyzed. As with the single pipe, the depths were set to 50cm and 100cm, respectively, for both diameters. The distance between the pipes was varied between 20cm and 60cm. The results showed almost no difference in the resulting average radial stress $\sigma_{r,avg}$ (Table IV).

Table IV. – Comparison of average contact pressure $\sigma_{r,avg}$ between single pipe and side by side under consideration of the installation process in layers.

Pipe distance 20 cm			
DN	Depth	Single pipe acc. to numerical simulation with layers	Side by Side buried pipe according to numerical results (Diff. in %)
65	50cm	8.10 kN/m²	8.16 kN/m² (0.74%)
65	100cm	17.00 kN/m²	17.03 kN/m² (0.02%)
250	50cm	10.18 kN/m²	10.51 kN/m² (3.24%)
250	100cm	18.84 kN/m²	18.97 kN/m² (0.07%)

Pipe distance 60 cm			
DN	Depth	Single pipe acc. to numerical simulation with layers	Side by Side buried pipe according to numerical results (Diff. in %)
65	50cm	8.10 kN/m²	8.19 kN/m² (1.11%)
65	100cm	17.00 kN/m²	17.07 kN/m² (0.41%)
250	50cm	10.18 kN/m²	10.48 kN/m² (2.95%)
250	100cm	18.84 kN/m²	18.85 kN/m² (0.00%)

Only for 50cm overburden depth the DN250 pipe shows a little increase of calculated stress by about 3%. This leads to a slight difference in the resulting normal stress distribution around the pipe.
As the effect is noticeable only for greater diameters and small overburden heights (regardless of distance between the pipes) the increase might be caused by the compaction process simulated in layers and loading/unloading steps.

Despite of the close distance of only half the diameter there hardly occurs any relevant shear stress between the two pipes. The major areas of shear stress reside on the upper left and right of each pipe as a result of the simulated compacting process as shown in Fig. 5.

In the final step, the stress conditions of the two pipes laid side by side were compared with the situation with the Piggy-Back laying technology. Both diameters, the DN65 and DN250, were calculated with variable vertical distances of 20cm and 60cm. The upper pipe was installed with an overburden height of 50cm.

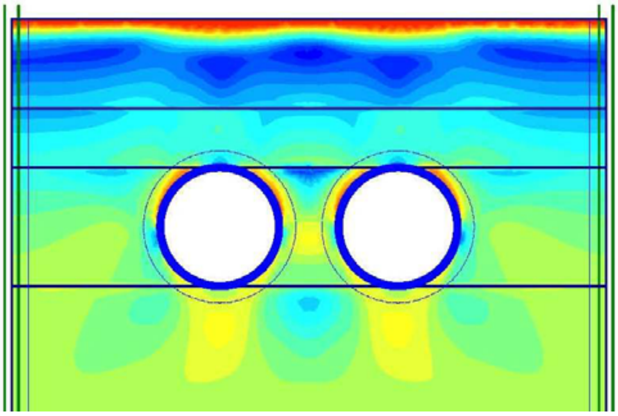
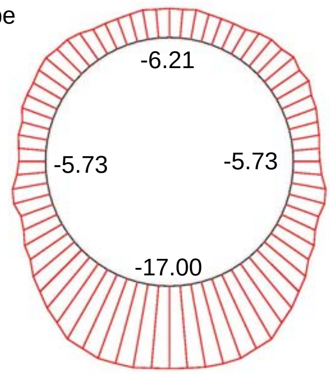


Fig. 5. Relative Shear Stress on two pipes DN250 laid side by side in 0.2m distance, H=0.5m.

An exemplary result for the radial stress distribution on the pipes is shown in Fig. 6. The upper pipe has an overburden height of 50cm and the lower pipe of 110cm, the vertical distance is 20cm. For the upper pipe, the average radial contact pressure is 9.49 kN/m^2, which is about 2.6% greater than the respective value for a single pipe with H=0.5m according to DIN EN 13941 (see Table III). For the lower pipe, the average contact pressure is 20.26 kN/m^2, which is considerably greater (17.9%) than the DIN EN 13941 value.

The results of all performed calculations are collected in Table V. Evidently, with the Piggy-Back situation the average radial stress $\sigma_{r,avg}$ on the upper pipe nearly matches the analytic assumption (Δ = 3%) from the EN 13941 for shallow depths of 50cm regardless of the diameter of the pipe when the vertical distance is 20cm. For a greater vertical distance of 60cm between the pipes the difference increases slightly (Δ = 6%). The average radial stress on the lower pipe, however, shows nearly the same average radial stress as calculated for the single pipe in the respective depth.



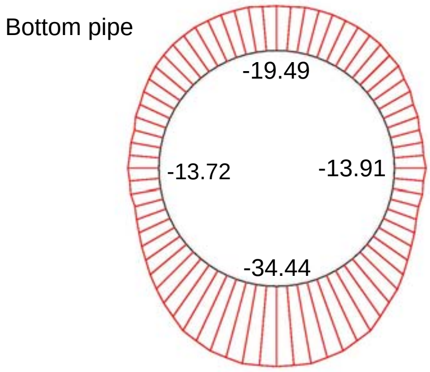


Fig. 6. Contact pressure on the DN250 pipes, H=0.5m, vertical distance 0.2m.

Table V. – Average contact pressure $\sigma_{r,avg}$.

DN	Depth	Single pipe according to DIN EN 13941	Piggy-Back buried pipe according to numerical results (Diff. in %)
H=0.5m, vertical distance 20cm			
65	50cm	*7.53 kN/m²*	7.74 kN/m² (2,7%)
65	84cm	12.03 kN/m²	13.76 kN/m² (14,4%)
H=0.5m, vertical distance 60cm			
65	50cm	*7.53 kN/m²*	8.02 kN/m² (6,4%)
65	124cm	17.31 kN/m²	21.15 kN/m² (22,2%)
H=1.0m, vertical distance 20cm			
65	100cm	14.14 kN/m²	16.50 kN/m² (16,7%)
65	134cm	18.64 kN/m²	22.45 kN/m² (20,5%)
H=0.5m, vertical distance 20cm			
250	50cm	9.15 kN/m²	9.49 kN/m² (2,6%)
250	110cm	17.18 kN/m²	20.26 kN/m² (17,9%)
H=0.5m, vertical distance 60cm			
250	50cm	9.15 kN/m²	9.83 kN/m² (6,2%)
250	150cm	22.47 kN/m²	27.30 kN/m² (21,5%)
H=1.0m, vertical distance 20cm			
250	100cm	15.86 kN/m²	18.04 kN/m² (13,7%)
250	160cm	23.79 kN/m²	29.29 kN/m² (23,1%)

The reason for the observed differences is obviously the interaction between the two pipes taking place when the pipes are located on top of each other. As shown in Fig. 7, the influence from the relative shear stress between the pipes of same distance and diameter is greater when installed on top of each other instead of laid side by side (see Fig. 5).

Regarding the average radial contact pressure the difference between the expected values from the DIN EN 13941 regulation for single pipes and the calculated values from the numerical simulations is generally rather small for the upper pipe (especially for the upper pipe and small overburden heights). The lower pipe shows an increased radial stress of about 14% to 23% mainly due to increasing overburden height.

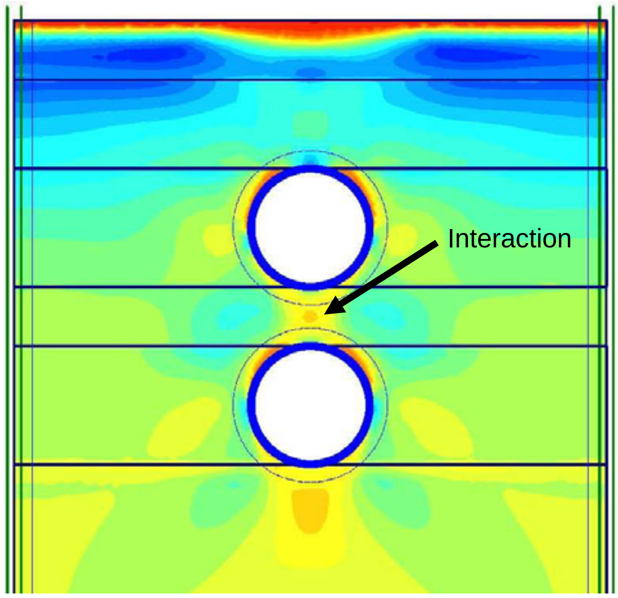


Fig. 7. Relative Shear Stress on two pipes DN250, H=0.5m and 0.2m distance, laid Piggy-Back.

CONCLUSIONS

For accurate design of district heating pipes the earth loads are one important input parameter for the calculation. The contact pressure acting on the pipe coating and the related friction forces have to be assessed as accurate as possible. The presented investigation gives a first starting point to understand the distribution of soil stresses in trenches with district heating pipes installed on top of each other.
The so called Piggy-Back pipe laying technology provides several advantages. Flexible routing around obstacles is one of them. The most relevant advantage seems to be narrow trenching and the related cost saving potential.

By numerical modeling, the average radial stresses for side by side and piggy-back laying technology were compared with the results from the current EN 13941 analytical approach. It is shown that the simulation of the construction process, i.e. layer-wise installation of the soil, affects the radial stresses. With the modeling procedure used here 8 to 20% greater radial stresses than from the analytical approach were obtained. The deviation becomes the greater, the greater the overburden depth is.
For the side by side laying technology, almost the same average radial stresses as for a single pipe were determined, even if a small distance between the pipes of 20cm was chosen.
For the piggy-back laid pipes, slightly smaller stresses or friction forces, respectively, than for side by side laying were obtained. However, the values were still greater than the results from the analytical approach of EN 13941. The upper pipe generally shows almost the same average radial stress as expected from DIN EN 13941, while the lower pipe shows increased average

stresses comparable to the results for the side by side laying technology.
For the investigated systems the general deviations regarding the average normal pressure between single pipe and vertically installed pipes were found to be rather small. Thus, as long as the exact distribution of stresses along the pipe perimeter is not of particular relevance, current calculation directives seem to be also suitable for the Piggy-Back laying technology. Nevertheless, for conditions with large pipe diameters and small distances between the pipes and also relatively large overburden heights a significant deviation is to be expected.

More research and in particular measurements are necessary to confirm these results. It should be noted that a purely numerical consideration seems not sufficient for a final assessment, since compaction processes and the related interaction behavior are difficult to simulate. In this investigation, a loading and unloading sequence with a surcharge load was chosen to simulate compaction. Measurements are needed to validate this procedure.

Inhomogeneous backfill compaction, which is probable in narrow trenches under in situ conditions, also affects the contact pressure. This is the reason why Piggy-Back pipe laying technology is often propagated in combination with liquid backfilling, where the installation of the backfill is done with fluid soil-binding constituents mixtures [6]. However, several degrees of freedom are added to the system by using this combination, as for instance the recipe of the components and time-dependent hardening.

In the end the balancing of the advantages and disadvantages also during operation and for maintenance of the Piggy-Back pipe laying technology will guide the decision for or against it.

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USING HIGH PERFORMANCE INSULATION IN DISTRICT HEATING PIPES

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Keywords: high performance insulation, aerogel, vacuum, district heating, heat losses

ABSTRACT
It is necessary to improve the distribution of district heating for the future in order to maintain its competitiveness. In recent decades a number of high performance insulation materials have been developed. This paper presents an investigation of high performance insulation materials in district heating pipes. Three different paths were chosen as the most promising; mixing aerogel granulates in polyurethane foam, hybrid insulation with layers of aerogel blankets within the polyurethane, or hybrid insulation with vacuum insulation panels.

The thermal conductivity of aerogel have been measured to as low as 13 mW/(m·K) and the thermal conductivity through the center of a vacuum insulation panel can be as low as 4 mW/(m·K). These can be compared to polyurethane which has a thermal conductivity around 25-26 mW/(m·K).

Prototypes of district heating pipes were produced in laboratory and the thermal conductivity of the pipes was investigated. The effective thermal conductivity of the hybrid insulation of the district heating pipes by aerogel blankets or vacuum insulation panels were 15-20% less than pipes insulated with pure polyurethane.

The high performance insulation materials are still expensive. However, the result of a simple payoff time analysis indicates that the vacuum insulation panels already might be economically beneficial the tested dimension of district heating pipes.

INTRODUCTION
Today, the society strives toward a decrease in the energy consumption. New buildings are designed for smaller power need and old buildings are retrofitted to decrease the energy losses. For district heating systems this means a change toward lower energy output from the pipes. That will lead to smaller flows and thus larger transport losses from the pipes. This gives an incentive to enhance the insulating properties of the district heating pipes. More polyurethane (PU) could be added around the pipes but larger dimensions would yield higher costs for digging and transport. For cylindrical geometries there is also an effect where the influence of the insulation decreases with the increasing radius.

At the same time, the material research has moved forward and there are new materials on the market with considerably lower conductivity than polyurethane. This work has been focused on two of these materials; aerogels and vacuum insulation panels (VIP). The materials have been tested for their compatibility with polyurethane and their thermal conductivity has been measured.

Aerogels
The first aerogels were developed by Kistler already in the thirties [1]. His hypothesis was that the shrinkage in dried gels was created by the tension from the water evaporation. To test the idea Kistler dried gels at temperatures and pressures above the critical point of their liquid phase. Above the critical point there is no transition between gas and liquid and the gas could be exchanged for air without any tension. This leads to a definition of aerogels as former gels that have been dried under such conditions so that the gel structure is preserved. Aerogels could be made from a variety of compounds but the most common aerogels are based on silica, why these are the focus of this study.

Although the aerogels have been around since the thirties, they are still quite expensive, which has delayed its usage in building applications. That is why it can be considered as a new material for building applications.

Silica aerogels are highly porous materials with a porosity which could be above 95% with small pores with a mean diameter around 10 nm [2]. The pores are smaller than the average path that the gas molecules in air travels before it collides with another molecule, called the mean free path of the gas. This makes the pore walls hinder the gas molecules from colliding with each other. The collisions between gas and pore walls are elastic and do not transfer as much energy as gas to gas collisions and thus, the heat transfer is decreased to levels below that of the gas itself. This effect is called the Knudsen effect. The thermal conductivity has been measured as low as 13 mW/(m·K) for opacified aerogels [3] and as low as 17 mW/(m·K) for transparent aerogel [4].

Silica aergels can be produced in various forms; as monolithic blocks, ground aerogel granulates or in reinforced composites. In this study we have looked at silica aerogel granulates shown in Figure 1 and fibre reinforced aerogel blankets shown in Figure 2.

Figure 1. The figure shows transparent silica aerogel granulates. (Photo: Axel Berge)

Figure 2. The figure shows a fiber reinforced aerogel blanket. (Photo: Axel Berge)

Vacuum insulation panels

Vacuum insulation panels (VIP) are built up of a core material in a protection envelope, enclosed by a thin diffusion tight metalized laminate, as seen in Figure 3. The properties of the panel depend on both the properties of the core material and of the diffusion tight laminate.

The core material governs the relationship between the pressure in the panel and the thermal conductivity. The relation between pressure and thermal conductivity is mainly dependent on the pore size. For smaller pores the thermal conductivity start to decrease at higher pressures, due to the Knudsen. The relation between air pressure and pore size can be seen in Figure 4 [5]. For this reason the commonly used core material is fumed silica with a mean pore size around 10-100 nm.

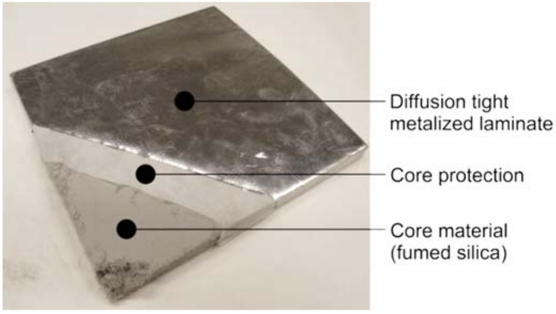

Figure 3. An opened vacuum panel showing the three different layers. (Photo: Axel Berge)

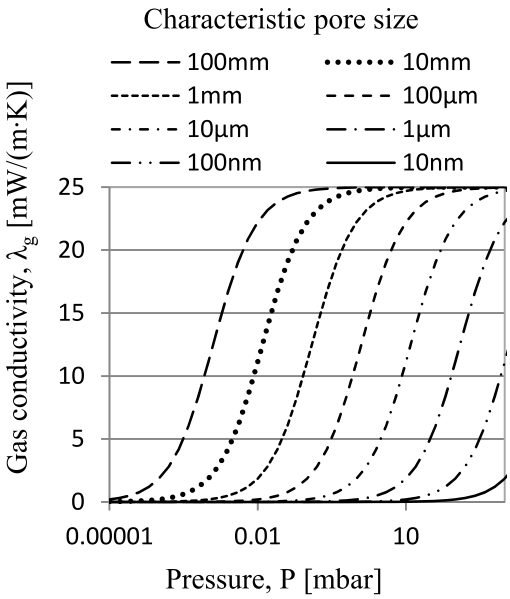

Figure 4. Relation between thermal conductivity through air and pore size [5].

A newly produced vacuum panel has commonly around 1-3 mbar internal pressure. At that pressure, the thermal conductivity of fumed silica was measured at various pressures by Simmler et al [6]. At 1 mbar the thermal conductivity reached down to around 5-6 mW/(m·K). When the pressure increases the thermal conductivity rise to 8-9 mW/(m·K) at 100 mbar and 20-21 mW/(m·K) at 1000 mbar, corresponding to atmospheric pressure.

The diffusion tight laminate enclosing the core material is commonly made of alternate layers of some polymer and aluminum. This leads to two conflicting interests. More and thicker aluminum layers will decrease the diffusion rate and thus increase the lifespan of the panels, but at the same time, the aluminum creates a thermal bridge along the edges of the panel which willll be effected by the thickness of the aluminum.

MEASUREMENT METHODS

The thermal conductivity has been tested with three different measurement methods, dependent on the type of samples. Small homogenous samples have been tested with transient plane heat source (TPS) when no larger samples have been available, material slabs have been tested with guarded heat flow meter and complete pipes have been tested with guarded hot pipe.

Measurements by TPS are covered in the standard ISO 22007-2. For measurements on low conductive materials, the influence from losses in the system increases. This creates an increased uncertainty in the results. In this work, all measurements have been done on low conductive materials why these effects have to be considered. For this reason relative measurements have been used instead of absolute measurements. The losses will influence all measurements in the same way and the samples can be ranked compared to each other.

Guarded heat flow meter is a method to measure the thermal conductivity of slabs of material. The measurements were done according to EN 12667:2001. The slab size was 300x300 mm.

Measurements with guarded hot pipe have been performed according to the standard SS-EN 253:2009. The standard is for homogenous pipes with polyurethane insulation and the output is a mean thermal conductivity of the insulating material. The set-up from the standard has been used in this work to measure the mean thermal conductivity of composite pipes with insulation layers of various materials.

The effective conductivity of each layer has been calculated using the equation for heat flow in radial geometries, shown in (1). Input data for the thermal conductivity of polyurethane was obtained from standard measurements of a reference pipe produced at the same time.

$$\frac{\ln\left(\frac{r_2}{r_0}\right)}{\lambda_{tot}} = \frac{\ln\left(\frac{r_1}{r_0}\right)}{\lambda_1} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{\lambda_2} \tag{1}$$

where r_0, r_1 and r_2 (m) are the steel pipes outer radius, the first insulation layers outer radius and the second insulation layers outer radius respectively, λ_{tot} (W/(m·K)) is the mean thermal conductivity from guarded hot pipe measurements and λ_1 and λ_2 (W/(m·K)) are the effective thermal conductivity of the first and the second insulation layers respectively.

RESULTS

Three different concepts were tested; aerogel granulates mixed into polyurethane before foaming, hybrid pipes with aerogel blankets and polyurethane and hybrid pipes with vacuum insulation panels and polyurethane. The tests focused on the thermal conductance due to choice of concept. The output data from measurements was used in a payoff time analysis.

Aerogel granulates

The aerogel granulates were mixed with polyol, pentane and isocyanate to form a polyurethane foam with granulates of aerogel spread inside. Four samples were created with an aerogel amount around 7 % of the total weight. The samples were tested with some variation in the choice of additives.

After hardening the polyurethane was cut in parts and the thermal conductivity was measured by transient plane heat source. The results from the transient plane source measurements are shown in Table 1.

Table 1.Thermal conductivity for samples with aerogel granulates mixed into the polyurethane. The thermal conductivity is the mean value from measurements at various positions of the samples.

	Thermal conductivity [W/m/K]		
Sample[1]	2	3	4
Mean value	0.0268	0.0240	0.0252

[1] The thermal properties of sample 1 were not measured because of shrinkage of the sample.

In Table 1 it can be seen that the variation in thermal conductivity between the samples is quite small and the thermal conductivities do not differ from the thermal conductivity of the polyurethane without aerogel granulates. The measurements showed that the addition of small amounts of aerogel granulates did not improve the thermal performance of the polyurethane why they were put aside.

Aerogel blankets

The thermal conductivity of the aerogel blankets was tested in a guarded heat flow meter. To test the blankets compatibility with the polyurethane foam, we tested a combined slab of aerogel blanket and polyurethane. The combined slab is shown in Figure 5. The thermal conductivity was measured with the warm side at 30°C and the cold side at 10°C which gives a representation of the conductivity at 20°C and the results are shown in Table 1. The measurements gave a thermal conductivity around 17 mW/(m·K) for the aerogel blankets, which is similar to the results of Pietruszka et al [7].

Figure 5. Sample preparation of combined polyurethane/aerogel blanket samples for guarded heat flow meter measurements. (Photo: Axel Berge)

Table 2. Results for aerogel blankets from guarded heat flow meter measurements.

	Thermal conductivity [mW/m/K]
Aerogel blanket	17.2
Aerogel blanket	16.3
20 mm PU, 10 mm Aerogel	22[1]
20 mm PU, 10 mm Aerogel	21.5[1]

[1] The effective thermal conductivity for the specific combination of the two materials from the measurement standard.

The blankets attached well to the polyurethane foam and the thermal conductivity of the combined material correspond to a thermal conductivity of 25 mW/(m·K) for the handmade polyurethane at 20°C which seems reasonable.

The aerogel blankest were also tested as insulation inside district heating pipe. Measurements were made on 1 m long pipes with the dimension DN 80/140. Two 200mm wide pieces of 10 mm thick aerogel blankets were wrapped around the pipe at two positions as shown in Figure 6. During production, the blankets were attached around the pipe with tape but after foaming the polyurethane held the blanket on place.

The measurement with guarded hot pipe gives thermal conductivity. For composite pipes this is not a true thermal conductivity but an effective thermal conductivity describing the heat conduction through the insulation of a certain pipe rather than the actual material properties. A difference in effective thermal conductivity will give the same difference in the energy loss and can thus be used to compare composite pipes with pure polyurethane pipes.

Figure 6. Set-up of pipe with aerogel/polyurethane composite insulation. (Photo: Axel Berge)

The results from the guarded hot pipe measurements are shown in Table 3. The composite shows a decrease of 5-7% in effective conductivity compared to pure polyurethane pipe. If the heat loss is considered completely radial and the conductivity of the polyurethane is assumed to be 28 mW/(m·K), as in the reference measurement, the effective conductivity of the aerogel segments can be calculated. This would represent a pipe were blankets are wrapped around the whole pipe and not only segments. The results from the calculation are shown in Table 4 where it can be seen that the aerogel blankets might reduce the effective conductivity of the pipe insulation by 13-18 percent. ´

Table 3. Results from guarded hot pipe for aerogel composite pipes.

	Effective thermal conductivity [mW/m/K]	Difference from PU [%]
PU (reference)	28	0
PU + Aerogel blanket	26.5	-5 %
PU + Aerogel blanket	26	-7 %

Table 4. Calculated conductivities for aerogel segments of aerogel composite pipes.

	Effective thermal conductivity [mW/m/K]	Difference from PU [%]
PU	28	0
PU + Aerogel blanket	24.3	-13 %
PU + Aerogel blanket	23	-18 %

Vacuum insulation panels

Similar to the aerogel blankets, the vacuum insulation panels were mounted around the steel pipe before foaming. Two 473mm long and 5 mm thick panels were taped around the steel pipe as shown in

Figure 7. The dimension of the pipe was DN 100/225 and to avoid cutting the vacuum in the insulation panels, the pipe was cut to 1060 mm for testing. At the same occasion a reference pipe with pure polyurethane was produced for comparison. The polyurethane was created with the same recipe as for the polyurethane in the pipe with vacuum insulation.

The pipes were tested with guarded hot pipe and the results are presented in Table 5. The results show a 16 % decrease in the effective thermal conductivity with vacuum insulation panels. The effective thermal conductivity of the vacuum insulation was calculated with Equation (1) to 12 mW/(m·K). The effective thermal conductivity contains the extra losses from the thermal bridges along the edges of the panels and will thus vary with the size of the panels. In other words, for larger panels, the effect from the thermal bridges will decrease and the thus the effective thermal conductivity.

Figure 7. Set-up of pipe with VIP/polyurethane composite insulation. (Photo: Axel Berge)

Table 5. Results from guarded hot pipe measurements for vacuum insulation composite pipes.

	Effective thermal conductivity [mW/m/K]	Difference from PU [%]
PU (reference)	27.8	0
PU + VIP	23.5	-16 %

Economic estimation

Based on the measured results a simple economic calculation was performed for a DN 100/225 pipe. The heat losses from the pipes were calculated according to EN 13941:2009 with the input data from Table 6. The increase in the production cost for pipes with composites were estimated to 6 € per meter pipe and the energy cost was set to 0.03 €/kWh.

Table 6. Input data for heat loss calculations.

Media temp, supply pipe	85°C
Media temp, return pipe	55°C
Outside temp	5°C
Distance c/c	0.5 m
Covering Height	0.8 m
Thermal conductivity, Aerogel	17 mW/m/K
Effective thermal conductivity, VIP	12 mW/m/K
Thermal conductivity, PU	26 mW/m/K
Thermal conductivity, ground	1.5 W/m/K

The payoff time was calculated as how long it would take for the decrease in energy cost to pay for the extra cost for the pipes. The results from the heat loss calculations and the payoff time calculation are shown in **Error! Not a valid bookmark self-reference.**. For 10mm thick layers of aerogel blankets or vacuum insulation panels, the payoff time would be 30 and 12 years respectively. These estimates are quite rough but they give an indication of the possible use of the tested materials. It seems as if the vacuum insulation panels are the more promising alternative.

Table 7. Results from heat loss calculation and payoff time calculation.

DN 100/225		standard	10 mm aerogel	10 mm VIP
Heat losses	W/m/°C	30	26	23
	kWh/year	259	231	198
Savings	kWh/year		28	61
	%		11%	23%
Savings/year: 0.03 €/kWh	€/year/m		0.83	1.82
Increased mtrl cost	€/m		18.1	14.7
Increased Production cost	€/m		6	6
Pay off time	Year		29.0	11.4

CONCLUSIONS

The addition of small amounts of aerogel granulates in the polyurethane foam did not give any measurable effect. The measured thermal conductivity was the same as for polyurethane without aerogel granulates why no more tests were conducted.

The thermal conductivity of aerogel blankets were measured to 17 mW/(m·K) and the effective thermal conductivity of vacuum insulation panels were calculated to 12 mW/(m·K). Both materials showed good compatibility with the polyurethane when used as pipe insulation. The pipe with 10 mm aerogel blanket decreased the effective conductivity of the whole pipe with 13-18% and 5 mm vacuum insulation decreased the effective conductivity of the whole pipe with 16 %.

When the results were put into heat loss calculations, considering the surrounding ground and reasonable media temperatures, 10 mm of aerogel blanket gave a decreased heat loss of 11%, and 10 mm vacuum insulation panels gave a decrease in the heat loss of 23%. The decreased heat loss leads to a payoff time of 30 years for the aerogel pipes and 12 years for the vacuum insulation pipes. These results indicate that the vacuum panels are a more promising alternative for further testing.

DISCUSSION

The economic calculation shows favor toward the vacuum insulation but both the vacuum insulation and the aerogel blankets have some potential drawbacks that have to be investigated further to give a final verdict.

Aerogel

Pietruszka et al shows that the aerogel blankets are sensitive to water immersion. The aerogel is hydrophobic but if liquid water gets into the district heating pipe, the large heat gradient over the aerogel will create a large diffusive vapor flow. The water will condensate in the aerogel which can absorb a large amount of water and the thermal conductivity will probably be affected [7]. This problem exists for polyurethane as well but not to the same degree for vacuum insulation panels.

Another risk with aerogel is the gas exchange with the polyurethane. The pores in the aerogel are filled with air, so there will be a gas exchange between the air in the aerogel and the carbon dioxide and cyclopentane in the polyurethane. The heavy gasses from the polyurethane will not increase the performance of the aerogel since the gas conduction is diminished through the small pores, alhowever, the polyurethane will deteriorate.

Vacuum insulation

The low thermal conductivity of the vacuum insulation panels are based on a low internal pressure. With the high temperatures in district heating pipes, the diffusion rate through the laminate will increase compared to room temperatures. This leads to a concern for the aging of the panels which has to be tested in further experiments. It is also problematic to evaluate the actual pressure in pipes after installation.

ACKNOWLEDMENTS
The work presented in this paper has been funded by Fjärrvärmeföreningen through the project “Högpresterande fjärrvärmerör”.

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REDUCTION OF HEAT LOSS IN THE DISTRICT HEATING NETWORK BY THE REPLACEMENT OF PIPE INSULATION USING PREFABRICATED POLYURETHANE FOAM SHELLS

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Keywords: District heating, energy efficiency, insulation, foam shells.

ABSTRACT

District heating is the most common heat source in many Nordic countries. For old systems the main problem is high heat losses that are mostly caused by bad insulation and oversized pipe diameter. The objective of this paper is to evaluate the reduction of heat loss by replacing the old mineral wool insulation with the prefabricated polyurethane foam shells on the main pipeline. For the case study a 500m main DN1200 pipeline in Tallinn was used. Two experiments were carried out to compare the heat loss with old and new insulation. As a result, the heat loss in pipes with old insulation was over 3.5 times higher than in pipes with new one.

INTRODUCTION

Energy sources are getting more expensive and it is important to reduce the costs, related to the fuel consumption, by increasing the energy efficiency. Furthermore, the increase of energy efficiency will reduce emissions from burning fossil fuels.

The energy efficiency in a district heating (DH) network can be increased by its renovation. Rehabilitation of DH network is a complex task where many parameters should be taken into account. There are three ways to optimize a district heating system with reducing the heat loss:

The low investment scenario assumes reduction of supply temperature and increased water flow. This is possible only in case the network pipe dimensions are larger than required. In this case the pressure will grow, which means that the number of damaged pipes may increase.

The medium investment scenario assumes replacement of pipe insulation. The insulation can be replaced when the steel casing of pipes is in good condition; otherwise the pipe should be fully replaced. Selection of insulation thickness is a complex task where many parameters should be taken into account: material and work cost, thermal conductivity of new and old insulation, pipe diameter, ambient temperature, water temperature and so on.

The high investment scenario assumes reconstruction of pipelines with the installation of pre-insulated pipes and increasing or decreasing their diameter, if needed [1].

The largest DH network in Estonia is the 429-kilometre long heating network of Tallinn municipality. Majority of the pipes were built with a view of future development during the rapid industrial growth. After collapse of the Soviet Union most large industries were closed and now the pipe diameters are oversized. As far as the pipe metal was in good condition and the insulation poor, it was decided to use the medium investment scenario and renovate the insulation of main pipelines with the view to reduce relative heat losses [2]. At the end of 2011 a large insulation replacement project was started in Tallinn. In the frame of the project it is planned to renovate the insulation of 11km long DN 1200 pipe. The project started with an experiment where the insulation of 500 m long pipe section was replaced with prefabricated polyurethane foam shells. The insulation thickness of the supply pipe was 90 mm, and that of the return pipe 70 mm. The aim of this research was to evaluate the results received during the experiment and to compare these results with the parameters, indicative for the pipes with old insulation.

THEORY AND EXPECTATIONS

The effective thermal insulation of piping system plays an important role in the reduction of heat loss and energy consumption for heat transmission and distribution in district heating [3]. The increase of insulation thickness will decrease the energy consumption for heating, but the investment will also increase and thus it is important to choose an optimum point where the total investment cost for the insulation and energy consumption can be minimized over the lifetime[4].

The amount of heat loss depends mainly on the thermal conductivity and thickness of insulation while all other parameters have less effect. The thicker the insulation, the smaller the heat loss is [5]. The heat loss versus insulation thickness of the supply and return DN 1200 pipe was calculated for the conditions of Tallinn DH network (Fig.1).

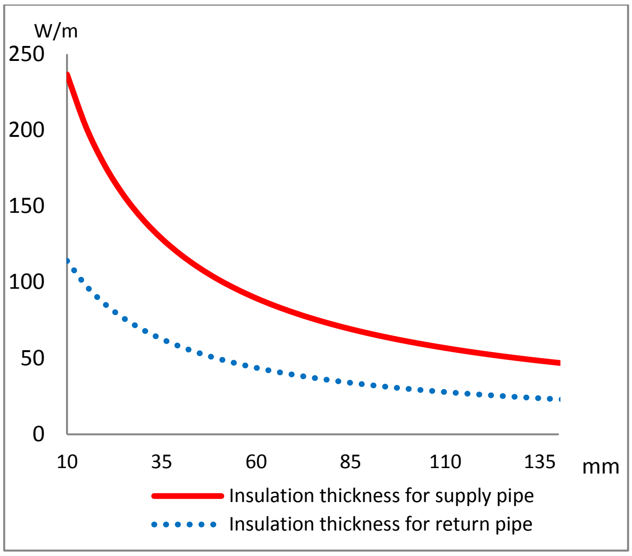

Fig.1 Heat loss (W/m) depending on the insulation thickness (mm) of the supply and return pipes. DN1200, temperature 75/50(yearly average).

According to the diagram, the optimal insulation thickness for the supply pipe is 80-100mm and that for the return pipe 60-80mm. The reduction of heat loss is almost the same and decreases very slowly when the insulation thickness is higher than optimal.

The expected average heat loss during heating season for new insulation with the thermal conductivity of 0.032 W/mK is 116 W/m on the supply and return pipes together for the Tallinn DH network case. Expected heat losses during experiment is 131 W/m because return and supply pipe temperature is same. In calculation factors like channel size, heat transfer between pipes and many others were taken into account [5].

Before replacing the insulation, the polyurethane foam shells were tested in the Tallinn University of Technology and the thermal conductivity was confirmed was confirmed (measured thermal conductivity was 0.0315W/mK). The shells were mainly made of polyurethane foam systems Suprasec 5005 and Daltofoam TE 44209 [6].

Nowadays the average estimated yearly heat loss from the pipe DN 1200 with old insulation is about 550W/m. As a result, the expected reduction of heat loss on main pipes should be about 4.7 times lower.

The experiment included the following steps:

- Disconnection of pipe sections from all the consumers;
- Connection between the supply and return pipe on one side;
- Placing of pump on the other side(The pump was required for creating circulation in pipes, thus avoiding thermal stratification of water);
- Preheating of pipes during a long time to reach the steady state;
- Leaving the pipes to cool for some days;
- Monitoring of the temperature during the whole period of experiment.
- Calculation of heat loss using the data on the time period of the experiment, volume of water and temperatures.

EXPERIMENT AND RESULTS

For the experiment a pipeline with the total length of 532m and outside diameter of 1220 mm was chosen. Visual difference between the old and new insulation can be seen in Fig.2 and Fig.3.

Fig.2 Pipelines with the old mineral wool and tar paper insulation. The packed insulation on top and sagged one in the bottom.

Fig.3 Pipes with the new prefabricated insulation from polyurethane foam shells and vapor barrier.

The old insulation is sagged and packed, the thickness of insulation on top of the pipe is not more than 2cm, below the free space between the pipe and insulation is over 10 cm.

The underground pipeline placed in a concrete channel was preheated to 73°C degrees during 24h to reach the steady state and avoid the heat loss for heating pipe, insulation and other elements. The temperature was conditioned to the temperature schedule, the yearly average supply temperature is 75-79°C.To avoid thermal stratification of water during the experiment, one pump was used in Point A to provide the water flow 1000m3/h (around 0,25m/s) during all the time of experiment. The same weather conditions were chosen for the experiment, that's why the experiment was realized in late spring and in the beginning of autumn. The daily outdoor temperature during both experiments was 12-17 °C, the soil temperature about 12°C. Temperature detectors with memory were in Points A and B (Fig.4).

Fig.4 Map of the experimental territory

The results taken from temperature sensors are displayed in Fig.5 and numerical results in

.

As it can be seen, the average temperature drop in the second experiment was about 3.8 times lower compared to the experiment with pipes having old insulation. We also noticed that the air temperature in the channel decreased; unfortunately the actual temperatures were not measured. The temperature variation during first experiment can be explained by the insufficiently preheated section of pipe, around 10m3 and 45-50°C, which is less than 1% of the whole pipe volume. The temperature variation during the second experiment was not significant.

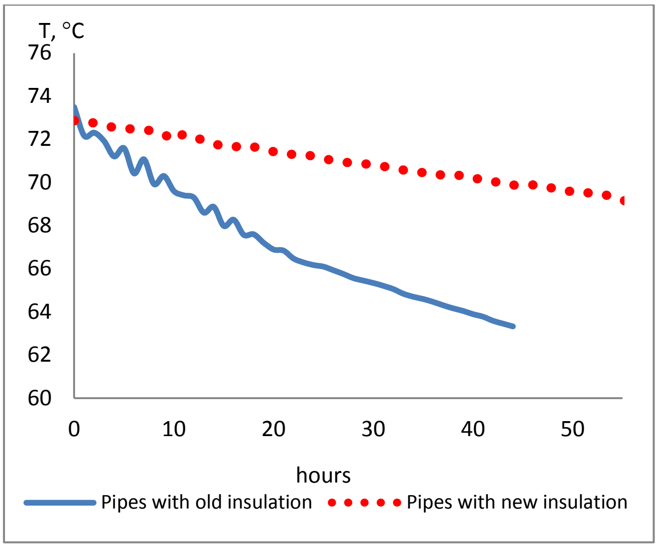

Fig.5 Temperature drop during the experiments

Table 1 Results of the experiment

	Old insulation	New insulation
T start, °C	73,6	72,9
T end, °C	63,7	69,8
Time, h	44	53
T drop, °C/h	0,225	0,0585

The temperature reduction dynamics can be taken as linear, because of the short time. In that case error will be not more than 2% with confidence level 95%.That is why the calculation of heat loss can be done in an easy way with using the equation(1).

$$Q = m \cdot c \cdot (t_1 - t_2) \qquad (1)$$

where

Q – lost heat amount (kWh);

m – mass of medium (kg);

c – medium heat capacity (kW/kgK)

t_1, t_2 – initial and final temperature (°C).

By dividing the amount of lost heat with the pipe length the actual heat loss per meter was found. The results are shown in Table **2**.

As it can be seen, the heat loss of old insulation is almost the same as estimated. The heat loss of new insulation is about 11W/m higher than expected.

Table 2 The calculated heat losses.

	Old insulation	New insulation
d T, °C	9,9	3,1
Time, h	44	53
Pipe length*, m	1064	1064
Pipe volume, m3	1137,4	1137,4
Heat loss, kWh	12782	4002
Heat loss*, W/m	546	142

*sum of the supply and return pipe

ECONOMICS

The real cost for the renovation of insulation on the DN1200 pipeline was about 1700€/m, but it may be much different depending on how much digging and restoration work for the channel is needed to be done. The heat loss saving is about 400W/m per return and supply pipe together compared with the old insulation. The actual yearly heat savings will be 3.5MWh/m/y. The natural gas price for large consumers in Estonia is about 50€/MWh as of spring 2012. It means that the economical saving is 175€ per each meter of the line in a year, meaning that the payback time is about 10 years. In addition, the water pumping power will be decreased and CO2 tax should be added what makes the payback time shorter. Moreover, because of the decreased water flow it helps to reduce the temperature schedule that further reduces the heat loss. The estimated life time of insulation is 30 years; so the project is economically profitable.

CONCLUSION

The heat pipe insulation renovation is a good way to decrease the heat losses and extend the life of pipes. Such renovation can be made only if the pipes are in good condition, because the renovation is expensive, payback period is also long. Taking into account the results of experiment in Tallinn DH network, when the insulation of 500 m long pipe section was replaced with prefabricated polyurethane foam shells, it can be argued whether the heat loss reduction was over 3.5-fold. It means that the payback period is about 10 years. After successful experiment, a decision was made to renovate the insulation of a 11km long DN 1200 pipe.

ACKNOWLEDGEMENT

The authors would like to express their appreciation to Tallinna Küte AS for the opportunity to provide the experiment and make necessary measurements.

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STATUS ASSESSMENTS OF DISTRICT HEATING PIPES

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ABSTRACT

Large parts of the existing pre-fabricated district heating pipe networks are close to reaching their technical life. There is a need to assess the status of the district heating pipes in order to plan maintenance and replacements of pipes. A first step towards developing a simple and cheap method for technical status assessments of existing pipes without shutting the pipes down has been taken.

The proposed mechanical field method is based on that the district heating pipes are uncovered and cylindrical samples still attached to the service pipes are created by removing material around them by use of hole drills. Laboratory equipment for pulling or turning the cylindrical samples off, while measuring load and deformation, has been developed.

INTRODUCTION

The aim with this work is to take a first step towards developing a simple and cheap method for technical status assessments of existing pipes without shutting the pipes down has been taken. The method can be a foundation for estimation technical or economical life of the district heating pipe. The economic life has come to an end when it is estimated that it is profitable to replace the pipe instead of continuing to use it.

The work is focused on pre-fabricated district heating pipes with a service pipe of steel, insulation of polyurethane and a casing pipe of polyethylene.

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. 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. This pipe type has dominated the market since the early 80's, and one might therefore expect that the need for replacement will increase with five to ten times the coming years. For Swedish conditions, this means that maintenance of the existing grid will require largely the same investment volume as new construction.

Extensive laboratory tests and field studies have carried out in Germany on ageing of pre-fabricated district heating pipes, see References [2], [3] & [4]. It was established that ageing of the polyurethane (PUR) foam does not follow the time/temperature relation in the EN 253 product standard, which is based on Nolte's experiments [5] of ageing of polyurethane in an oxygen free environment. This discrepancy is likely due to oxidative degradation of the foam, see also References [6] & [7]. The significance of this phenomenon with respect to long term strength and thermal insulation capacity remains to be clarified. This work is also publish as an internal report

DEFINITION OF TECHNICAL LIFE

It is not motivated to define the technical life based on a standard requirement on the axial shear strength of 0.12 MPa in EN 253, since the pipe will not be subjected to such large shear stresses between the service pipe and the polyurethane foam. Based on the standard EN 13941, the shear stress between service pipe and the polyurethane has been calculated for a few cases. The shear stress is based on the linear built up of the fix force along the friction length. For some cases extreme cases the shear stress reaches about one third of the requirement 0.12 MPa.

Instead, it is suggested that the definition of life is based on a reduced value. The technical life of a pipe can be estimated based on the measured axial shear strength, an assumed yearly reduction of the axial shear strength at the specific service temperature of the pipe and a life criterion based on the smallest allowable axial shear strength.

Table 1: Calculation results of shear stress by use of EN 13941. Weight density of soil 18 kN/m^3, lateral soil coefficient 0.5, service pressure 16 bar, Young's modulus 210 GPa, Poisson's ratio 0.3 and thermal expansion 11 10^{-6} K^{-1} of steel have been used.

Dimension	Temperature [K]	Friction [-]	Cover [mm]	Shear stress [MPa]
DN 100/225	160	0.6	2000	32
DN 100/225	90	0.6	2000	32
DN 100/225	160	0.4	600	6.9
DN 100/200	160	0.6	2000	29
DN 100/250	160	0.6	600	36
DN 65/160	160	0.6	2000	35
DN 65/160	160	0.4	600	7.3

AGEING OF DISTRICT HEATING PIPES

There are different ways for accelerated aging of polyurethane foam. Either can the polyurethane foam be aged out- or inside a container. The container can be a district heating pipe or have some other shape. Here, we have chosen to use accelerated ageing of district heating pipes in the laboratory and pipes which have been in service.

Accelerated ageing of pipes in the laboratory

The temperature field should also be chosen. Here, we have heated the service pipe to 160°C and outside casing it is room temperature. For the polyurethane in a pipe in service the temperature field will be similar, but the boundary conditions differ.

Accelerated ageing in the laboratory is motivated by the fact that the temperature load is known. It is the foam close to the service pipe that will age fast due to thermal degradation. For the activation energy 150 kJ/mol, the Arrhenius equation gives 70 times faster ageing at 160°C than 120°C, and 180 times faster at 160°C than 80°C.

However, the diffusion of oxygen through casing will not increase that much compared to the situation in service. Suppose that the temperature of the casing is increased from 15°C in service to 30°C in the laboratory, diffusion rate will be twice as high for the activation energy 35 kJ/mol.

In the investigations two district heating pipes of dimension DN 100/225 and type Contipipe manufactured by LOGSTOR have been used. The pipes had no diffusion barrier. However, the production process had to be interrupted before these pipes were manufactured and the bonding between the service pipe and the polyurethane was not as good as it should have been. Good bonding was only verified for about half of the circumference.

In the investigations a non-aged pipe, and pipes aged 1800 h, 3600 h and 5400 h were used. The pipes were aged standing by use of circulated heated oil.

Pipes from service

A few pipes, which have been in service and aged naturally, have also been investigated, see Table 2. The blowing agent is Freon 11 (CFC 11) in all the pipe but the newest, where cyclopean was used.

MECHANICAL TESTING

Two kinds of mechanical tests have been carried out. First, standard tests characterizing the change of axial shear strength and the change of compressive strength due to ageing have been done. Second, tests in order to develop a simple mechanical field method have been carried out.

Axial shear strength

The tests of the axial shear strength have been carried out in room temperature as described in EN 253 with test object of length 200 mm.

Table 2: Investigated district heating pipes from service.

Notation	Installation	Dimension	Blowing agent	Temperature	Flow / Return
GA	1986	DN40/125	CFC11	75-100	F
GBF	1987	DN300/500	CFC11	75-100	F
GBR	1987	DN300/500	CFC11	40-70	R
GCF	1991	DN250/450	CFC11	70-105	F
GCR	1991	DN250/450	CFC11	40-60	R
GDR	2007	DN200/355	CP	40-60	R

The axial shear strength is

$$\tau_{ax} = F_{ax}/(\pi D_s L) \qquad (1)$$

where

F_{ax} = measured axial force [N]
D_s = outside diameter of service pipe [mm]
L = length of test object [mm]

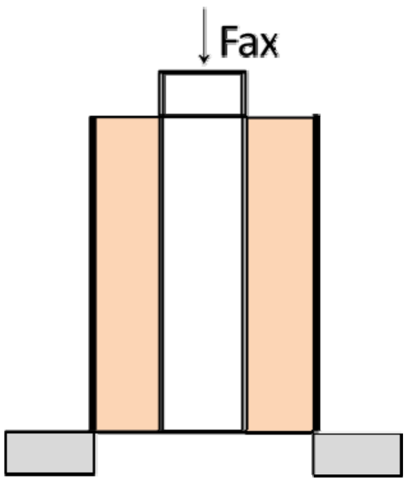

Figure 1: Sketch of axial shear strength test.

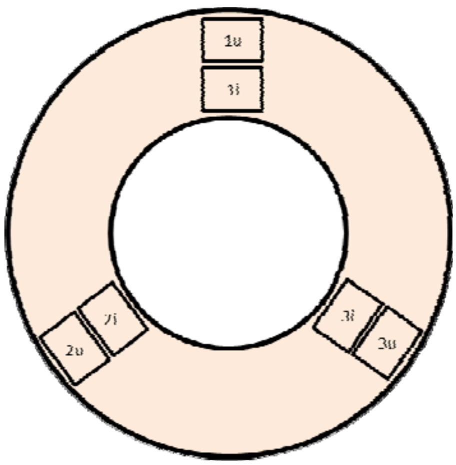

Figure 2: Sketch of positions of test specimens for compressive strength.

Compressive strength

The tests of the compressive strength have been carried out in room temperature as described in EN 253. In order to investigate the influence of the temperature, test specimens have been taken both close to the service pipe and far away from it, see Figure 2. The specimens have been collected within a length of 180 mm along the pipe. The size of the test specimens before testing is 30x30x20 mm. The compressive strength is the stress at 10% compressive strain in the radial direction.

DEVELOPMENT OF MECHANICAL FIELD METHOD

The purpose of the work is to develop a simple and cheap mechanical field method for technical status assessment of existing pipes without shutting the pipes down.

Based on two ideas, two methods have been tested for characterizing the bonding between the polyurethane and the service pipe. In both methods cylindrical test specimens still bonded to the service pipe are uncovered, see Figure 3. Two hole drills were used for shaping the test specimens: a larger with an outside diameter of 38 mm and a smaller with an inside diameter of 27 mm. In the methods, the test specimens have been either pulled or turned loose from the service pipe. Aluminium pipe holders with an inside diameter of 27 mm are attached to the test specimens by use of glue, see Figure 4.

Pulling specimens loose

A tensile testing machine was used for pulling the cylindrical test specimens of polyurethane loose. In most tests the feeding speed was 0.5 mm/minute.

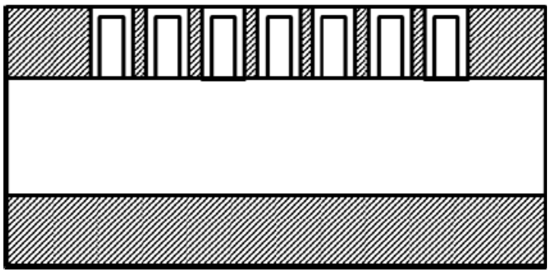

Figure 3: District heating pipe with uncovered cylindrical test specimens still attached to the service pipe.

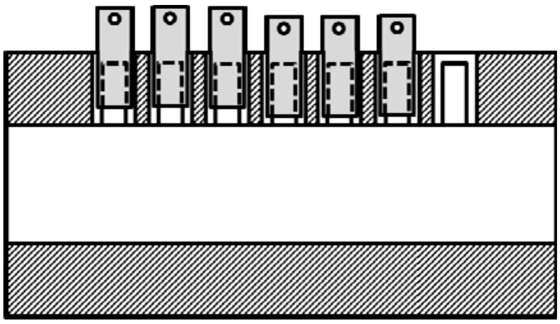

Figure 4: District heating pipe with cylindrical test specimens on to which aluminium pipes holders have been fixed by use of glue.

Figure 5: Picture of laboratory equipment for pulling cylindrical specimens loose.

Figure 6: Picture of laboratory equipment for turning cylindrical specimens loose.

Turning specimens loose

A rig for turning cylindrical specimens of polyurethane loose, while measuring the applied torque and the rotation of the holder, has been manufactured, see Figure 6. The rig has a piece of plastic material mounted on an aluminium bar with seven cylindrical holes. The size of the holes is adjusted to fit the aluminium pipes. The holes are located just above the cylindrical test specimens of polyurethane.

The holes in the plastic material can be used as bearings useful for precise drilling of specimens, guidance while gluing aluminium pipe holders and carrying out the tests while turning the specimens loose.

The tests are carried out manually by hand, while the applied torque and the turning angle are measured. A static torque transducer located below the bearing is used for measuring the torque needed for turning the test specimen loose. The frictional torque at the bearing is hereby eliminated. A wire potentiometer and a wheel are used for measuring the rotation of the holder.

CELL GAS ANALYSIS

The partial pressures of the gases p_i [Pa] in the cells of the foams were determined according to a method thoroughly described in Reference [9]. Foam sample cylinders (diameter about 21 mm, length 40-60 mm) were ground in a closed system. This system was flushed with dinitrogen oxide for removing all air surrounding the sample, but also for making it possible to determine the true volume of the sample. The outer cell layer will always be more or less damaged during sampling, which makes it impossible to determine the true volume of the sample only by using a slide calliper. After flushing the sample was ground into powder. The released cell gas was collected in a glass syringe and the syringe volume was determined. The content of the released gas was analysed by use of a gas chromatography, which was equipped with a thermal conductivity detector. The concentration of each gas x_i [% of volume] in the cell gas was determined and the total cell gas pressure P_{tot} [Pa] was calculated. The small volume of dinitrogen oxide penetrating the foam during flushing was considered, when calculating P_{tot}. The partial pressures of the cell gases were calculated as

$$p_i = x_i \cdot P_{tot} \qquad (2)$$

RESULTS OF STANDARD MECHANICAL TESTS

The axial shear strength has been measured for non-aged pipes, and accelerated aged pipes. The requirement on the shear strength in EN 253 is 0.12 MPa. The shear strength is in principle decreasing with ageing time. A pipe from service in 25 years has also been investigated. The latter pipe has been manufactured with a blowing agent CFC11 and is still in good shape.

The compressive strength of the polyurethane foam has been measured for non-aged pipes, and accelerated aged pipes. The requirement on the compressive strength in EN 253 is 300 kPa. The compressive strength is increasing with ageing time. Too few samples have been tested for verifying that the compressive strength is lower for the specimens taken closer to the service pipe. The hardening process continues before the degradation process of the foam has a large influence. A pipe from service in 25 years has also been investigated and the compressive strength was found to still be satisfying.

RESULTS OF MECHANICAL FIELD METHOD

Ultimate tensile stresses for the pulling method are shown in Figure 9. Often, in the tests with longer specimens the fracture occurred far from the service pipe. Fracture also occurred inside the aluminium holder, when the glue had moved during appliance of the holders. For testing the foam close to the service pipe the length of the specimens was decreased. However, fracture still occurred inside the aluminium holder. The foam becomes more brittle and stiffer after ageing. Since the bonding varied around the circumference, the test specimens were taken along a generatrix, where the bonding was considered as good.

Ultimate shear stresses for the turning method are shown in Figure 10. When longer test specimens were used, fracture occurred perpendicular to the principal stress direction pertaining to tension. At the periphery the maximum shear stress is as large as the tensile principal stress. For elimination tensile fracture, shorter test specimens were used in the following investigations. For the shorter test specimens the fracture was initiated in the foam at the service pipe, see Figure 11. Also here, the specimens were taken along a generatrix, where the bonding was considered as good.

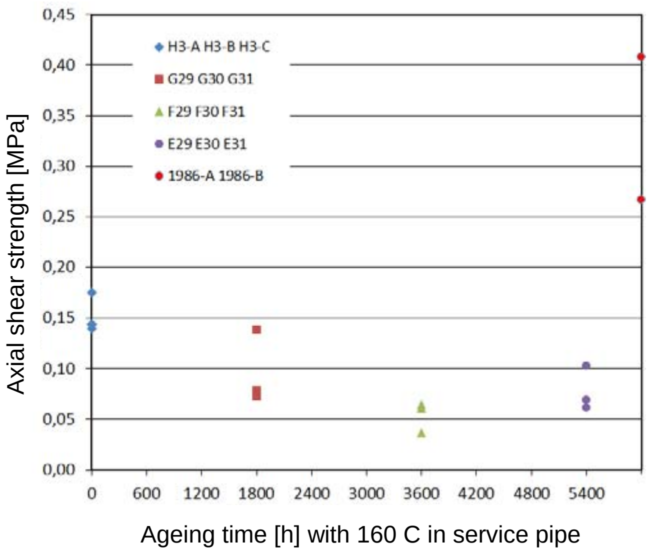

Figure 7: Axial shear strength of accelerated aged district heating pipes and a pipe GA which have been in service in 25 years.

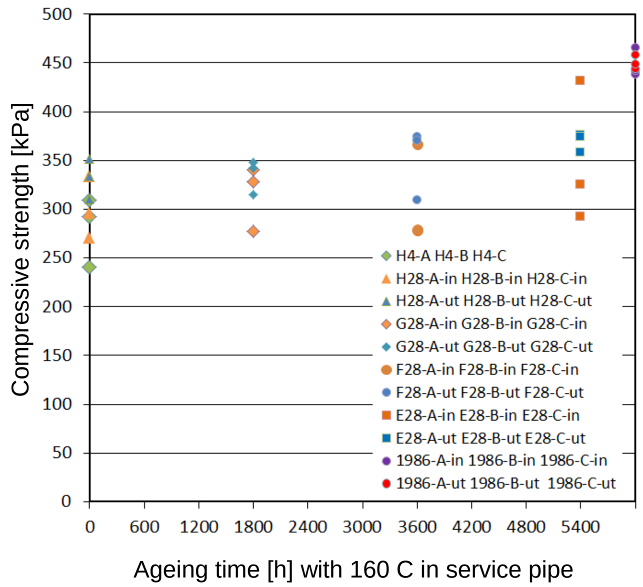

Figure 8: Compressive strength of accelerated aged district heating pipes and a pipe GA which have been in service in 25 years.

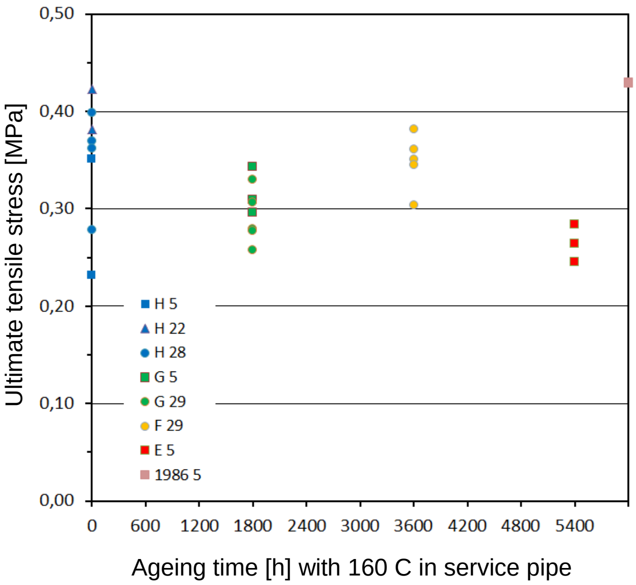

Figure 9: Measured ultimate tensile stress of test specimens as function of ageing time in laboratory and also for a pipe GA which have been in service for 25 years. Length of specimen is part of notation.

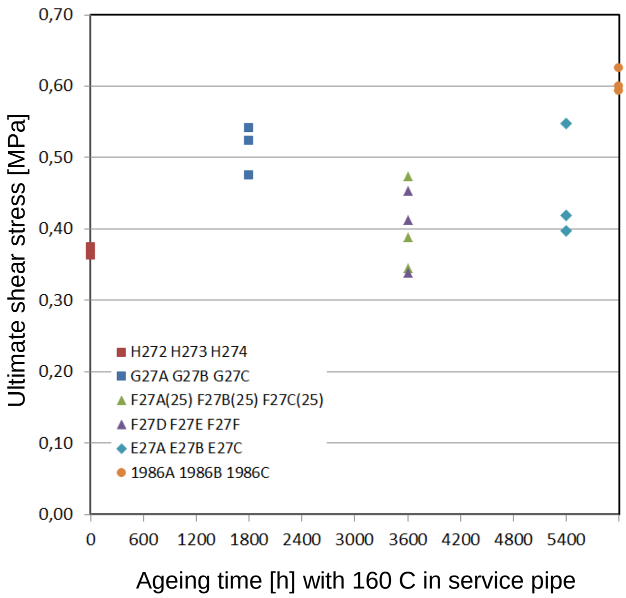

Figure 10: Measured ultimate shear stress of test specimens as function of ageing time in laboratory and also for pipe GA which have been in service for 25 years. For 3600 h, results for specimens of both length 25 mm and 5 mm are given.

Discussion about development of field method

The purpose of the field method is to estimate the bonding between polyurethane and the service pipe in a simpler manor. In order to analyse the measurements linear regressions have been carried out, see Figure 12. The axial shear strength is the mean ultimate shear stress over a short piece of pipe.

Regression curves have also been determined for the turning and pulling methods, see Figure 13 and Figure 14. The coefficients are given in Table 3. Confidence intervals containing 95% of all outcomes are given for the coefficient in Figure 15 and Figure 16.

Figure 11: Picture of specimens from turning method.

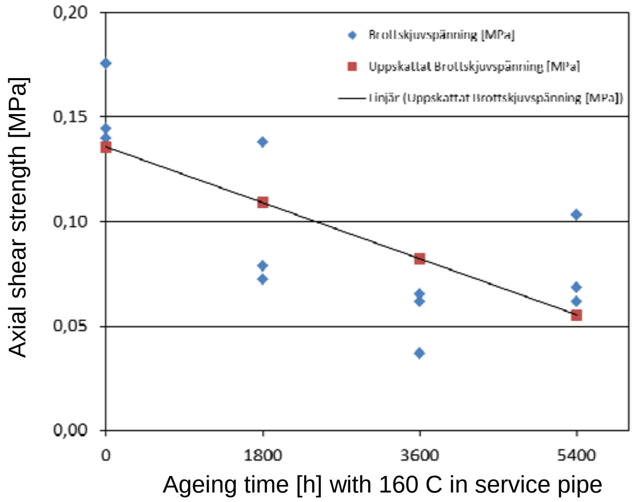

Figure 12: Regression curve for axial shear strength.

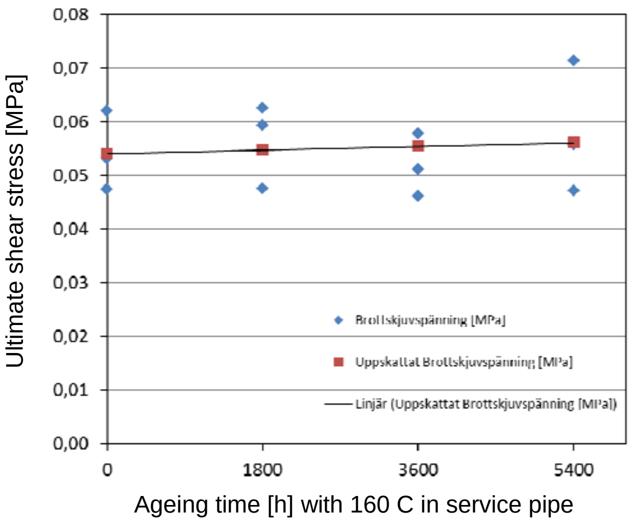

Figure 13: Regression curve for ultimate shear stress obtained from turning method.

The slope of the regression curve for the axial shear strength shows that the strength decreases due to ageing. However the corresponding decrease cannot be found for the turning or pulling method. The decrease of the axial shear strength can be accomplished by a uniform decease of the bonding around the service pipe, or a non-uniform decrease where the zone without bonding increases. In the latter case the bonding may be more or less unchanged in the areas where it was initially good.

The linear regression of the axial shear stiffness gives a decrease of 14.9 Pa/h=0.13 MPa/year at the temperature 160°C. For the activation energy 150 kJ/mol this means a decrease of 0.0019 MPa/year at the temperature 120°C.

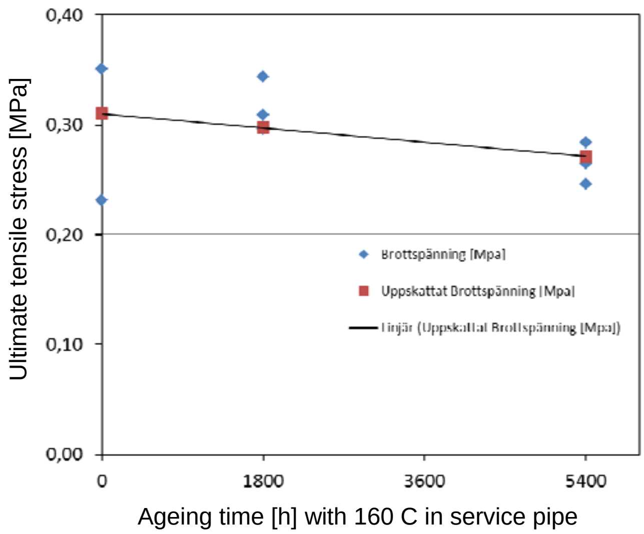

Figure 14: Regression curve for ultimate tensile stress obtained from pulling method.

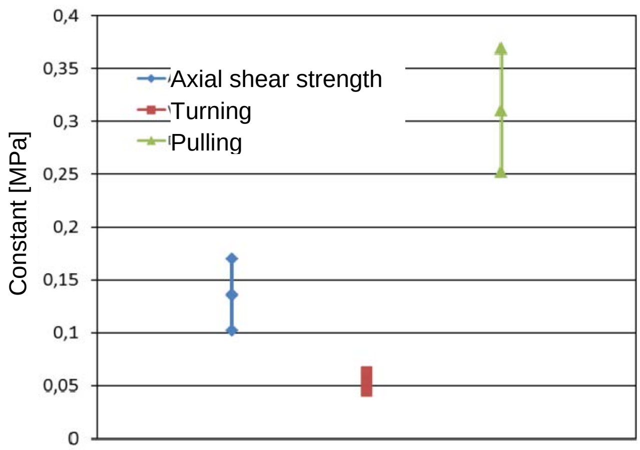

Figure 15: Confidence interval for constant in linear regressions.

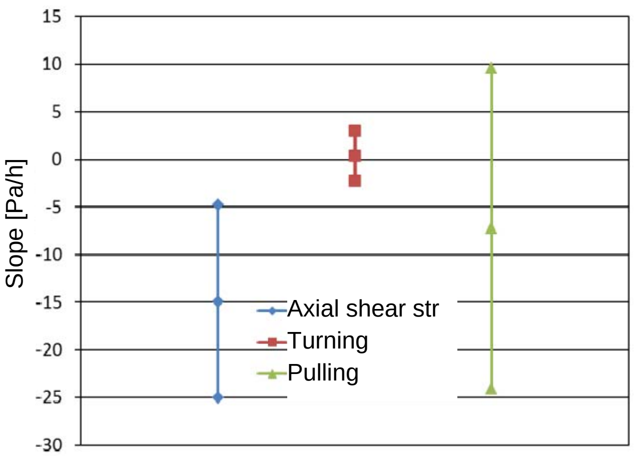

Figure 16: Confidence interval for slope in linear regressions.

Table 3: Coefficients in linear regressions.

Coefficient	Axial shear strength	Turning	Pulling
Constant [MPa]	0.136	0.054	0.310
Slope [Pa/h]	-14.912	0.379	-7.242

Table 4: Partial pressures p(i) and total pressure P_{tot} in cells of foams (density 71-75 kg·m^{-3}) of new pipes. All pressures are given in kPa at room temperature. Ratios of partial pressures of nitrogen and oxygen are also given. District heating pipes were placed at room temperature and hot oil circulated in service pipe during 0-5400h.

Time (h)	0	1800	3600	5400
$p(O_2)$	2.1	1.0	0.7	0.7
$p(N_2)$	0.9	3.4	2.0	3.3
$p(CO_2)$	38	41	41	37
p(CP)	38	35	32	31
P_{tot}	79	81	77	72
$p(N_2)/p(O_2)$	0.4	3.4	2.7	4.7

RESULTS OF CELL GAS ANALYSES

Table 4 shows the change of the cell gas composition of the foams of district heating pipes where the steel pipes were exposed to circulating hot oil (160°C) during 0-5400h. The isocyanate reaction was not complete at start since $p(CO_2)$ increased until 3600h. Carbon dioxide is formed from the reaction between isocyanate and water. For new pipes, it is often found that $p(O_2)$ is higher than $p(N_2)$. However, oxygen and nitrogen from air will diffuse into the foam and some oxygen will be consumed in oxidation reactions. This is partly seen from the increasing $p(N_2)/p(O_2)$ ratio. The change of the cell gas composition is small and will only give rise to minor changes of the thermal conductivity of the foam.

Table 5: Density, partial pressures p(i), total pressure P_{tot} in cells of old foams studied. All pressures are given in kPa at room temperature. Ratios of partial pressures of nitrogen and oxygen are also given.

Time (h)	GA	GBF	GBR	GCF	GCR	GDR
Density [kg·m^{-3}]	72	70	66	78	81	68
$p(O_2)$	3.1	1.1	3.4	2.9	12	1.7
$p(N_2)$	52	14	16	12	58	4.6
$p(CO_2)$	4.8	25	22	28	25	61
p(CFC11)	58	42	31	33	26	-
p(CP)	-	-	-	-	-	15
P_{tot}	120	83	74	77	122	84
$p(N_2)/p(O_2)$	17	12	4.8	4.2	4.8	2.7

The cell gas composition of the foam in the old pipes is given in Table 5. The value represents the composition in the middle of the foam. Since the foam of all pipes except GA is thick, samples can be taken at different radial positions of the foam. These samples show that the pressures of oxygen and nitrogen (diffusing into the foam) are higher close to the polyethylene jacket and the pressure of CFC11 (diffusing out of the foam) is higher close to the steel pipe. Carbon dioxide diffuses faster than the other cell gases and exhibits almost the same partial pressure at all radial positions.

All pipes have been in service for over 20 years except pipe GDR, which only has been used for 4 years. The flow pipes GA and GBF have high $p(N_2)/p(O_2)$ ratios indicating oxidation. Pipe GCF has probably only been used at a rather low temperature not giving rise to oxidation.

The thermal conductivity of the cell gas can be calculated from the cell gas composition according to the Wassiljewa equation with the modification of Mason and Saxena. The conductivity of the cell gas in the foam of pipe GBF can be calculated to 0.0122 W/mK at 50°C. If it is assumed that the initial partial pressures of the foam in pipe GBF were 0.5 (O_2), 1 (N_2), 60 (CO_2) and 50 kPa (CFC11), the cell gas conduction was 0.0121 W/mK at 50°C 25 years ago. Since the contribution from radiation and conduction in the solid polymer is unaffected by the aging, the insulating capacity of pipe GBF is almost unchanged after 25 years!

The diffusion of oxygen and nitrogen into the foam increases the thermal conductivity but the diffusion is slow since the polyethylene jacket is rather thick and some oxygen is consumed in oxidation reactions. Carbon dioxide diffuses faster out of the foam than CFC11. That means that the relative volume of CFC11 (with a very low λ-value) increases and that compensate for the increase of thermal conductivity caused by oxygen and nitrogen.

All pipes except GA are of large dimensions and have thicker polyethylene jackets than according to today's standard, i.e., the jacket of pipe GBF is 9.3-8,8 mm thick but today's standard prescribes only 5.6 mm.

CONCLUDING REMARKS

In the performed tests, the fracture initiation occurs between the service pipe and the polyurethane foam when turning the sample off, while the fracture occurs in the polyurethane foam when pulling the sample off. For the axial shear strength tests the fracture can occur in different ways. Since the temperature in the polyurethane is highest at the service pipe, the degradation is most severe there. This means that the fracture is initiated at the polyurethane at the service pipe, when the technical life due to normal degradation is reached.

The axial shear strength is clearly decreasing during accelerated ageing in the laboratory, but the corresponding reduction has not been found for the pulling or turning method. The advantage with the turning method is that the fracture is initiated at the same position as for the axial shear strength tests. The test methods need to be verified further and adapted for usage in the field.

Requirements on and definitions of technical life have been discussed. It has been concluded that it is not motivated to define the technical life based on the standard requirement in EN 253 on the axial shear strength 0.12 MPa, since the pipe will not be subjected to such a large shear stress between the service pipe and the polyurethane foam. Instead, it is suggested that the definition of life is based on a reduced value. The technical life of a pipe can be estimated based on the measured axial shear strength, an assumed yearly reduction of the axial shear strength at the specific service temperature of the pipe and a life criterion based on the smallest allowable axial shear strength.

The ratio of the partial pressures of nitrogen and oxygen can be calculated from a cell gas analysis. This ratio indicates the extent of oxidation of the foam. In order to be able to make reliable predictions and give target values, further foam samples from other old pipes must be analysed.

The thermal conductivity of a district heating pipe can be calculated from a cell gas analysis. It is also possible to predict the future insulating capacity and heat losses of the district heating system and the indirect environmental impact these losses correspond to. Thus, cell gas analysis is a useful tool for evaluating the status of a district heating system from technical as well as environmental point of view.

Some old pipes studied have a thicker polyethylene jacket than today's standard. The thick jacket, the large dimensions (long diffusion paths) and the slow diffusing insulating gas CFC11 (now forbidden) have contributed to the slow change of the cell gas composition. One pipe had almost the same insulating capacity after 25 years in service.

ACKNOWLEDGEMENTS

This work has been partly financed by Research foundation of Göteborg Energi and by SP. District heating pipes have been donated by LOGSTOR. Mr Alberto Vega assisted in laboratory work. The rig has been manufactured by Mr Anders Persson. Fruitful discussions with Professor Ulf Jarfelt, Mr Lars Jacobsson and Mr Lennart Hansson are gratefully acknowledged.

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SELECTION OF OPTIMAL PIPE DIAMETERS IN A DISTRICT HEATING NETWORK USING MINIMISATION OF ANNUAL TOTAL ENERGY AND EXERGY CONSUMPTION

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Keywords: District heating, Optimisation, Energy, Exergy, Pipe diameters selection

ABSTRACT

The determination of optimal pipe diameters in a district heating network was conducted using minimisation of annual total energy and exergy consumption. At first, the district heating pipe diameters under the maximum load condition was sized based on a range of target pressure losses (50-2000 Pa/m) using two different supply and return temperature modes (high and low). Then an optimisation model was developed using the FICO™ Xpress optimisation tool. Optimal operation of district heating design cases over a year was carried out to minimise annual total energy/exergy consumption at steady state condition. The district heating design cases with minimum optimal annual total energy/exergy consumption were determined and district heating pipe diameters were found.

INTRODUCTION

In order to implement sustainable heating systems, the improvement of energy efficiency in the energy production, distribution and the replacement of fossil fuels using various renewable energy sources, are major technological challenges that have to be addressed [1-4]. District heating (DH) systems, particularly for densely populated urban environments, have proved to be more efficient compared with individual boilers [5]. A DH system can improve energy efficiency, especially when it is used with Combined Heat and Power (CHP) plants. It can also accommodate a variety of renewable energy sources [6]. However heat losses in a DH and electrical energy consumption of circulating pumps present the major drawback of DH compared to the individual heating systems such as gas/electric boiler. Therefore, better design as well as better energy management during operation, are required in order to improve energy/exergy performance of DH network.

For the assessment of DH network energy and exergy methods were used. The energy method is based on the first law of thermodynamics. Using this method heat losses and electricity consumption of pumps were assumed to be equally important. Using energy method, selection of optimal pipe sizes is based on minimising the annual total energy consumption (heat energy losses plus pump energy consumption), of DH network.

The exergy method is based on the second law of thermodynamics [7]. Using the exergy method it was assumed that the quality of heat was lower than that of electricity. Therefore, heat losses were less important than the electricity consumption of pumps. Using this concept sizing of DH network is based on minimising the annual total exergy consumption (heat exergy losses plus pump exergy consumption), of DH network.

Exergy analysis has been used to analyse energy performance of buildings [8] and district heating networks [9, 10]. A key review on exergetic analysis and assessment of renewable energy resources is given in [11]. The concept and application of exergy analysis for low temperature heating and high temperature cooling is given in [12].

This study presents an extended analysis of the previous studies by the same authors [13, 14]. In the previous studies two DH design cases, low pressure DH with target pressure loss (TPL) of 100 Pa/m and high pressure DH with TPL of 1200 Pa/m were designed and analysed. The annual pump energy consumption and heat losses as well as the annual operating costs of DH cases were calculated and compared.

This study presents an optimisation method to select the optimal pipe diameters in a DH network to minimise annual total energy/exergy consumption. The results obtained using both methods, energy/exergy, are compared and analysed.

METHOD

To select optimal pipe diameters the optimisation method synthesises design and operation of DH, shown in Fig.1. At first at maximum load (full load), DH pipes were sized for a range of TPL values, using different temperature modes. Then, the optimisation of DH design cases according to heating load variation was performed. The objective of the optimisation was to minimise annual total energy/exergy consumption of DH. Optimal supply temperature and mass (volume) flow rate were obtained. Consequently, optimal annual energy/exergy losses and pump energy/exergy consumption were calculated. The DH design cases with minimum optimal annual total energy/exergy consumption were found. Hence, the optimal pipe diameters using each method and temperature mode were determined. The process of pipe sizes selection is shown in Fig.2.

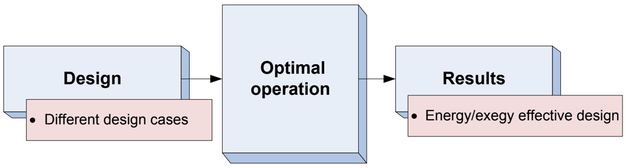

Fig.1. Block diagram of the design study

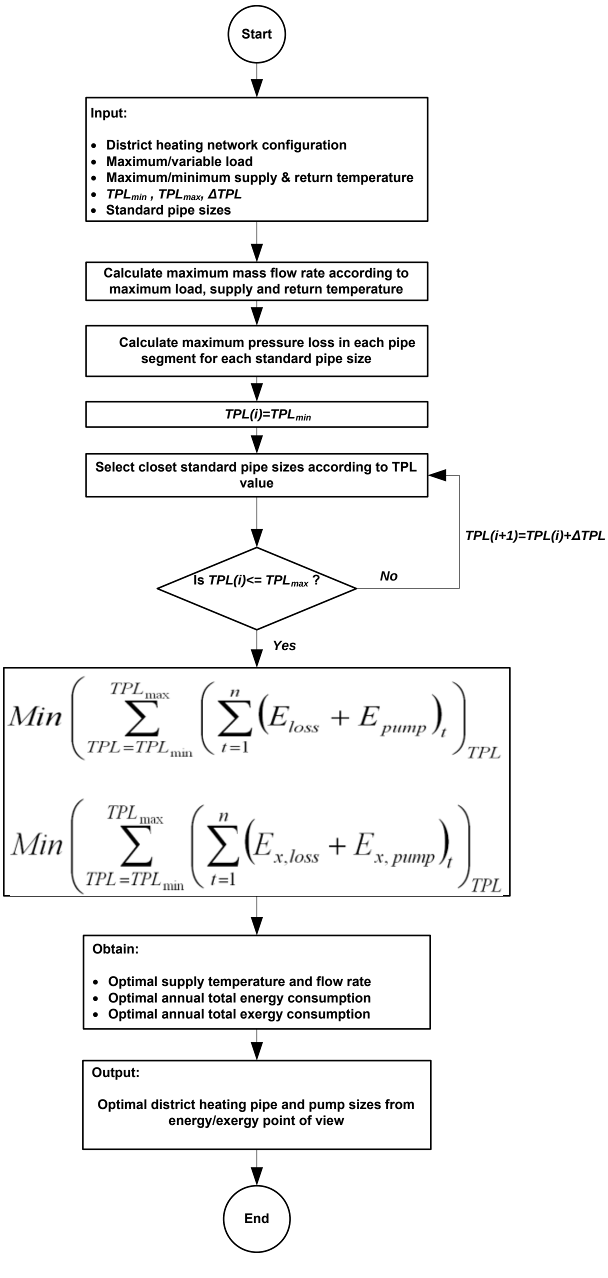

Fig.2. The process of pipe size selection

The optimisation of DH network was performed using minimisation functions (1) & (2).

Minimisation of the annual total energy consumption:

$$Min \sum_{TPL=TPL_{\min}}^{TPL_{\max}} \left(\sum_{t=1}^{n} \left(E_{loss} + E_{pump} \right)_t \right)_{TPL} \quad (1)$$

Minimisation of the annual total exergy consumption:

$$Min \sum_{TPL=TPL_{\min}}^{TPL_{\max}} \left(\sum_{t=1}^{n} \left(E_{x,loss} + E_{x,pump} \right)_t \right)_{TPL} \quad (2)$$

Heat loss in each pipe section was calculated using the temperature difference between the pipe inlet and outlet temperature [13, 14]. Total heat losses in the network are the summation of the heat loss in each pipe section of the supply and return pipes.
Exergy loss associated with energy loss in each pipe section was calculated using [7]:

$$\dot{E}_{x,loss,j} = (1 - \frac{T_g}{T_{w,j}}) \dot{E}_{loss,j} \quad (3)$$

It was assumed that pipes are laid underground, hence ambient temperature was assumed equal to the ground temperature (T_g). An average ground temperature of +7 ℃ was assumed over the year [15]. Hot water temperature (T_w) in each pipe section of supply and return was assumed as the average temperature of pipe inlet and pipe outlet temperature.

$$T_{w,j} = \frac{T_{inlet,j} + T_{outlet,j}}{2} \quad (4)$$

The exergy consumption, due to the pump electrical energy dissipation, to overcome flow resistance is dominated as the electrical energy degraded to low quality of thermal energy. The electrical energy given to the pump was assumed as the exergy consumption of the pump:

$$\dot{E}_{x,pump} = \dot{E}_{pump} \quad (5)$$

Energy and exergy rate of pump in kW was calculated using the following equation:

$$\dot{E}_{x,pump} = \dot{E}_{pump} = \left(\frac{\Delta p_{pump} \dot{m}}{1000 \rho \eta_{pump}} \right) \quad (6)$$

Where, pump differential pressure is the total pressure loss (pressure loss in supply and return pipes plus

pressure loss in consumer's heating substation), of route with maximum pressure drop in the network [13, 14].
Main parameters of DH network such as supply/return temperature, mass flow rate and pressure loss were constrained.

$$T_{s,\min} \leq T_s \leq T_{s,\max} \quad (7)$$

$$T_{r,\min} \leq T_r \leq T_{r,\max} \quad (8)$$

$$\dot{m}_{\min} \leq \dot{m} \leq \dot{m}_{\max} \quad (9)$$

$$\Delta p_{pump} \leq \Delta p_{pump,\max} \quad (10)$$

Pre-insulated single steel pipes with pressure rating up to 25 bar and maximum operating temperature of 140 ℃ were used [16]. Pipe diameters calculated based on the TPL values were not consistent with those available in the market. Therefore, using binary variables the available pipe with a diameter which was closest to the calculated pipe diameter was selected.
Two temperature modes high (T_s/T_r:120/70 °C) and low (T_s/T_r:65/25 °C) were investigated. For the high temperature mode maximum supply temperature of 120 ℃ at the heat source side and maximum return temperature of 70 ℃ at the consumer's heating substations were considered. Minimum, supply temperature of 70 ℃ at the source side and return temperature of 30 ℃ at the consumer's heating substations were taken into consideration. For the low temperature mode, supply and return temperature was reduced to the minimum level. The maximum supply temperature of 65 ℃ at the heat source side and maximum return temperature of 25 ℃ at the consumer's substation was assumed. During operation using low temperature mode, supply and return temperature were fixed over the year. Hence flow rate was controlled to balance demand and supply.
The TPL between the minimum of 50 Pa/m and maximum of 2000 Pa/m were considered in this study. The change step of TPL (ΔTPL) of 50 Pa/m was used.
The optimisation model was formulated as a mixed integer nonlinear (MIN) programming, using FICO™ Xpress optimisation. Xpress optimisation allows modelling and solving of large and complex optimisation problems. Successive (sequential) linear programming (Xpress-SLP) was used. The Xpress-SLP is a solver for nonlinear optimisation problems. More detailed information of the optimisation model can be found in [13, 14].

CASE STUDY

A DH network based upon a real project redevelopment in South Wales, UK, was used as the case study [17]. A simplified diagram of the DH pipe connection is shown in Fig.3.

Consumers were geographically split into a set of clusters. Consumers have different occupancy type and building size within a cluster. Each cluster was connected to the DH network using a heating substation. Maximum energy demand for space heating (SH) and domestic hot water (DHW) was calculated based on estimated area for each building [18-19].

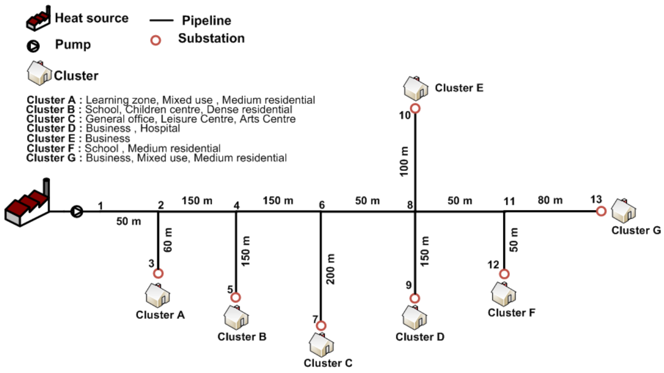

Fig.3.Simplified diagram of the DH case study

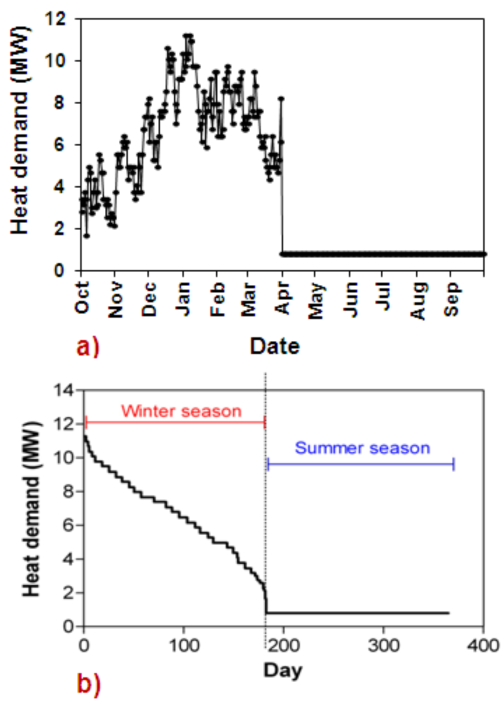

Fig.4. a) Total heat load variation, b) load duration curve

Average daily DHW requirement calculated for each building was assumed to be constant over the year. The energy demand for SH varies according to outdoor temperature. Hence, average daily SH demand was calculated using the concept of heating degree days [20-22]. The base temperature of 15.5 °C was assumed and the minimum outdoor temperature was considered to be -3 ℃. The total heating demand of SH was calculated for each day over one year. The heating load was divided into two main seasons. The winter season lasts for 182 days and includes energy demand for SH and DHW. For the rest of the year (summer season) only energy demand for DHW was taken into account. The total heat demand a), and annual load duration curve b) are shown in Fig.4.

RESULTS

Minimising annual total energy consumption

Annual energy losses and consumption versus TPL (different DH design cases), for two temperature modes are shown in Fig.5.

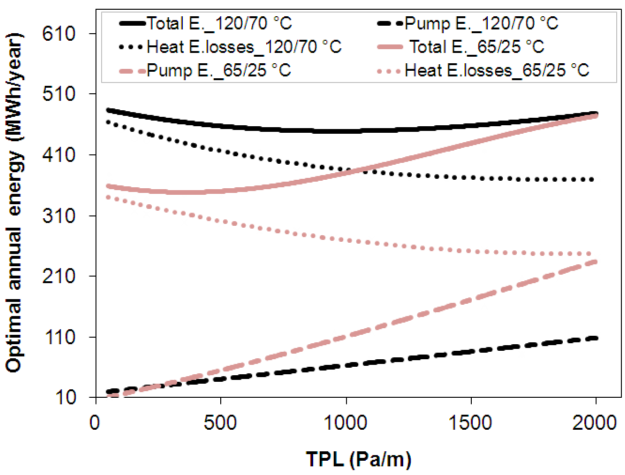

Fig.5. Optimal annual energy

It is shown that heat losses increase and pump energy consumption decreases as the TPL increases. Using different temperature modes heat losses and pump energy consumption are different as the TPL increases. Heat losses are higher for the high temperature mode compared with the low temperature mode. However, due to the larger flow rate in the low temperature mode, pump energy consumption is higher compared with the high temperature mode. Overall, optimal annual total energy consumption (heat losses plus pump energy consumption) in low temperature mode is less in comparison to the high temperature mode.
For the high temperature mode, minimum optimal annual total energy consumption happens for the design case based on TPL of 800 Pa/m. For the low temperature mode DH design case with much lower TPL of 200 Pa/m is the case with minimum optimal annual total energy consumption. The difference is related to the system flow rate. For the low temperature mode, due less temperature difference between supply and return pipes flow rate is larger than for the high temperature mode. Hence, pump energy consumption is larger. Therefore, to reduce the impact of pump energy consumption, pipe with larger diameters were obtained. However for the high temperature mode, to reduce the impact of heat energy losses, pipe with small diameters were found.

Minimising annual total exergy consumption

Annual exergy losses and consumption versus TPL for two temperature modes are shown in Fig.6.
Fig.6 shows that using both temperature modes, annual exergy losses reduce almost linearly as the TPL increases. Annual pump exergy consumption increases in the same manner. For the high temperature mode, the minimum optimal total annual exergy consumption occurs when DH pipes are sized based on TPL 100 Pa/m. For the low temperature mode, using the TPL of 50 Pa/m, the optimal annual total exergy consumption is minimum.
Comparison of optimal annual total exergy consumption for both temperature modes shows that for the DH design cases with TPL less than 850 Pa/m, low temperature mode has less annual total exergy consumption. Nevertheless, for the DH design cases based on TPL larger than 850 Pa/m, the high temperature mode has less annual total exergy consumption. The reason is due to the fact that mass flow rate using high temperature is less than in low temperature mode. Hence, using low temperature mode, for DH cases with higher TPL, pump exergy consumption is substantial which in turn increases the annual total exergy consumption of DH.

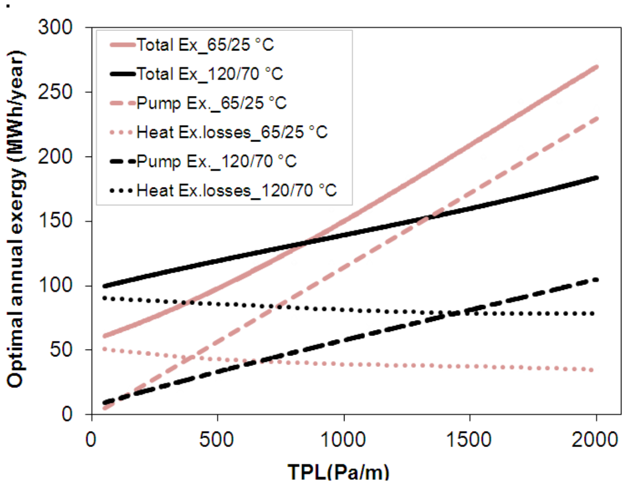

Fig.6. Optimal annual exergy

Comparison

Optimal results obtained using exergy and the energy methods are presented in Table A1 and Table A2 (Appendix).
For the minimisation of annual total energy consumption, due to the impact of heat losses, the DH design case with small pipe diameters and large pump size was obtained. While for the minimisation of annual total exergy consumption the DH design case with larger pipe diameters and smaller pump size was found.
Comparison of results using different temperature modes shows that for the high temperature mode

recommended pipe diameters are smaller and pump size is larger compared with the low temperature mode. As it was previously explained, mass flow rate is larger using low temperature mode compared with high temperature. Therefore, pipes with larger diameters were obtained to reduce the impact of pump energy/ exergy consumption.

CONCLUSION

Minimisations of annual total exergy/energy consumption were conducted to obtain the optimal pipe diameters in a DH pipe network. For energy method, due to the importance of heat losses in the DH network, it was found that to minimise annual total energy consumption the pipe diameters had to be sized based on a large TPL. For the exergy method, the pump exergy consumption was more important than the heat exergy losses. Therefore to minimise annual total exergy consumption the DH pipe diameters had to be sized using smaller TPL.

For the DH with large flow rate it was found that it was more energy/exergy effective to select pipes with larger diameters and smaller size pump in comparison with DH network with less flow rate. Using the DH cases with smaller flow rate, it was more energy/exergy effective to reduce pipe diameters and increase pump size to mitigate the impact of heat losses.

ACKNOWLEDGEMENT

The research comprises part of the Supergen-Highly Distributed Energy Future (HiDEF) work stream via EPSRC funding. The authors wish to thank Supergen-HiDEF consortium for their continued financial and technical support. The authors also thank Marc Rees for access to the case study data.

Nomenclature

$\dot{E}$	energy rate, MW
E	energy, MWh
$\dot{E}_x$	exergy rate, MW
E_x	exergy, MWh
η	efficiency
$\dot{m}$	mass flow rate, kg/s
p	pressure , Pa
Δp	differential pressure, Pa
P	pump power , kW
T	temperature , K
ρ	Water density, kg/m^3

Subscripts and superscripts

j	Index for pipe
inlet	Input
loss	Losses
min	Minimum
max	Maximum
n	Number of time step
pump	Pump
r	Return
s	Supply
t	Time step
outlet	Output

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Appendix

Table A1 Optimal pipe selection, using energy method

Energy method- (T_s/T_r: 65/25 ℃)						Energy method- (T_s/T_r: 120/70 ℃)					
Pipe No.	**From node**	**To node**	**DN (m)**	**Maximum velocity (m/s)**	**Maximum pressure loss (Pa)**	**Pipe No.**	**From node**	**To node**	**DN (m)**	**Maximum velocity (m/s)**	**Maximum pressure loss (Pa)**
Pipe01	1	2	0.25	1.47	6938	Pipe01	1	2	0.2	1.84	14551
Pipe02	2	3	0.125	0.95	8708	Pipe02	2	3	0.08	1.85	60905
Pipe03	2	4	0.25	1.24	14639	Pipe03	2	4	0.15	2.75	142316
Pipe04	4	5	0.125	1.04	26052	Pipe04	4	5	0.08	2.03	182584
Pipe05	4	6	0.2	1.52	29887	Pipe05	4	6	0.15	2.17	88744
Pipe06	6	7	0.125	0.98	30996	Pipe06	6	7	0.08	1.92	217607
Pipe07	6	8	0.2	1.14	5577	Pipe07	6	8	0.125	2.34	43860
Pipe08	8	9	0.125	1.28	39426	Pipe08	8	9	0.1	1.60	83413
Pipe09	8	10	0.1	1.06	24206	Pipe09	8	10	0.08	1.32	51408
Pipe10	8	11	0.125	0.96	7474	Pipe10	8	11	0.08	1.89	52472
Pipe11	11	12	0.08	0.96	13680	Pipe11	11	12	0.065	1.17	26832
Pipe12	11	13	0.1	0.89	13804	Pipe12	11	13	0.065	1.69	89756
Average pressure loss (Pa/m)				177		**Average pressure loss (Pa/m)**				817	
Maximum flow rate(kg/s)				72		**Maximum flow rate(kg/s)**				58	
Maximum pump power (kW)				24		**Maximum pump power (kW)**				79	
Maximum pressure differential (kPa)				268		**Maximum pressure differential (kPa)**				1097	

Table A2 Optimal pipe selection, using exergy method

Exergy method- (T_s/T_r: 65/25 ℃)						Exergy method- (T_s/T_r: 120/70 ℃)					
Pipe No.	**From node**	**To node**	**DN (m)**	**Maximum velocity (m/s)**	**Maximum pressure loss (Pa)**	**Pipe No.**	**From node**	**To node**	**DN (m)**	**Maximum velocity (m/s)**	**Maximum pressure loss (Pa)**
Pipe01	1	2	0.3	1.02	2637	Pipe01	1	2	0.25	1.18	4443
Pipe02	2	3	0.15	0.66	3287	Pipe02	2	3	0.125	0.76	5563
Pipe03	2	4	0.3	0.86	5563	Pipe03	2	4	0.25	0.99	9380
Pipe04	4	5	0.15	0.72	9836	Pipe04	4	5	0.125	0.83	16677
Pipe05	4	6	0.25	0.98	9126	Pipe05	4	6	0.2	1.22	19155
Pipe06	6	7	0.15	0.68	11702	Pipe06	6	7	0.125	0.79	19876
Pipe07	6	8	0.25	0.73	1703	Pipe07	6	8	0.2	0.91	3574
Pipe08	8	9	0.2	0.50	3213	Pipe08	8	9	0.15	0.71	9533
Pipe09	8	10	0.15	0.47	2766	Pipe09	8	10	0.125	0.54	4696
Pipe10	8	11	0.15	0.67	2822	Pipe10	8	11	0.125	0.77	4793
Pipe11	11	12	0.125	0.39	1250	Pipe11	11	12	0.1	0.49	2646
Pipe12	11	13	0.125	0.57	4179	Pipe12	11	13	0.1	0.71	8853
Average pressure loss (Pa/m)				46		**Average pressure loss (Pa/m)**				85	
Maximum flow rate(kg/s)				72		**Maximum flow rate(kg/s)**				58	
Maximum pump power (kW)				10		**Maximum pump power (kW)**				12	
Maximum pressure differential (kPa)				116		**Maximum pressure differential (kPa)**				169	

BASIC METHODS FOR AUTOMATED FAULT DETECTION AND ENERGY DATA VALIDATION IN EXISTING DISTRICT HEATING SYSTEMS

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Keywords: District heating, District energy, Data management, Fault detection, Fault diagnosis, Billing, Automation

ABSTRACT

Fault detection and diagnostics (FDD) of district heating substations (DHS) are important activities because malfunctioning components can lead to incorrect billing and waste of energy. Although FDD has been an activate research area for nearly two decades, only a few simple tools are commonly deployed in the district energy industry. Some of the methods proposed in the literature are promising, but their complexity may prevent broader application. Other methods require sensor data that are not commonly available, or cannot be expected to function well in practice due to oversimplification. Here we present two basic methods for improved FDD and data validation that are compatible with the data acquisition systems that are commonly used today. We propose that correlation analysis can be used to identify substations with similar supply temperatures and that the corresponding temperature difference is a useful quantity for FDD. The second method is a limit-checking approach for the validation of thermal power usage, which is sensitive to faults affecting both the primary flow and temperature sensors in a DHS. These methods are suitable for automated FDD and are demonstrated with hourly data provided by a Swedish district energy company.

INTRODUCTION

District energy management systems deal with substantial amounts of measurement data. Operators find it difficult to detect potential instrumentation and operational problems because of the data deluge and the high system complexity. It is important to have trustworthy measurement information for customer billing purposes. Accurate measurements are also needed for control systems to function properly, so that the overall energy losses are minimized. A district heating substation (DHS), see Fig. 1, is a challenging process for fault detection and diagnostics (FDD) because it is nonlinear; load conditions change in a way that is difficult to predict reliably; the standard instrumentation is designed for control and billing purposes, not for automated FDD; and there are numerous potential sources of errors. A DHS consists of several components that can break down or change behaviour over time, as expected for any kind of instrumentation. For example, incorrect information can be generated if there is a bias change or high level of noise in the signal from a sensor, or if there is a malfunctioning flow meter or temperature sensor. Defect or incorrectly dimensioned valves can degrade the energy efficiency of the system and also need to be detected through the effects on the measurements.

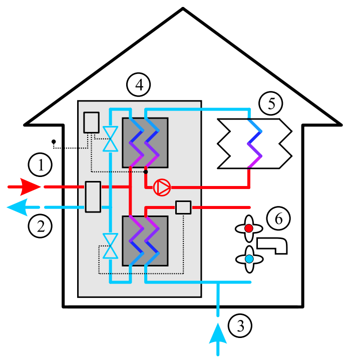

Figure 1. Schematic illustration of a building with a district heating substation (DHS). Indicated in the figure are the primary water supply (1), primary return water (2), tap water supply (3), district heating substation (4), heating system (5), and tap water (6). The DHS includes an electronic energy meter and control system with related sensors and actuators.

Modern energy management systems have integrated alarm and warning functionalities, and tools for data visualization that are used by the operators to detect faults. Limit checking with manually set thresholds for outlier detection [1] is commonly used [2]. This is a difficult task that requires experienced operators. If the thresholds are set too loose, then faults can go undetected. Tight thresholds can cause a deluge of false alarms and warnings that are impossible or expensive to deal with. Therefore, loose thresholds are used and faults can go undetected, or a long period of time can elapse before a fault is detected. This implies that customers can be charged incorrectly, which is problematic for the whole district energy industry. FDD has been an active field of research for nearly two decades, see [1], [3]-[7] for general reviews. There has also been considerable research and development targeted toward developing FDD methods for DHS, see [8]-[11] for examples and reviews. Methodologies that has been proposed include: a sophisticated method for detection of abnormal energy usage in buildings [12] that is based on the generalized extreme studentized deviate (GESD) many-outlier procedure [13] and a modified z-score [14] that quantifies how far away outliers are from typical observations; a data mining approach to detect unexpected changes in the energy efficiency of buildings using algorithmic exploration of district heating billing data [15]; numerous methods for FDD of heat exchangers, see Chapter 10 in [7] for a comprehensive summary and review; attempts to model the time variation of energy usage with analytical models [16]; and FDD approaches based on detection of changes in the correlation coefficient of time series measurements [16]-[17]. A method for detection of abnormal electricity use in buildings that potentially can be generalized to DHS is presented in [18]. It is based on GESD outlier detection for identification of abnormal energy usage, and canonical variate analysis is used to describe the daily electricity consumption so that it can be grouped into different clusters for construction of classification models.

Although there are several generic tools and promising new methods for FDD of DHS, the application of these results is not yet common in district energy systems. The methods that are commonly used for FDD of DHS are simple and typically based on limit checking of quantities [2]. Improved methods for automated FDD that can be applied in the current district energy management systems are needed. The development of such tools are also motivated by the trend towards more demanding energy market regulations and an increasingly competitive energy market, which requires collection of energy distribution data at high rate for accurate control and billing purposes.

There are a number of key components in a district energy substation that potentially can malfunction and lead to errors in the measurement data and reduced system efficiency. Common components include [19]: cables, valves, flow meter(s), temperature sensors, pressure sensors, pipes, heat exchangers, electronic control system and an electronic energy integration unit. Measurement errors can result if any of these components malfunction, which can occur for a number of different reasons. Common faults and issues include [2],[8],[11]:

- Malfunctioning valves, flow meters and temperature sensors.
- Incorrect installation of substation and associated instrumentation. Such as: incorrect cabling causing electromagnetic compatibility (EMC) issues; splices on flow-sensor cables causing pulse-bounces; incorrect grounding or galvanic isolation; incorrect dimensioning of components, such as valves and flow meters; use of sensors and energy meters that are incompatible.
- Incorrect configuration of meters, sensors and control system.
- Faults or reset of energy meters, for example during a blackout or lightning strike.
- Faults introduced during maintenance, or intentionally by customers (fraud).
- Fouling or leakage in heat exchangers and pipes.
- Energy meters are misidentified in the management system.

Faults like these can result in errors in the energy management system, such as:

- Incorrect energy usage information.
- Unrealistic values of measured quantities.
- Drift of sensor values over time.
- Excess noise or fluctuation in measurement time series.
- Constant sensor readings.

In addition to the difficulties mentioned above, FDD of DHS is further complicated because the data that are typically available through the energy management system are sampled approximately once per hour, which is a severe under-sampling for the detection of some faults. The long sampling time also makes it difficult to filter out the heating of tap water, which is irregular and difficult to predict. Furthermore, low-pass filters are not commonly used and the local outdoor temperature sometimes has to be estimated from meteorological data because the locally measured temperature is used by the DHS control system only. Therefore, the measurements have a stochastic component that makes it difficult to design robust and sensitive methods for FDD.

A typical heat meter used in a DHS consists of a few essential parts: two temperature sensors, one flow sensor, and an embedded computer that calculates and communicates the energy flow from the primary side of the DHS. The flow sensor measures the flow through the primary side of the heat exchangers (in indirectly coupled systems) and the temperature sensors measures the temperature of the incoming and returning water on the primary side, see Fig. 1. The energy transfer from the primary supply pipe to the heat exchanger(s) can thereby be calculated by the computer in the heat meter [19]. The data that is commonly available through the heat meter and data acquisition system of district heating suppliers are often limited to the flow and temperature of primary supply and return water. The control system and the sensors on the secondary side of the heat exchanger(s) are typically not the property of the district energy supplier. Therefore, information about that part of the DHS is usually not available. The primary supply temperature, T_{ps}, the primary return temperature, T_{pr}, and the primary flow, V'_p, are used to calculate the thermal energy that is delivered to the substation, which forms the basis for billing. In this work we therefore focus on basic methods for FDD and validation using these quantities. We also limit this work to hourly samples of data, which is common practice in the data acquisition systems used in Sweden, so that the methods can be implemented in the energy management systems using software.

Some modern energy meters have integrated functions for basic FDD, which in principle is an appealing approach since the meter has access to high-resolution measurement data. A major difficulty preventing the common use of this functionality in current district energy systems is the risk of generating a deluge of warnings and false alarms due to incorrect or improper configuration, which is non-trivial to change and would cause problems in the data acquisition systems that may prevent reliable collection of information needed for billing.

METHODS

For a method to be applicable in existing DHS and management systems it should fulfil a few practical requirements; the method should only depend on information and measurement data that is commonly available through the management system; the method should enable improved detection and / or diagnosis of faults; the method should require a minimum of human involvement after implementation. If these basic requirements are not met the proposed method would require substantial investments, or it would be useless. Several proposed methods for the detection and diagnosis of faults in district heating systems fail to comply with one or more of these requirements and are therefore not widely used today. In particular, this is often the case for precise model-based methods because they depend on information from sensors that do not exist, or sensors on the secondary side of the heat exchanger(s) that are not commonly accessible through the management system. The methods proposed here have been defined in collaboration with representatives from eight Swedish district heating companies, two companies that develop software for energy distribution systems and the Swedish District Heating Association [2]. This collaboration was organized to make sure that the proposed methods address relevant problems in a feasible way. Focus here is on basic methods for FDD that can be applied and implemented in current district energy systems using software.

Validation of the primary supply temperature

The primary supply temperature varies with the outdoor temperature, see Fig. 2. A common method used for fault detection using the measured primary supply temperature is limit checking with a constant threshold set slightly above the maximum expected temperature. This means that a threshold for T_{ps} is defined, and that an alarm is raised if the measured T_{ps} exceeds that threshold. Another test that is commonly used is that the primary return temperature should be lower than the primary supply temperature. A technical fault that leads to a drift or fluctuation of the primary supply temperature can remain undetected for an extended period of time when these methods are used, especially during seasons when T_{ps} is low. A more sensitive method for validation of the primary supply temperature is therefore needed.

There are many DHS in a district heating system that are connected to the same supply pipe and therefore should have similar supply temperatures. Therefore, we propose that the supply temperature can be validated by comparison with one or a few nearby DHS, see Fig. 3.

Geographical variations of the supply temperature are expected due to thermal losses in the distribution network, and this effect is more prominent at long distances and low flows through the primary side of the heat exchangers. It is therefore important to compare the supply temperatures between DHS that have similar supply temperatures. If coordinates of the DHS are available, one can use that information to identify geographical neighbours for the comparison. However, we find that the correlation coefficient between two

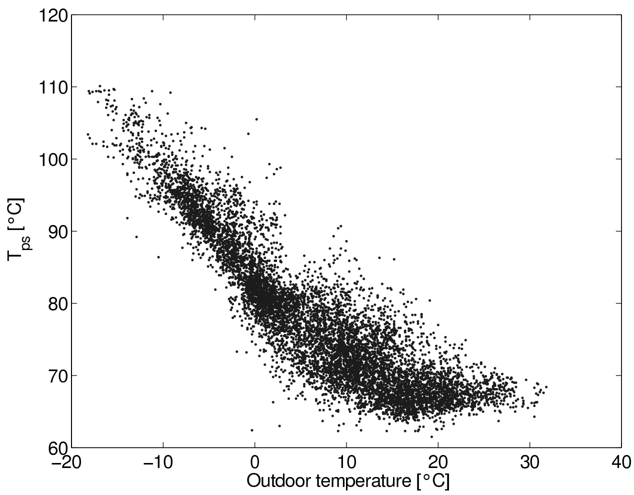

Figure 2. The primary supply temperature versus the outdoor temperature. This is a typical example that illustrates how the supply temperature measured in a DHS can change with respect to the outdoor temperature.

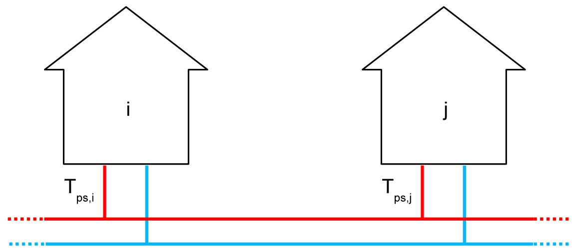

Figure 3. The primary supply temperature, $T_{ps,i}(t)$, of one substation i can be compared with the supply temperature, $T_{ps,j}(t)$, measured at another substation j located in the same district heating network.

supply temperature time series $T_{ps,i}(t)$ and $T_{ps,j}(t)$ is a better indicator of the similarity of the two supply temperatures than the geographical distance. This is to be expected, because a short distance between two DHS does not guarantee that they are connected to the same segment of the distribution network. Another benefit of using the correlation coefficient is that geographical coordinates of the DHS are not needed. Coordinates can anyway be used to identify a subset of nearby DHS that may have highly correlated supply temperatures to reduce the time needed for calculation of the correlation coefficients. Using this method we find that the one-day moving average of the difference $\Delta T_{ps}(t) = T_{ps,i}(t) - T_{ps,j}(t)$ between DHS is a few degrees Celsius. Therefore, this difference is a useful quantity for detection of abnormal changes in the supply temperature of a DHS. Faults can be detected through limit checking with constant thresholds for the average and standard deviation [1] of $\Delta T_{ps}(t)$; see the next section for further information.

For this method to work properly one has to account for the seasonal variations of the supply temperature, otherwise the correlation coefficient is dominated by seasonal variations and does not give a useful indication of the similarity of the supply temperatures, see Fig. 4. The process of removing long-term trends and seasonal variations from time series is called detrending. Four common detrending approaches are [20]: differencing, curve fitting, filtering, and piecewise approximation with polynomials. For example, a time series that is non-stationary in the average can be made stationary by taking the first difference of the samples, x(t), at time t and t-1, w(t) = x(t) - x(t-1), where t is given in units of the sampling time. First-order differencing is used here and it has a significant effect on the correlation coefficient of supply temperatures, see Fig. 4. We find that the comparison of supply temperatures between DHS with highly correlated $T_{ps}(t)$ results in a smaller temperature difference and is the preferred method. The DHS with the highest correlation coefficient is often a geographical neighbour, but not necessarily the closest neighbour. Preliminary results obtained using this method are presented in the next section.

Validation of the primary flow and return temperature

We have so far not identified a robust method that enables FDD of the primary flow and return temperature independently. Unlike the case with the primary supply temperature, there is no explicit redundancy in the sensor system that can be used to validate these quantities. This problem can possibly be solved in cases where the DHS and management system can provide information about the flow and temperatures on the secondary side of the heat exchanger(s) [7]-[8]. Another difficulty is that direct

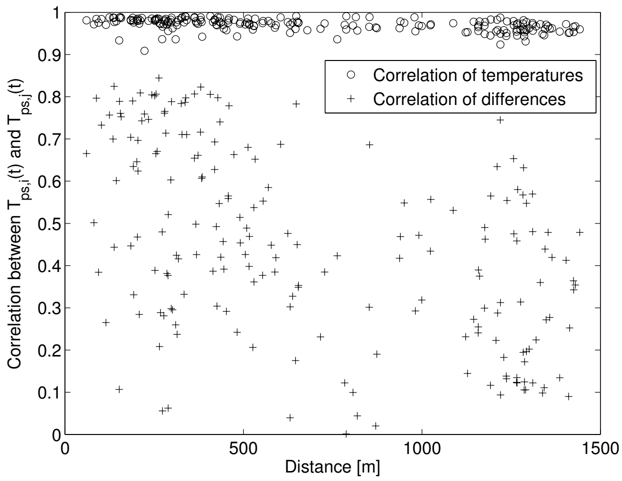

Figure 4. Correlation between the time series of primary supply temperatures $T_{ps,i}(t)$ and $T_{ps,j}(t)$. The values of $T_{ps,i}(t)$ originates from the same substation as that in Fig. 2. The values of $T_{ps,j}(t)$ comes from 200 nearby substations. The sequences $T_{ps,i}(t)$ and $T_{ps,j}(t)$ are highly correlated because of the common seasonal variations. First-order differencing of $T_{ps,i}(t)$ and $T_{ps,j}(t)$ reduces the influence of the seasonal variation and leads to a more discriminating indicator for the similarity of the supply temperatures.

measurements of the primary flow are not always available, and may anyway be useless due to fluctuations caused by the commonly used pulse-based signalling system between the flow meter and the energy integration unit. It has been suggested [17] that flow and temperature sensors should be low-pass filtered to improve the quality and usefulness of DHS measurement data, but such techniques have not yet been widely adopted by the industry. The hourly flow and thermal power information that is commonly available through the DHS management system is calculated by the energy meters and represent hourly averages of these quantities.

The thermal power reported by the energy meter of a DHS is an important quantity for FDD because it is related to the billing information and the contract with the district heating supplier, and it depends in a characteristic way on the outdoor temperature, see Fig. 5. The thermal power is calculated by the energy meter of a DHS using T_{ps}, T_{pr}, and V'_p. Therefore, faulty values for any measurement of these three quantities can lead to an incorrect thermal power value, which in turn affects the billing information. A common method used for validation of thermal power values is limit checking with linear thresholds [2]. For example, linear upper- and lower-limit thresholds that are set at a certain relative distance from the mean of the trend in a specific interval of outdoor temperatures can be used. If a thermal power value does not lie in-between these thresholds that data point is tagged, and it can be replaced with the average power value at that outdoor

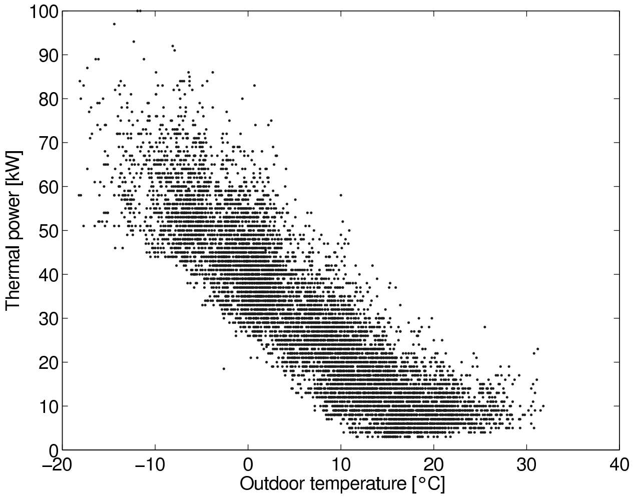

Figure 5. Thermal power versus the outdoor temperature. The data illustrated here originates from the same substation as that in Fig. 2. These values represent one-hour averages of the thermal power and are calculated by the energy meter in the substation using T_{ps}, T_{pr}, and V'_p.

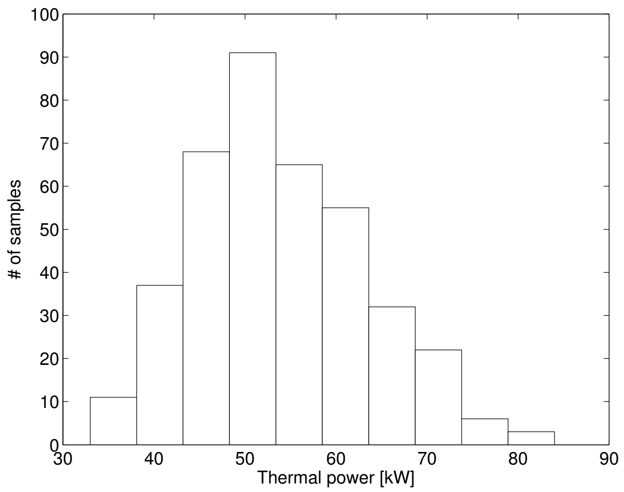

Figure 6. Distribution of hourly thermal power averages at an outdoor temperature of -5 ± 1 °C. The data represented here originates from the same substation as that in Fig. 5.

temperature. This method is insensitive to faults because the linear thresholds must be set at a safe distance from the average trend to avoid false alarms. Another problem is that faults causing constant sensor values can remain undetected for extended periods of time when this method is used. For example, a malfunctioning valve or flow sensor can lead to a constant flow value and an incorrect thermal power value that cannot be detected until the outdoor temperature has changed significantly. A more sensitive method for validation of the thermal power delivered to the substation is therefore needed.

The method for detection of abnormal energy usage in buildings developed in [12] is one interesting example that deserves further development and testing. Here we introduce a similar but, perhaps, less advanced and more comprehensible approach for fault detection using the thermal power values. Instead of using linear thresholds for outlier detection in the relation between thermal power and outdoor temperature, it is possible to set constant thresholds on the average and standard deviation of the thermal power within limited intervals of the outdoor temperature. This is a basic method used in FDD, see Chapter 7 in [1], which has a few benefits compared to the outlier detection method described above. First, the moving average and standard deviation of the thermal power varies less than the power values themselves. Therefore, more tight thresholds can be used. Second, thresholds on the standard deviation can be used to detect abnormal fluctuations in the measurement data. For example, EMC problems and a stuck valve or flow meter can potentially be detected with this method.

An example illustrating how the thermal power values are distributed at a certain range of outdoor temperatures is presented in Fig. 6. The shape of this distribution varies between substations and it is caused by multiple effects; the thermal power needed to heat tap water varies over time; the local outdoor temperature is not accessible through the data acquisition system of the heat supplier in this case and therefore needs to be estimated from meteorological data; and trends in the outdoor temperature are not considered here. For example, the thermal power needed at -5 °C can be lower during a transition from higher to lower temperature compared to a transition in the reversed direction. The moving mean and standard deviation of this distribution is likely to change when a fault appears. If the mean and standard deviation before (after) the introduction of the change are denoted by μ_0 and σ_0 (μ_1 and σ_1), the following cases can be identified:

- The mean changes; $\mu_1 = \mu_0 + \Delta\mu$. $\sigma_1 = \sigma_0$.
- The standard deviation changes; $\sigma_1 = \sigma_0 + \Delta\sigma$. $\mu_1 = \mu_0$.
- Both the mean and the standard deviation change.

There are a number of classical tools for the detection of such changes, see chapters 7.3-7.5 in [1]. A basic example is detection of changes in the mean with binary thresholds that are set relative to the standard deviation, which is a test that is analogous to the method based on linear thresholds for outlier detection that is described above. This method works well as long as the change of the mean that is to be detected is larger than the standard deviation. If that is not the case, then theory of statistical hypothesis testing has to be applied. Basic examples are the Student's t-test or Run-sum tests for detection of a change in the mean of a (normal) distribution, and the F-test for detection of a change in the variance. While these methods enables detection of small changes in the mean and standard deviation, they require numerous measurements before and after the change occurred, which prevents early detection of faults. A combination of tests based on binary thresholds and statistical hypothesis testing for both the mean and standard deviation / variance is therefore motivated. It should be noted, however, that these hypothesis tests are only precise for normally distributed residuals and therefore are approximate methods when used in this context.

An issue that further complicates FDD using limit checking and hypothesis testing with thermal power data is that the power can vary significantly with the weekday and the time of day, in addition to the seasonal variations that are linked to the outdoor temperature. For example, such changes can result from scheduling of ventilation and heating systems in buildings used for stores, offices and schools. A pattern recognition algorithm for determining days of the week with similar building energy consumption profiles is presented in [21]. In the case of DHS we find that a simple clustering analysis is sufficient to distinguish time periods during a week with significantly different thermal power values, which typically occurs when the outdoor temperature is low; see the next section for results. Clustering algorithms that can be used include the classical k-means algorithm and density based clustering [22].

RESULTS

The examples presented in this paper are based on real-world data provided by a district energy company that is based in Stockholm. The data was extracted from the management system and is recorded at one-hour intervals for a period of about one year. Here we present preliminary results obtained using the methods that are introduced in the previous section.

The difference of primary supply temperatures, $\Delta T_{ps}(t) = T_{ps,i}(t) - T_{ps,j}(t)$, of two nearby substations i and j at different primary flows is presented in Fig. 7. The values of $T_{ps,i}(t)$ originates from the same substation as that in Fig. 2. The values of $T_{ps,j}(t)$ comes from a nearby substation that is selected in two different ways; in one case the substation j is located at a minimum geographical distance from the substation i; in the other case substation j is selected so that the correlation between the first-order differences of $T_{ps,i}(t)$ and $T_{ps,j}(t)$ is maximal, see Fig. 4 and related text for further information. The latter approach has the advantages that information about the geographical coordinates of the substations are not needed, and it usually results in a more narrow distribution of $\Delta T_{ps}(t)$, which is beneficial for fault detection with limit checking. Typically, the difference $\Delta T_{ps}(t)$ is a few degrees Celsius and decreases with increasing flow. The trend towards increasing $|\Delta T_{ps}(t)|$ at low flow is rather steep in these examples. It is not uncommon that the maximum variation of $|\Delta T_{ps}(t)|$ is 2–3 °C. Therefore, faults can be detected through limit checking with constant thresholds for the moving average and standard

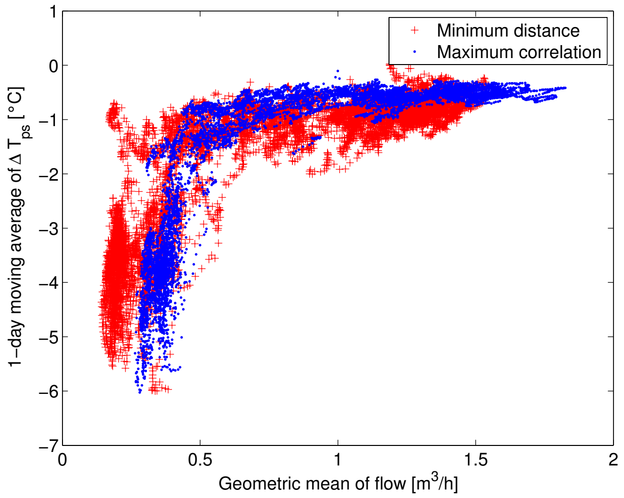

Figure 7. Differences of primary supply temperatures of nearby substations, see Fig. 3 and the text for further information.

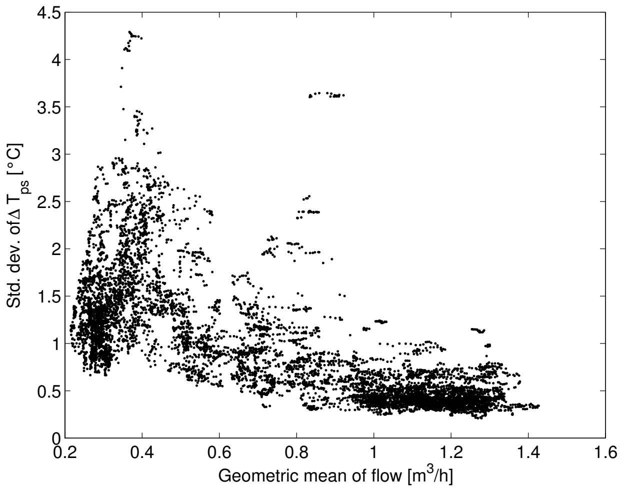

Figure 8. One-day moving standard deviation of $\Delta T_{ps}(t)$ for the high-correlation example illustrated in Fig. 7.

deviation of $\Delta T_{ps}(t)$, possibly using different thresholds in the low- and high-flow domains. The moving standard deviation of $\Delta T_{ps}(t)$ is also a useful quantity for FDD because it varies within a few degrees Celsius, see Fig. 8 for one example.

The geometric mean of two flows is defined as the square root of their product. Other measures of the effective flow is possible, but the geometric mean is a simple function that discriminates between the high-flow domain, where the supply temperatures are similar, and the low-flow domain where the effect of cooling of the supply water is more prominent and the difference between the supply temperatures can be higher. An example illustrating the relationship between the geometric mean of the flows and the outdoor temperature is presented in Fig. 9.

In Fig. 10 we present estimates for the variation of the one-day moving averages and standard deviations of $\Delta T_{ps}(t)$ at high flow for 200 different DHS. For each

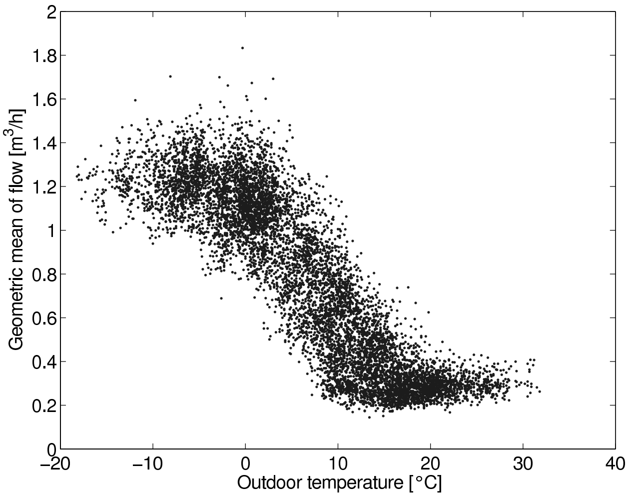

Figure 9. Relationship between the geometric mean of the primary flows and the outdoor temperature. This example corresponds to the high-correlation example in Fig. 7.

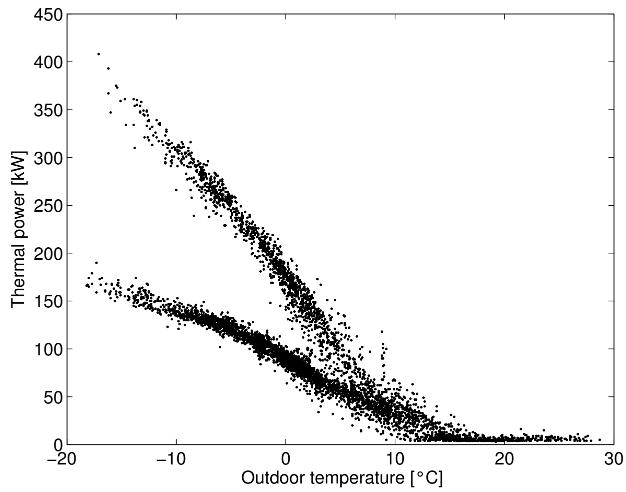

Figure 11. Example of a DHS located in a building with offices and stores, which has a time-varying thermal power need. Compare with Fig. 5.

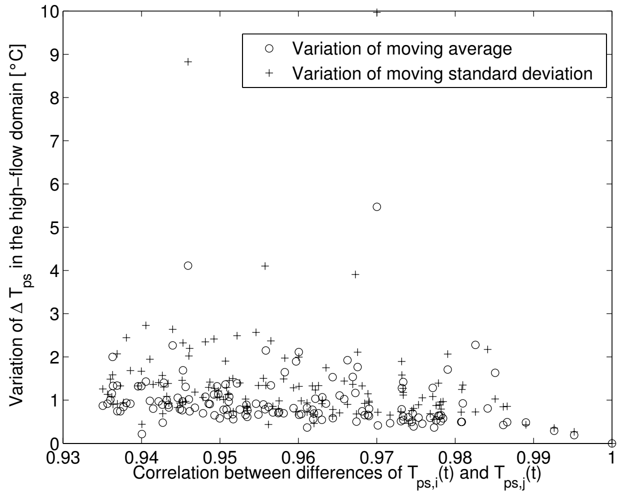

Figure 10. Variation of the one-day moving average and standard deviation of $\Delta T_{ps}(t)$ at high flow for 200 district heating substations. The variation corresponds to the difference between the maximum and minimum value of the moving average or standard deviation.

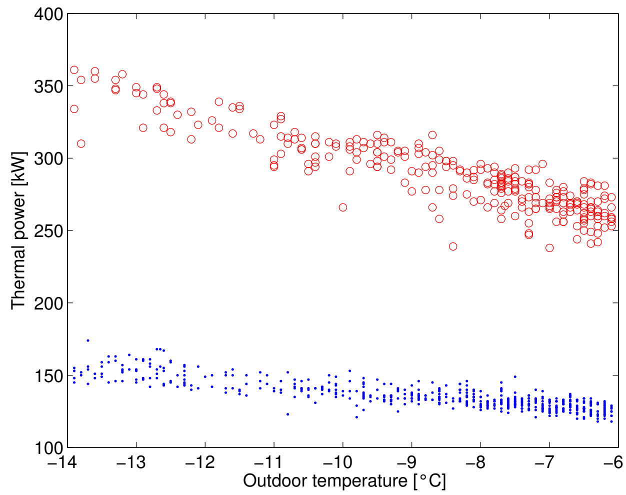

Figure 12. Cluster analysis of the thermal power usage at low outdoor temperatures for the example illustrated in Fig. 11. Two clusters are identified, one at high thermal power (red open disks) and one a low power (blue dots).

DHS the median of the geometric mean of the flows is calculated and all data points with a mean flow that is higher than the median are included in the estimate. The variation is calculated as the difference between the maximum and minimum average (or standard deviation) of $\Delta T_{ps}(t)$ at mean flows higher than the median. The majority of these 200 substations have variations that are lower than three degrees Celsius. A few percent of the substations have higher variations and are worth investigating in more detail, for example in order of decreasing variations for the mean and standard deviation. A manual inspection of the outliers identified here reveals that the corresponding $\Delta T_{ps}(t)$ have jumps and suspect clusters of outliers that were recorded during brief periods of time.

Next, we illustrate how cluster analysis can be used to define different fault detection conditions for different weekdays and time of day. This is useful when the power needed by a DHS varies significantly over time, for example between office hours and nights, see Fig. 11 for one example.

In this case a limit-checking approach with a linear upper and lower threshold values is insensitive to faults because the thresholds need to be set at safe distances from the two tails. Therefore, different limit-checking conditions should be used for the two tails. Clustering analysis of the thermal power data at low outdoor temperatures can be used to discriminate between measurement values that belongs to different tails, see Fig. 12. Each data point corresponds to a particular weekday and time of day. Therefore, schedules for the time of high and low thermal power usage can be generated, see Fig. 13. In this case the DHS uses more power during office hours compared to weekends and nights.

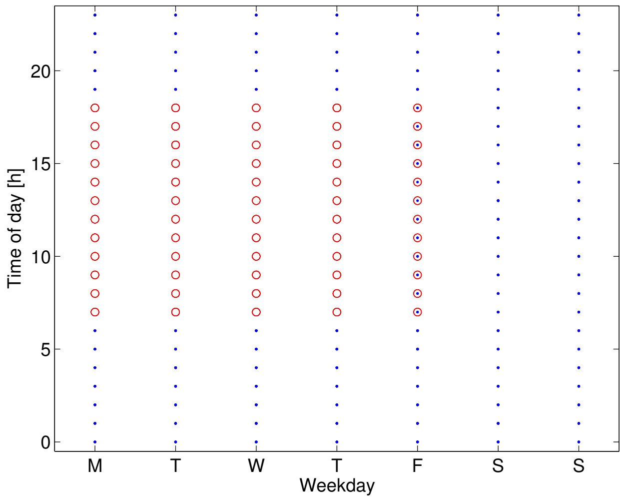

Figure 13. Schedule illustrating periods of high and low thermal power usage for the clusters identified in Fig. 12.

CONCLUSIONS

We propose two basic methods for improved FDD of DHS and preliminary results using hourly measurement data. Correlation analysis can be used to identify DHS with similar supply temperatures and the corresponding temperature difference is a useful quantity for FDD with a precision of a few degrees Celsius, which is a significant improvement over currently used methods. The second method is a further development of a method currently used for fault detection of the thermal power usage. It uses the moving average and standard deviation of the power for more robust and sensitive fault detection with limit checking, and cluster analysis for definition of fault detection conditions. The proposed methods are based on basic FDD tools and are compatible with current data acquisition systems. They can therefore be further tested and implemented with software in district energy management systems at low cost.

ACKNOWLEDGEMENT

This project is part of the research program Fjärrsyn, which is operated by the Swedish District Heating Association using funds from associated district energy companies and the Swedish Energy Agency.

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N-DIMENSIONAL FAULT DETECTION AND OPERATIONAL ANALYSIS WITH PERFORMANCE METRICS

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Keywords: Operating reliability, Operational visualization, Fault detection, Performance metrics, Contour mapping

ABSTRACT

A district heating consumer substation is a complex entity, consisting of a range of interacting components such as valves, pumps, heat exchangers and control systems. The energy efficiency of a consumer sub-station is dependent on several things, e.g. settings of the control system, dimensions and operational behaviour of hardware and accumulation of sediments in the heat exchanger. Visualizing this operational functionality of consumer substations has been studied in several previous projects.

This paper addresses certain shortcomings inherent in those previous works by presenting a novel visualization approach using parallel coordinates and scatter plot matrices. A comparison between these and previous visualization techniques is presented and discussed. Furthermore, the paper presents a scheme for statistical analysis based on n-dimensional relationships found in parallel coordinates and scatter plot matrices, thus providing key performance indicators appropriate for large-scale detection and analysis. It is shown that the presented visualization techniques are at least equal to previous attempts in regards to fault detection and operational analysis, while simultaneously addressing several of their shortcomings. Furthermore, it is shown that the subsequent statistical analysis provides a workable starting point for system-wide fault detection and analysis within any district heating system.

INTRODUCTION

Faulty hardware such as pumps and valves or soil accumulation within the heat exchanger can, and most likely will, result in deteriorating operational behaviour and can over time cause substantial financial damage. Furthermore, substandard operational behaviour in a consumer substation not only affects the individual building but might also influence the district heating system as a whole, e.g. causing increased primary return temperatures. Thus, there is incentive for both property owners and energy companies to detect faults and deviating operational behaviour as well as arranging for possible repair and readjustment.

Fault detection in consumer substations have been studied extensively in previous work, and a range of different approaches in regards to fault detection have been presented and evaluated. An interesting fault detection scheme which has been previously presented is fault detection using contour mapping. Contour mapping visualizes primary return temperatures and mass flow in relation to time and outdoor temperature. By using contour mapping it is possible to visualize large amounts of operational data in a single figure, which greatly streamlines the practical analysis process. However, contour mapping does retain some issues regarding computational load during generation, susceptibility to errors during the extra-/intrapolation process, subjectivity during evaluation phase resulting in lack of automation potential and being confined to the three-dimensionality present in maps. This paper studies these problems and compares contour mapping to other visualization techniques, namely parallel coordinates and scatter plot matrices. Furthermore the paper studies the potential for extended performance metrics analysis using statistical techniques in order to facilitate large-scale analysis. Specifically the problem of analysing the relationships between different variables is studied. Also, outlier detection is discussed and a technique for automated outlier management is presented.

RELATED WORK

Fault detection and operational analysis in consumer substations have been the focus of much research for many years. Previous work has shown the potential inherent in analysing collected data, and has also presented work-flow overviews of the process as in [1] and [2]. The basic idea has been to find a way to prioritize between all consumer substations present in a district heating system in order to pin-point substations with technical, and by extension financially, sub-optimal behaviour. These papers study the functionality and quality of service as well as the efficiency of the substation.

Similar work is presented in [3] which investigate five different methods for fault diagnosis in consumer substations. This paper uses similar data analysis as well as simulation and modelling of components within the substation.

Further work is presented in [4] which focus on fault detection by using data available through the heat meter, i.e. temperatures and mass flow on the primary side of the substation. Furthermore, this paper evaluates the possibilities for separating hot water energy consumption in relation to the total district heating usage.

It is becoming increasingly common that energy companies use hourly measurement data collected from the heat meter. This obviously increases the size of the dataset which in turn increases the need for automated analysis methods. In [5] two methods for identifying incorrect measurement data are presented. The first method is based on a simulation model which uses historical data in order to estimate feasible datasets. The second method is based on a statistical model which correlates operational data among consumers with similar consumption behaviour.

The problem of analysing the increasing amounts of data was further studied in [6]. Previous work was focused on detecting faults, while this paper presented a way to visualize the data through the use of contour mapping in order to facilitate the fault identification process. This work was later extended in [7] which aimed to increase the efficiency of the process.

In [7] it was shown that energy companies already working with process supervision were facing severe problems due to increasing amounts of data. This problem is in no way limited to district heating systems. The problem of visualizing large amounts of data is studied in the scientific fields of *scientific visualization* and *information visualization*. Scientific visualization deals with data that have correspondence in physical space, whereas information visualization deals with visualization of abstract data that doesn't necessarily have a relation to the physical world [8]. The main idea is to amplify cognition by using visual artefacts. In [9] the process of understanding data is described thoroughly through the "continuum of understanding". This continuum is defined as starting with *data*, which are entities which in themselves lack any meaning. An example of data might be a temperature reading from a substation. The second step of the continuum is *information*, where the data is processed, organized or otherwise presented. An example would be to sort the temperature data in relation to time or other measurement data. The third step is *knowledge*, were the information provided through the previous step is understood through experience in regards to the process in question. The fourth and final step is *wisdom*, in which an advanced level of understanding of the underlying processes makes it possible to express qualified judgement.

In order to manage the large amounts of data generated within modern district heating system it is imperative that the technical analysis systems used transcend from the first step of *data* presentation to the second and third step of *information* and *knowledge* presentation.

N-DIMENSIONAL ANALYIS

A consumer substation is a pseudo-chaotic system in that it is largely predictable from a macroscopic viewpoint, while being highly stochastic on a microscopic level. This basically means that even if it is impossible to predict when individual people will, for example, take a shower and thus activating hot water usage, it is possible to predict that the building will on average increase its energy utilization as the outdoor temperature drops. In this paper we are interested in the operational behaviour on a macroscopic scale as an average of the function of the consumer substation in question.

The sensory equipment in a consumer substation provides a wealth of measurement data. On the primary side the heat meter will measure the supply and return temperature as well as the mass flow which is available to the energy company for billing purposes. Many modern control systems provide facilities for measuring and saving data on the secondary side of the substation, e.g. supply and return temperatures in the heating system. In addition to this many building owners have installed systems for measuring and collecting indoor temperature data. All information contained in this dataset represents the operational status of the substation and building.

By examining these variables and how they relate to each other it is possible to evaluate the status of the substation. In n-dimensional analysis the relationships between these different variables are studied. In contour maps these relationships are visualized in a map where $n = 3$, i.e. outdoor temperature, hour and return temperature or mass flow. This is done in order to study the relationship between these three variables, since they have to be put in relation to each other in order to make sense. In contour mapping the purpose is actually to do a $n = 4$ analysis. Since contour maps cannot represent more than three dimensions, two contour maps have to be made which are then subjectively compared.

Using such methods it is possible to evaluate the relationships, such as how the return temperature changes in relation to mass flow fluctuations during different times of day and outdoor temperatures. It is the relationship between these variables which are important for the analysis, and not the variables themselves.

OUTLIERS

An outlier is a measurement which is numerically far apart from the main body of data. Outliers can have many reasons in general, although in relation to a consumer substation they are mostly caused by measurement errors. Outliers have a tendency to distort visualization efforts and disturb analytical analysis, which makes it important to properly manage them. It is not uncommon for outliers to be present in operational measurement data. If this data is used in an automated analysis or control process, these outliers must not only be detected, but also somehow managed and possibly removed. Algorithmically rejecting outliers is sometimes not considered good scientific practice. However, it can be argued that it is appropriate in cases where the error distribution is known within some confidence. For example, in the case of a consumer substation it might be considered safe to assume that certain mass flow levels or temperature variations must be measurement errors.

PARALLELL COORDINATES AND SCATTER PLOT MATRICES

Parallel coordinates is a visualization technique in which every attribute corresponds to a vertical axis [10]. These axes are arranged in parallel by equal distance. The relationships between the variables are shown as lines from one axis to another. Parallel coordinates is a powerful tool for evaluating the correlation between large groups of variables. There are two main management tools for parallel coordinates which are present in most visualization software packages. The first tool is the ability to re-order the axes, which makes it possible to arrange variables in suitable order to ease the study of their relationships. The other tool is brushing, were certain intervals of a variable can be chosen. This makes it easy to follow the relationship among the entire set of variables. The figure shows parallel coordinates with and without brushing (Fig. 1). The brushing is done on the outdoor temperature variable at an interval around 4-4.5°C.

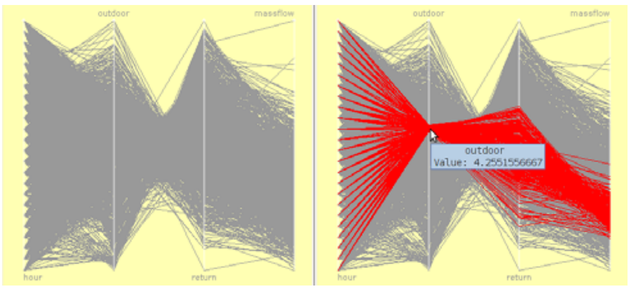

Fig. 1 Parallel coordinates with (right) and without (left) brushing

A scatter plot matrix is an extension of the common 2-dimensional scatter plot [10]. A single scatter plot is obviously restricted to two dimensions, but by arranging scatter plots side by side in a matrix form it is possible to extend the dimensionality. This will result in an n by n matrix, where n equals the number of variables being studied.

PERFORMANCE METRICS

The mean, median and standard deviation is the starting point for the performance metric analysis. These values form a foundation for much of the metrics described in this paper and are further described in [11]. The mean is simply the average of the dataset in question, i.e. given a set of data $\{x_1, \ldots, x_n\}$, the arithmetic mean $\bar{x}$ is defined as in (1).

$$\bar{x} = \frac{x_1 + x_2 + \cdots + x_n}{n} = \frac{1}{n}\sum_{1=n}^{n} x_i \qquad (1)$$

For a dataset with an odd number of observations the median m is defined as shown in (2).

$$m := (n+1)/2)th\ value \qquad (2)$$

With an even number of values m is defined as shown in (3).

$$m \coloneqq \left[(n/2)th\ value + \left((n/2)+1\right)th\ value\right]/2 \qquad (3)$$

The standard deviation σ is defined as shown in (4). The part under the square root sign is the variance of the data.

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad (4)$$

Tests for outliers are normally based on an assumption that the dataset has a bell-shaped probability density function, i.e. that the data follows a Gaussian distribution. In regards to consumer substation data this implies that the dataset to test for outliers should not be the entire dataset, but rather a series of filtered subsets of this. The reason for this is that a Gaussian density function assumes a univariate dependency. For example, if return temperature sensory data is collected throughout a heating season this dataset will not have a univariate dependency since the return temperature changes in relation to other variables such as the mass flow which in turn is dependent on other variables such as the outdoor temperature, thereby giving the dataset a multivariate dependency. In order to perform analytical outlier detection the data should therefore be sorted into subsets with univariate dependency, e.g. in the case of the return temperature the data might be ordered in relation to intervals of outdoor temperature and hour of the day. Incidentally this is exactly what is done during contour mapping, indicating the relationship between these techniques. However in the case of analytical performance metrics the resulting data is easier to evaluate since it is presented as an objective numerical value instead of a map-like display open to subjective interpretation.

The mean alone cannot be used to find outliers since it is not robust [12]. However, the quota between the mean and median can be used as a simple outlier detection metric. One problem with this quota metric is that is relative to the type of dataset in question, e.g. the quota confidence interval for the primary return temperature is different from the mass flow quota interval. Furthermore, this metric is sensitive to the amount of outliers present. However, based on its computational simplicity it can still be used to rank the content of large datasets. Other, slightly more complex, metrics include Chauvenet's criterion, Peirce's criterion or Grubbs' test for outliers [13].

Chauvenet's criterion uses $\bar{x}$ and σ. First the difference between the data point and $\bar{x}$ is compared to the size of σ. This value is then used to estimate the probability of this data point occurring in relation to the data distribution. Based on this probability the statistic value can be calculated. If the statistic value is less than 0.5 the data point is tagged as an outlier according to Chauvenet's criterion. The value of 0.5 implies a Gaussian function with $\sigma^2 = 1$. In this paper a lower value is used (0.1) which implies $\sigma^2 > 1$. This is an adjustment to empirical observation which has shown that the dataset in question normally follows a Gaussian distribution with larger standard deviation.

A critical aspect of performance metric analysis is to evaluate the strength of the relationship between two or more variables, in order to identify faults and operational status. Such correlation analysis is normally performed by using multiple regression procedures. In its simplest form this is the 2-dimensional example, which can be visualized through a scatter plot and formally represented as in (5).

$$\boldsymbol{Y} = a + b\boldsymbol{X} \tag{5}$$

However, this can easily be extended into n-dimensional space using a linear equation of the form shown in (6).

$$\boldsymbol{Y} = a + b_1\boldsymbol{X}_1 + b_2\boldsymbol{X}_2 + \cdots + b_{\boldsymbol{n}}\boldsymbol{X}_{\boldsymbol{n}} \tag{6}$$

The basic idea is to analytically evaluate the relationships between variables such as return temperature, mass flow, outdoor temperature and time of day.

The issue with multivariate dependency is equally important regarding operational analysis, especially since the multiple correlation process is not commutative. This means that the order in which the different variables are compared matters. In order to extend the visualization techniques into a performance metric the data is first sorted and intra/extrapolated in regards to time of day and outdoor temperature. The resulting matrix can then be intersected across outdoor temperature intervals and evaluated through correlation techniques. In this paper we use the Pearson correlation coefficient to evaluate the relationship between variables [14]. The Pearson correlation coefficient is a value between +1 and -1, showing the relationship between variables. The Pearson correlation coefficient is described as shown in (7)

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \tag{7}$$

RESULTS

Comparing visualization techniques is a highly subjective process, although scientific rigor can be achieved through standardized statistical analysis of empirical research [15]. In this paper we compare two consumer substations (A and B) using (i) contour mapping, (ii) parallel coordinates together with scatter plot matrices and (iii) analytically calculated performance metrics. A third consumer substation (C) is also studied on the basis that the data-set contains known outliers. The evaluation of (i) and (ii) are obviously somewhat subjective. However, the inclusion of (iii) provides an analytical basis for comparison.

All these three consumer substations are similar in basic technical set-up in order to minimize extraneous influences. Furthermore, they all have similar tap water usage profiles.

All temperature values are shown in °C, while all mass flow values are shown in kg/hour.

Operational analysis

The operational status of substations A and B is such that A is considered to be functioning well, while B is showing clear signs of soil accumulation within its heat exchanger. The relation between primary return temperature and mass flow in substation A is visualized using contour mapping (Fig. 2). In the figure it is easy to see that increased mass flow is correlated with decreasing return temperatures, which is to be expected in a normally functioning substation.

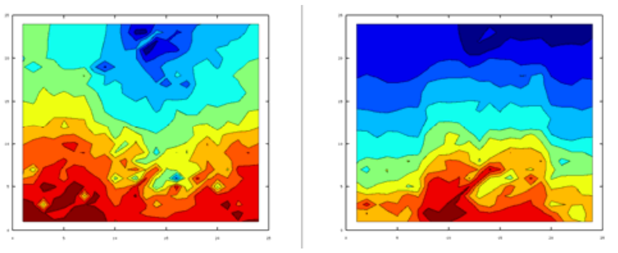

Fig. 2 Contour maps with return temperature (left) and mass flow (right) in substation A

The dataset from substation B is then visualized using the same technique (Fig 3).

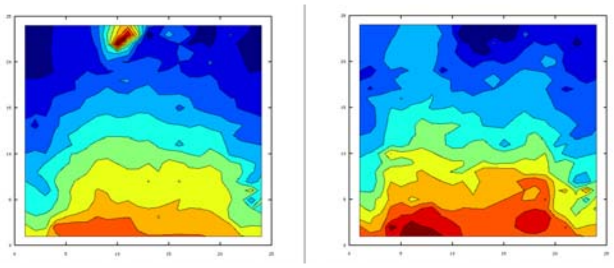

Fig. 3 Contour maps with return temperature (left) and mass flow (right) in substation B

In Fig. 3 it is apparent that the relationship between the return temperature and the mass flow are reversed compared to Fig 2. The heat exchanger isn't able to cool off the water flowing through it as the mass flow increases, which implies some level of soil accumulation.

The dataset from substation A is then visualized through the use of parallel coordinates and scatter plot matrices (Fig. 4).

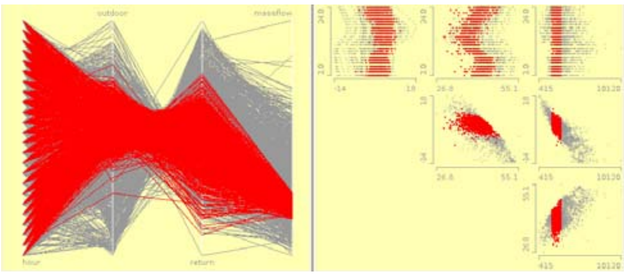

Fig. 4 Parallel coordinates and scatter plot matrix for substation A

The data has been brushed in relation to an area of mass flow data in order to visualize the relationship within the three other dimensions showing return temperature, outdoor temperature and time of day. The corresponding visualization is also done regarding substation B (Fig. 5).

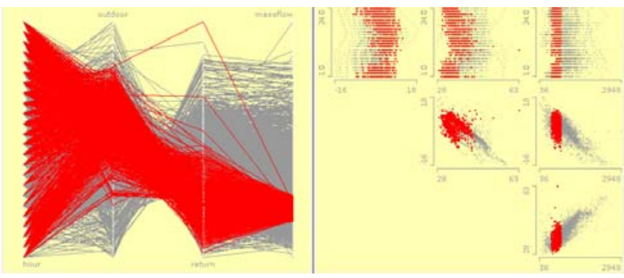

Fig. 5 Parallel coordinates and scatter plot matrix for substation B

Comparing Fig 4 and Fig 5 it is apparent that the former has a more pronounced inverse relationship between mass flow and return temperatures. The scatter plot matrix help establish the distribution of these relationships. By further brushing it is possible to follow the relationships between the four variables.

The same datasets from substation A and B are then evaluated using performance metrics in order to identify and quantify the relationships visualized through contour mapping and parallel coordinates together with scatter plot matrices. The resulting values are shown in Table 1.

Table 1 Operational analysis using performance metrics

	A – ret	***A –flow***	***B – ret***	***B – flow***
Max	55.09	10120	63	2947.5
Min	26.9	415	27.5	36.167
Mean	43.763	3040.4	38.79	928.8
Median	43.802	2820	38.17	888.5
Pearson	-0.66		0.86	

The performance metrics in Table 2 provides numerical values to the relationship between the return temperature and the mass flow. Using visualization techniques it is only possible to subjectively identify this relationship, without providing an absolute frame of reference for it. In the data it is clear that substation A is functioning better than B, since there should be a negative relationship between these two variables, i.e. when the mass flow increases the return temperature should decrease.

Outlier detection

The dataset from substation C contain erroneous data in the form of severe measurement errors. It is obvious that the contour mapping becomes heavily distorted when such outliers are present (Fig. 6).

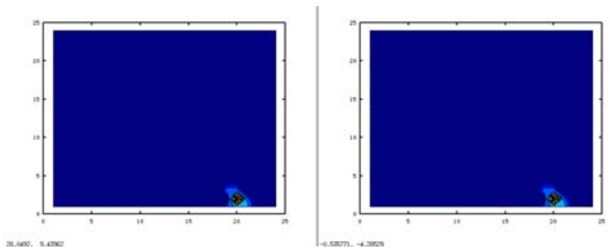

Fig. 6 Outliers in contour maps

Likewise, it is easy to identify the outliers using parallel coordinates and scatter plot matrices (Fig. 7).

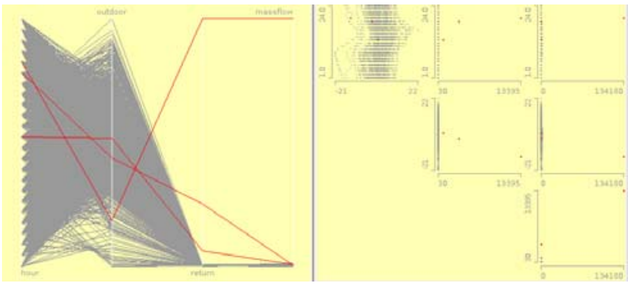

Fig. 7 Outliers in parallel coordinates and scatter plot matrix

Even without brushing it is easy to identify the outliers in the parallel coordinates, and the scatter plot matrix display a distinct compression of the main dataset due to the presence of these outliers. However, for clarity the three outliers are brushed in relation to primary return temperature.

Even though these visualization techniques provide an obvious way to identify the outliers, they provide no means of easily handling them without manually filtering the underlying data.

Unlike contour mapping and parallel coordinates with scatter plot matrices, performance metrics provide a way to not only numerically quantify the outliers but also to remove them. Using Chauvenet's criterion the first outlier detected in the return temperature data results in a value of about 0.000000000003818 which is far less than 0.1, which clearly marks it as a spurious outlier. The value should in fact be even less since the data point actually has a deviation of 54σ, however Matlab/Octave has problems calculating deviations less than 8σ due to the infinitely small numbers involved. As the actual value of this data point is in fact 13395°C it can safely be concluded that this must be a measurement error. Similarly the first outlier found in the mass flow data is also marked as an outlier due to the fact that it is showing a mass flow of 134180 kg/hour. This mass flow value, as well as the return temperature value, is obviously a spurious outlier considering the physical constraints of a normal consumer substation. After removal of the detected outliers, Chauvenet's criterion is iterated until no further outliers are found. The starting and final values of this process in relation to the return temperature data is shown in Table 2.

Table 2 Outlier detection using performance metrics in relation to return temperature data

	Before	***After***
Mean	53.23	47.62
Standard deviation	246.48	4.82
Outlier (max)	13395	68.2
Outlier – mean	13341.77	20.58
σ	54.13	4.27
Probability	1.22e-15	1e-4
Data points	3127	3124
Chauvenet's value	3.82e-12	0.31

The same dataset was then analysed in relation to the mass flow data, which is shown in Table 3.

Table 3 Outlier detection using performance metrics in relation to mass flow data

	Before	***After***
Mean	735.65	693.02
Standard deviation	2399.3	241.88
Outlier (max)	134180	1749.2
Outlier – mean	133444.35	1056.18
σ	182.4	2.52
Probability	1.22e-15	0.045
Data points	3127	3124
Chauvenet's value	3.82e-12	140.58

In total three outliers were found in the data set using performance metrics. By iteratively identifying and removing these, the statistical relevance of the data was greatly increased.

DISCUSSION

The dataset in the presented analysis only make use of measurements collected through the heat meter. There is obviously a lot of other data that might be interesting to include in the analysis, such as indoor temperatures, heating system data or tap water usage. The reason that only data from the heat meter is used is simply because this data is readily available to the energy company.

It should be noted that contour maps and parallel coordinates differ in one important regard. A contour map requires extra-/interpolation in order to work. This is due to the fact that array structures are turned into matrices. This not only requires considerable amount of computing power, but is also prone to error since no existing algorithm can guarantee truth. On the other hand, a visualization solution based on parallel coordinates will only use the unspoiled raw data set.

The main advantage of using parallel coordinates and scatter plot matrices compared to contour maps is that they facilitate the study of multivariate relationships in one visualization artefact. The importance of this only increases as more variables are introduced into the analysis.

An important aspect of parallel coordinates is the use of brushing. Contour mapping requires no such manipulation during use since they are fixed. However, it can be argued that this is actually an advantage for parallel coordinates since it facilities the possibility to angle the visualization in the desired direction and to compare and highlight different aspects of the dataset.

In regards to visualization contour maps have an advantage in that they are related to the time of day over the x-axis, which might make it more directly accessible. Brushing has to be used in order to analyze hourly dependencies using parallel coordinates. This might be done by brushing high mass flow values and studying their relationship with the hour-data. With scatter plot matrices this process is easier since the row of matrices relating to hours basically correlates to a contour map.

It can be noted that contour maps as well as parallel coordinates and scatter plot matrices are sensitive to outliers. Statistically this is due to compression of the dataset, which causes heavy distortion when visualized. Using performance metrics outliers will instead result in different numerical values which serve to not only to identify the presence of outliers but also facilitate their ranking and possible removal.

Given a group of consumer substations it is easier to evaluate their operational status using a list of sorted numbers than maps or graphs. This supports the conclusion that performance metrics are superior to visualization techniques when evaluating larger groups of substations, and certainly if the evaluation process is to be automated.

CONCLUSIONS

In this paper we have compared contour mapping with parallel coordinates and scatter plot matrices in relation to fault detection and operational analysis in consumer substations within a district heating system. It is shown that the same operational relationships can be visualized using parallel coordinates and scatter plot matrices as in contour mapping, while at the same time decreasing the computational complexity and error sensitivity and enhancing the multivariate analysis.

We have also studied the possibilities of using performance metrics as a basis for large-scale operational analysis within district heating systems. Performance metrics is an extension of the previously discussed visualization techniques in that they remove the need for subjective interpretation. It is shown that such statistical analysis is able to detect, identify and analytically evaluate the same relationships studied in relation to the visualization techniques.

FUTURE WORK

The focus of this paper was to study data collected through the heat meter. In the future other data will be included in the analysis in order to develop a complete model of the operational status, not only of the consumer substation, but rather the whole building in relation to indoor climate and energy saving measures. This work is expected to intensify as the amount of available data increases through progress in communication and sensory equipment [16].

Furthermore, the performance metrics analysis will be extended end enhanced in order to facilitate large-scale fault detection and operational analysis. As the operational constraints harden for most energy companies it becomes increasingly interesting for them to help building-owners manage their consumer substations as smoothly as possible.

ACKNOWLEDGEMENT

The authors would like to thank Dr. Stefan Axelsson at Blekinge Institute of Technology for valuable discussions regarding visualization techniques.

We thank NODA Intelligent Systems AB for the use of operational data.

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THE PERFORMANCE CHARACTERISTICS OF PLATE HEAT EXCHANGERS USED IN DISTRICT HEATING AND COOLING WITH GEOMETRIC DESIGN PARAMETERS

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Keywords: Plate heat exchanger, Water, Heat transfer, Pressure drop, Geometric design parameter, energy efficiency

ABSTRACT

It is required to reduce installation area and costs for plate heat exchangers used in district heating and cooling. This can be achieved by maximizing the capacity of a single heat exchanger with improved heat transfer efficiency. Performance data and appropriate design tool are essential for optimal design of plate heat exchangers. In this study, the effects of the geometric design parameters such as chevron angle, corrugation length, corrugation depth, and the number of plate on the heat transfer and pressure drop characteristics of plate heat exchangers are investigated experimentally. In addition, the heat transfer and pressure drop correlations as a function of various geometric design parameters are suggested. More than 95% predicted data of the correlations showed relative deviations less than ±10% as compared with the experimental data.

INTRODUCTION

Plate heat exchangers show better thermal performance than conventional heat exchangers. The plate heat exchangers are much smaller and more efficient in the viewpoint of space utilization than conventional heat exchangers. Therefore, the plate heat exchangers have been widely used in district heating and cooling. However, it is still required to reduce installation area and costs for the plate heat exchangers by improving heat transfer efficiency. An appropriate design tool with a wide range of performance data has to be developed for optimal design of the plate heat exchangers.

Researches on the performance characteristics and performance prediction of plate heat exchangers have been conducted extensively. Focke et al. [1] experimentally investigated the heat transfer and pressure drop characteristics of a plate heat exchanger as a function of Chevron angle and Reynolds number (Re). Heavner et al. [2] also investigated the heat transfer characteristics of a plate heat exchanger with respect to Re and Chevron angle. Muley and Manglik [3] confirmed that the heat transfer coefficient increased with the increase in the enlargement factor, and proposed the correlations of Nu and friction factor as a function of Chevron angle and enlargement factor. Martin [4] and Dovic et al. [5] developed a theoretical model based on the Leveque equation for the heat transfer correlation. Martin [4] identified the internal flow characteristic in a plate heat exchanger, and defined a friction factor. Dovic et al. [5] and Shah et al. [6] suggested a friction factor as a function of the aspect ratio (b/l) in a Sine-shaped duct.

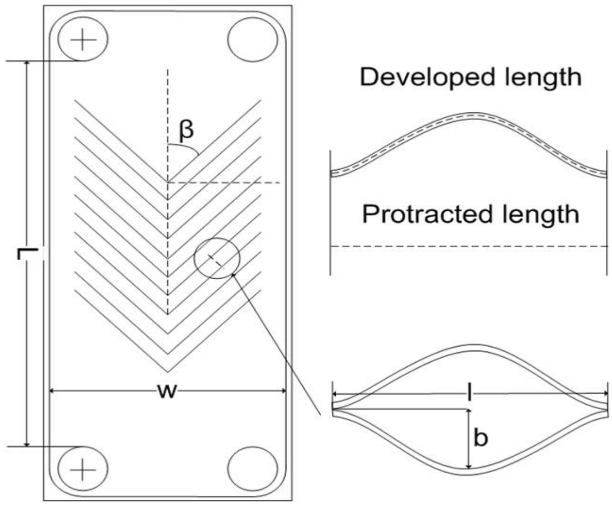


Fig. 1 Schematic of a Chevron-type plate.

The plate heat exchanger has various geometric design parameters as shown in Fig. 1. These parameters affect the performance characteristics of the plate heat exchanger. Though the performance characteristics of plate heat exchangers have been investigated extensively, the studies on the effects of the geometric design parameters except chevron angle are very limited in the open literature. In this study, the effects of the geometric design parameters such as chevron angle, corrugation length, corrugation depth, and the number of plate on the heat transfer and pressure drop characteristics of plate heat exchangers were investigated experimentally. In addition, the heat transfer and pressure drop correlations as a function of various geometric design parameters were suggested.

EXPERIMENTAL PROCEEDURE

Fig. 2 shows a schematic diagram of the experimental setup for measuring the heat transfer and pressure drop characteristics of the plate heat exchangers. The heat transfer rate and pressure drop were measured while controlling the experimental conditions of hot and cold water. The temperatures of hot and cold water at the inlet and outlet of the plate heat exchanger were

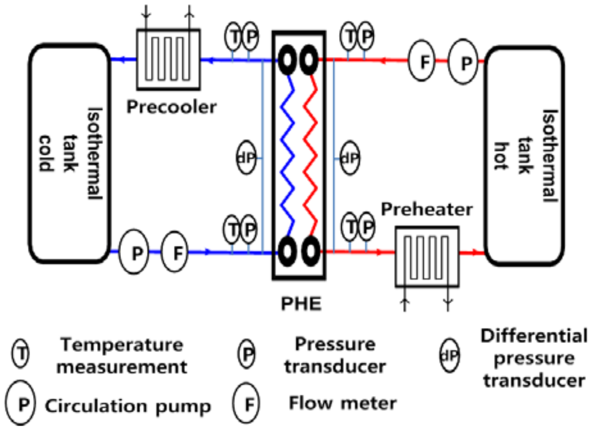


Fig. 2 Schematic of experimental setup.

measured by T-type thermocouples. Volumetric flow meters were installed in the hot and cold water loop, and measured the flow rate in each loop. In addition, for measuring pressure and pressure drop, the absolute pressure gauge and differential pressure gauge were installed in the inlet and outlet of the plate heat exchanger. In order to reduce the heat loss from the surrounding, the experimental apparatus was insulated sufficiently. Table 1 shows the accuracy and measurement range of measuring instruments used in this experiment apparatus. Table 2 shows the range of geometric design parameters and experimental conditions.

The heat transfer rate and pressure drop were measured with the variation of the flow rate and geometric design parameters of the heat exchanger while maintaining the temperatures of hot and cold side water constant. All measurements were conducted after satisfying steady-state conditions: ±0.1℃ of average temperature difference and ±5% in the variation of the pressure and flow rate.

Nusselt number (Nu) was determined by Eqn. (1) to (6). The surface temperature for each plate was estimated by the modified Wilson plot method proposed by Fernandez-Seara et al. [7].

$$Q_c = \dot{m}_c C_{p,c}\left(T_{c,o} - T_{c,i}\right) \tag{1}$$

$$Q_h = \dot{m}_h C_{p,h}\left(T_{h,i} - T_{h,o}\right) \tag{2}$$

$$Q_{avg} = \left(Q_c + Q_h\right)/2 = UA\Delta T_{LM} \tag{3}$$

$$\Delta T_{LM} = \frac{\left[\left(T_{h,i} - T_{c,o}\right) - \left(T_{h,o} - T_{c,i}\right)\right]}{\ln\left[\left(T_{h,i} - T_{c,o}\right)/\left(T_{h,o} - T_{c,i}\right)\right]} \tag{4}$$

$$\frac{1}{U} = \frac{A\Delta T_{LMTD}}{Q_{avg}} = \frac{1}{h_c} + \frac{t}{k_w} + \frac{1}{h_h} \tag{5}$$

$$\mathrm{Nu} = \frac{hD_h}{k_f} \tag{6}$$

In addition, the friction factor was calculated by Eqn. (7).

Table 1 Uncertainties of parameters

Parameters	Accuracy	Full scale
Temperature	±0.1 ℃	-200 ~ 200 ℃
Flow meter	±0.5 %	0 ~ 200 m^3/h
Pressure transducer	±0.25 %	0 ~ 2000 kPa
Differential pressure transducer	±0.25 %	0 ~ 2000 kPa

Table 2 Test conditions

Classification			Unit	Value
Design parameter	Chevron angle (β)		°	30/30,30/60, 60/60
	Plate width (W)		mm	946,930,540
	Plate length (L)		mm	1728,1340,1056
	Aspect ratio (b/l)		mm	0.192, 0.227, 0.254
	Corrugation length/ Plate length (l/L)		mm	0.00296, 0.00509, 0.00630
	Plate thickness (t)		mm	0.5
	Number of plate (N)			19, 39, 69
Process	Hot water	Inlet temp.	°C	31±0.1
		Inlet press.	kPa	100~300(±5%)
	Cold water	Inlet temp.	°C	25±0.1
		Inlet press.	kPa	100~300(±5%)
	Flow rate		m^3/h	40 ~ 150

$$f = \frac{2\Delta PD_h}{\rho u^2 L} \tag{7}$$

Cross-sectional area (A_c), cross-sectional perimeter (L_p), hydraulic diameter (D_h), and enlargement factor (Φ) were calculated by Eqn. (8) to (10).

$$A_c = bw \tag{8}$$

$$L_p = 2(b + \Phi w) \approx 2(\Phi w) \quad (\because b \ll w) \tag{9}$$

$$D_h = \frac{4A_c}{L_p} = \frac{2b}{\Phi} \tag{10}$$

The uncertainties of the heat transfer rate, friction factor, Re, and Nu were obtained using Moffatt's method [8]. The maximum errors of the calculated heat transfer rate, friction factor, Re, and Nu were ± 3.7%, ± 5.4%, ± 4.2%, and ± 6.3%, respectively.

EXPERIMENTAL RESULTS

Fig. 3 shows the variations of Nu and friction factor with Re at different Chevron angles. Nu increased with the increase of Re at the same Chevron angle. Based on the same Re, Nu increased by approximately 64% when the Chevron angle increased from 30°/30° to 30°/60°, while it increased by approximately 97% when the Chevron angle increased from 30°/60° to 60°/60° because of the increase in the flow velocity. Generally, the friction factor decreased with the increase in Re. The friction factor increased by approximately 143% and 430% when the Chevron angle increased from 30°/30° to 30°/60° and from 30°/60° to 60°/60°,

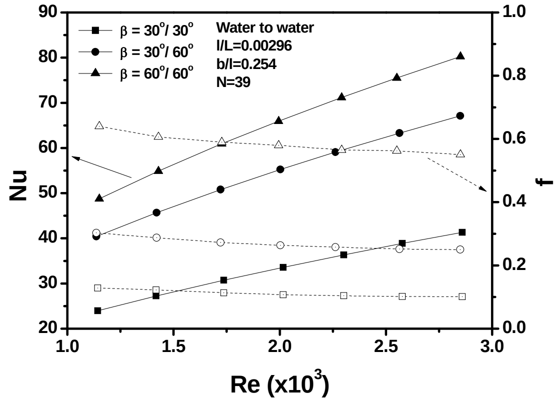


Fig. 3 Variations of Nu and f with Chevron angle.

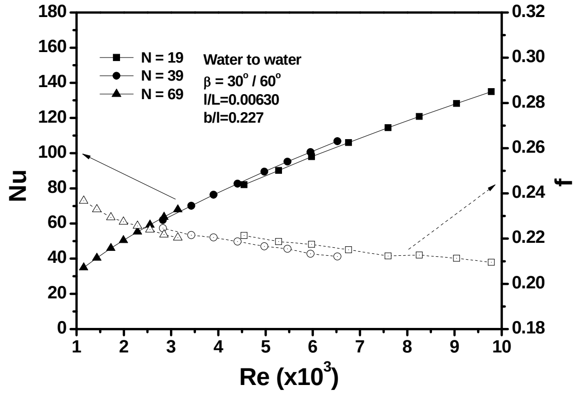


Fig. 5 Variations of Nu and f with number of plate.

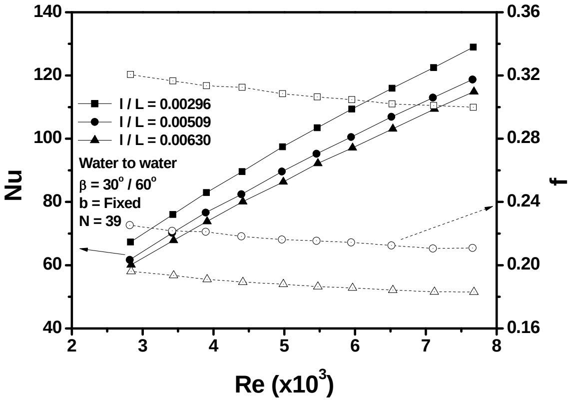


Fig. 4 Variations of Nu and f with corrugation length.

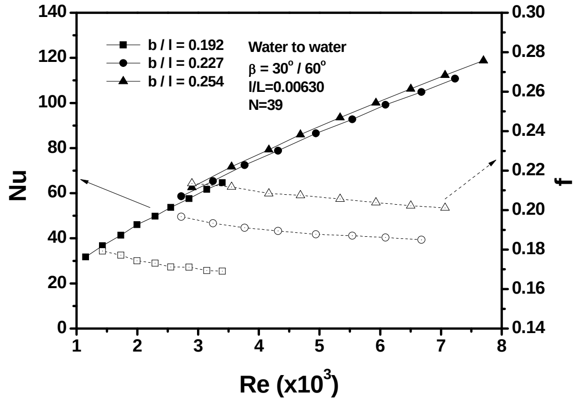


Fig. 6 Variations of Nu and f with corrugation depth.

respectively, because of the increase in the flow resistance.

Fig. 4 shows the variations of Nu and friction factor with Re at different corrugation lengths. At the same Re and corrugation length, Nu increased up to 10%, and the friction factor decreased up to 39% with the increase in the corrugation length. As the corrugation length increased, the number of corrugations decreased, resulting in the decrease in the intersection between the plates. Accordingly, the formation of turbulence can be reduced and the pressure drop can be decreased.

Fig. 5 shows the variations of Nu and friction factor with Re at different number of plates. Nu increased by approximately 5% with the increase in the number of plates from 19 to 39, and increased by approximately 3% with the increase in the number of plates from 39 to 69. This result indicates that there is the effect of the end-plate. The end-plate effect can occur when the heat from the most outer part of channels is transferred toward one side. Because of the end-plate effect, the reduction in the heat transfer performance decreases with the increase in the number of plates. However, the friction factor decreased by approximately 1.4% with the increase in the number of plates from 19 to 39, and decreased by approximately 1.2% with the increase in the number of plates from 39 to 69.

Fig. 6 shows the variations of Nu and friction factor with Re at different corrugation depths. At the same Re, the Nu and the friction factor increased up to 9% and 25%, respectively, with the increase in the aspect ratio of the plate. As mentioned earlier, the heat transfer coefficient and friction factor increased because of the increase in the formation of turbulent with the increase in the corrugation depth.

THE VALIDATION OF CORRELATIONS

Based on the experimental results, empirical correlations were proposed for the performance prediction of plate heat exchangers by considering the geometric design parameters. The correlations of the heat transfer and pressure drop were proposed by applying the π-theorem. Table 3 shows dimensionless parameters affecting the performance characteristics of the plate heat exchanger. Based on the database of the experimental results, the coefficients and exponents of the correlations were determined by using the nonlinear regression method. The final heat transfer and pressure drop correlations are given by Eqn. (11) and (12), respectively.

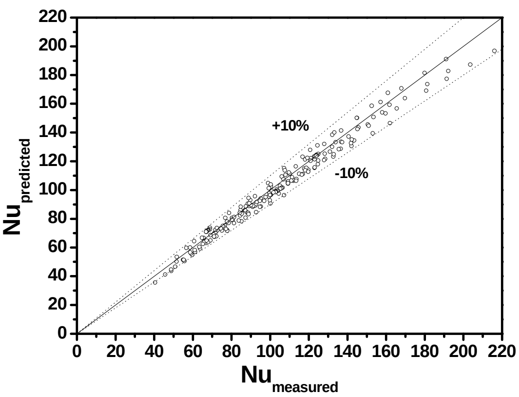
$$\pi_1 = 0.0339\pi_2^{0.6521}\pi_3^{0.1058}\pi_4^{0.0042}\pi_5^{0.2586}\pi_6^{0.7616} \quad (11)$$

$$\pi_7 = 3.23\times10^{-4}\pi_2^{-0.0682}\pi_3^{0.1668}\pi_4^{-0.0216}\pi_5^{0.8229}\pi_6^{2.3890} \quad (12)$$

Table 3 Non-dimensional π-group

π -group	Non-Dimensional parameter	Effects
π_1	$\mathrm{Nu} = \frac{hD_h}{k_f}$	Heat transfer
π_2	$\mathrm{Re} = \frac{\rho u D_h}{\mu}$	Mass flow rate
π_3	$\frac{l}{L}$	Corrugation length
π_4	N	Number of plate
π_5	$\frac{b}{l}$	Corrugation depth
π_6	β	Chevron angle
π_7	f	Pressure drop

Fig. 7 shows the comparison of the measured data with the predicted data using the present correlations. More than 95% predicted data showed relative deviations less than ±10% as compared with the experimental data.



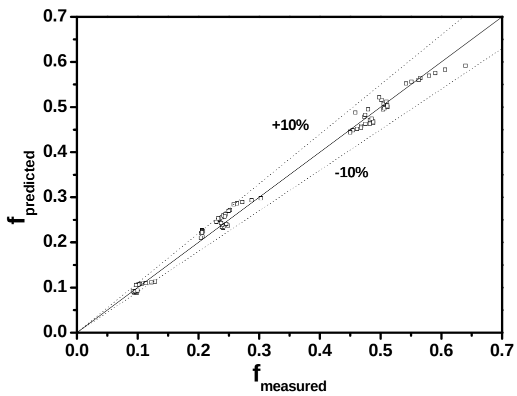


Fig. 7 Comparison between predicted data and measured data.

CONCLUSION

In this study, the heat transfer and pressure drop of the plate heat exchanger were investigated by varying geometric design parameters. The heat transfer coefficient was most significantly affected by the Chevron angle. The heat transfer coefficient increased with increase of the Chevron angle, the number of the plates, and the corrugation depth, while it decreased with increase of the corrugation length. The friction factor was most significantly affected by the Chevron angle. The friction factor increased with increase of the Chevron angle and the corrugation depth, while it decreased with increase of the corrugation length and the number of plates. In addition, the correlations of the heat transfer and pressure drop were proposed as a function of various non-dimensional terms. More than 95% predicted data showed relative deviations less than ±10% as compared with the experimental data.

NOMENCLATURE

A	: Heat transfer area [m^2]
b	: Corrugation depth (mm)
C_p	: Specific heat (W/kg-K)
D_h	: Hydraulic diameter, 2b/Φ (mm)
f	: Friction factor
h	: Heat transfer coefficient (W/m^{2}-K)
k	: Thermal Conductivity [W/m-K]
L	: Plate length [mm]
l	: Corrugation length [mm]
$\dot{m}$	: Mass flow rate [kg/s]
N	: Number of plates
Nu	: Nusselt number
Q	: Heat transfer rate [W]
Re	: Reynolds number, $\rho u D_h/\mu$
t	: plate thickness [mm]
ΔT_{LM}	: Log-mean temperature difference [K]
U	: Overall heat transfer coefficient [W/m^{2}-K]
u	: Flow velocity [m/s]
w	: plate width [mm]

GREEK SYMBOLS

β	: Chevron angle [°]
μ	: Viscosity [kg/m-s]
ρ	: Density [kg/m^3]
Φ	: Enlargement factor

SUBSCRIPTS

avg	: average
c	: cold
f	: fluid
h	: hot

i : inlet

o : outlet

w : wall

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IMPACT OF LOWERING DT FOR HEAT EXCHANGERS USED IN DISTRICT HEATING SYSTEMS

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Keywords: Energy Efficiency, District Heating, Low Temperature District Heating (LTDH), District heating networks, Logarithmic mean temperature difference, Domestic Hot Water (DHW)

ABSTRACT

This paper describes the impact of using heat exchangers designed for operation at low supply temperature and at small logarithmic mean temperature difference (dT) compared to the level specified and applied today. Heat exchangers with a lower design dT in the consumer installation are designed for District Heating (DH) systems with reduced supply and return temperatures. This results in heat loss savings for the DH distribution network and increased energy conversion efficiency and power production at the DH plant. On the contrary investment cost is increasing in case of reduced temperature difference between DH flow and return.

A key challenge for optimal and competitive DH system operation is reducing heat loss in the DH network. In most countries new building regulations require considerable reduction of heat consumption in individual buildings compared to earlier requirements. The ratio between network heat loss and heat consumption in buildings will even be more in focus in future. To address this challenge, the impact of applying heat exchangers operating at low dT in consumer installations and low supply temperatures is analysed. Further, the potential of using surplus heat is increased as the temperature levels decreases.

INTRODUCTION

Denmark aims at 100% renewable energy supply in 2050. DH is one of the solutions how to achieve this goal. Well-known advantage of CHP and DH is the possibility using surplus heat from power plants, industrial processes and waste incineration, which otherwise would be lost. The incineration of unrecyclable waste in a CHP plant is a well-known solution how to process the increasing volume of municipal waste, and in Denmark it covers 20% of heat demand for DH. More stringent requirements to the energy performance of buildings are introduced generally, and thus heat losses from DH network become a key issue for DH in future. One central component in relation to the potential for reducing heat losses from the DH network is heat exchangers placed in the consumer installation. The design conditions for the heat exchangers, for DHW as well as for space heating, determine the flow and temperature levels in the DH network which are the main influencing parameters in regard to DH distribution losses. The aim of this paper is to analyse how far it’s economical to decrease the DH flow temperature. On one side the cost of the consumer substation increases, due to the increased heat exchanger surface needed to address the low temperature operation. On the other side the thermal loss decreases for the DH network while the investment in larger DH sizes increases. Finally the increased CHP plant efficiency increases when operating at lower DH flow temperatures (turbine condensing temperature). The optimal DH flow temperature level depends on the balance of the mentioned parameters.

HEAT EXCHANGER DEVELOPMENT

Previously shell and tube heat exchangers where widely applied. This type of heat exchangers typically needed a high dT for operation due to the low convective heat transfer coefficient on primary as well as on secondary side. When introducing the gasket plate heat exchanger more than 80 years ago, the convective heat transfer was improved and by this a reduced dT could be realised. A lower dT can in principle be obtained by all types of heat exchanger technology, simply by compensating the lover convective heat transfer by increased area. The advantage of plate heat exchanger in addition to the improved convective heat transfer is that the heat transfer area can be considerably increased without making the heat exchanger excessively large and costly. Typically the so called fishbone or chevron pattern was used. Later on, in the year 1977, the brazed heat exchanger was invented, anyhow still using the same plate design as for the bolted heat exchanger. The introduction of the brazed heat exchanger further reduced the costs. With the continuous heat exchanger improvements the costs is greatly impacted by the heat exchanger technology used. During operation of DH system the optimal dT at a specific point of time will depend on the balance between the improved overall DH system efficiency costs reduction and the cost of the improved heat transfer for the heat exchanger. This can clearly be seen in Figure 1, which shows historical evolution of dT in Danish DH systems.

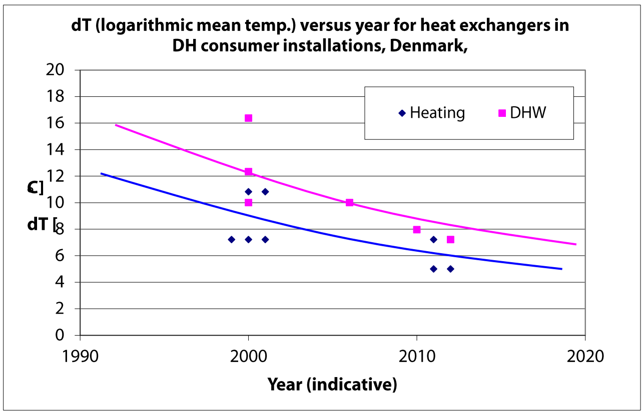

Fig. 1: dT (logarithmic mean temperature) trend over time

Based on the Danish data [1] there is clearly a tendency towards lower dT over time. An example of change for dT for heating could be 90/45-40/70°C to 70/30-25/65°C, and for domestic hot water (DHW) a change of dT could be 60/20-10/45°C to 52/20-10/45°C.

By the year 2005 a new plate design was developed by Danfoss, named the micro plate heat exchangers (MPHE) pattern [2]. With this world wide patented technology heat exchangers result in a higher heat transfer, lower pressure loss and reduced material consumption pr. transferred energy unit. The difference in performance is mainly a result of speed variation reduction for the MPHE pattern compared to the traditional chevron pattern. The figure below shows an example of the difference for the flow lines:

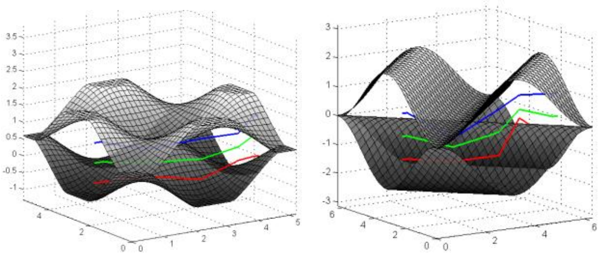

Fig. 2: Heat exchanger plate profiles for Danfoss MPHE and traditional chevron pattern, including flow lines. (Units in mm).

As shown in figure 2, flow lines for MPHE have less speed variation compared to the chevron pattern. Looking at the green lines, it can be seen that the flow path for the MPHE pattern is 2D while its 3D for the traditional chevron pattern. This means a more streamlined and smooth flow through the profile which results in lower flow speed variations. The lower speed variation for the MPHE results in an average better heat transfer pr. pressure loss unit. This is because the high speed spots only result in limited increase in heat convection but significant increase in pressure drop [3]. By higher heat convection / pressure drop relation, bigger well defined brazing points can be afforded, leading to a stronger plate, which again enables a reduced plate thickness.

Looking at the consequences of reducing dT, as an example DHW preparation is analysed. The capacity is 33 kW, reflecting a typical one family house, and dT is variable. DHW is heated from 10°C to 45°C, where supply and return temperature are reduced accordingly to dT value. As it can be seen from figure 3, lowering dT has drastic impact on the needed heat transfer area, and thus on heat exchanger cost. There are tree curves, each representing a defined pressure loss for the heat exchanger. The lowest is a typical value of 10 kPa, where the two others represent rather high pressure loss compared to what is normally specified for consumer installations. Pressure losses for the curves are 50 kPa and 200 kPa, respectively. Additionally, the end user cost is included, and is related to the needed heat transfer area.

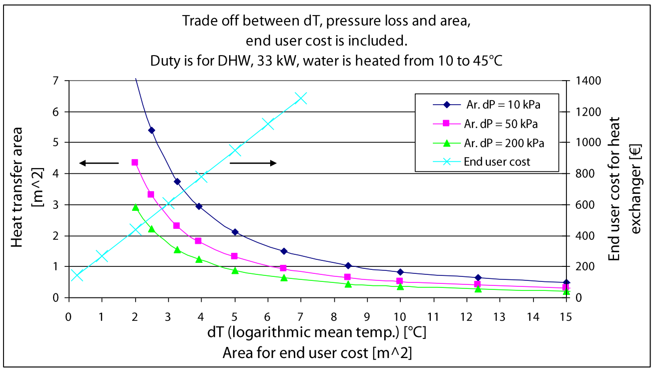

Fig. 3: Trade-off between dT, pressure loss, heat transfer area and end user costs

With figure 3 as the starting point, one relevant question is: what is the optimal dT, and what is the optimal pressure drop to be specified for the heat exchanger. For instance by setting dT constant and increasing the pressure loss from 10 kPa to 50 kPa approx. 37% of the heat transfer area can be saved. By increasing the pressure loss from 10 kPa to 200 kPa approx. 57% heat transfer area can be saved. This is practically independent of dT value. It is clear that the reduction of dT has strong impact on the needed heat transfer area, this simply due to the fact that the area goes to infinity when dT goes towards zero. On the other hand increased pressure loss requires increased pump work.

TEMPERATURES FOR CONSUMER INSTALLATIONS

When quantifying the yearly performance of the consumer installation, especially the return temperature has to be addressed. The return temperature is a result of the influence from the DHW and heating circuit for space heating. The DHW return temperature depends on whether there is tapping of DHW or whether the system is running in idle mode, meaning no tapping. During idle mode, DH water is bypassed through a temperature regulated bypass thermostat, [4]. The heating return temperature is affecting during the heating season only. Two yearly sets of flow, supply and return temperatures are calculated, one with traditionally designed heat exchangers for DHW and heating, and one for future LTDH and low dT operation.

From table 1 it can be seen that the weighted DH return temperature is reduced from 36.4°C to 24.3°C. This is 12°C. The secondary return temperatures (T SR) are different for the two situations, this because towards the future it can be expected that the demands to the design temperatures for the radiators increases.

TEMPERATURE IMPACT ON DH DISTRIBUTION LOSSES

This section highlights the advantages and possible disadvantages from a technical, economical and energy related perspective for LTDH networks compared with traditional district heating networks [5,6,7].

The low temperature system and the traditional district heating system are compared in a network system supplying new low energy houses fulfilling the Danish energy frame building regulation BR10 (2010) class 2015. The comparisons between the systems are based on simulations of a new built area.

The new build area consists of 116 family houses with a living area of 159 m2 each. All of the new houses build have floor heating. The temperature needed for space heating is therefore only 30-35˚C. For domestic hot water the temperature requirement at the tap is set to 45˚C.

In traditional systems and future LTDH systems with DHW storage tanks and without any temperature booster for DHW, the supply temperature must be 55-65˚C, depending on the location of the DHW tank (primary or secondary side of the DH supply system, meaning if there is DH water in the tank or DHW in the tank). The legionella bacteria must be addressed with the DHW storage tank on the secondary side. If consumer installations are equipped with instantaneous heat exchangers for the preparation of DHW, then 55˚C is sufficient as DH supply temperature. For a LTDH with integrated heat pump for preparation of DHW the supply temperature can be even lower (practically down to 30°C which is fulfilling the floor heating temperature demands in low energy buildings. The heat pump then has to lift the DH temperature level used for DHW preparation up to 55°C. The analysed network is shown in Figure 4.

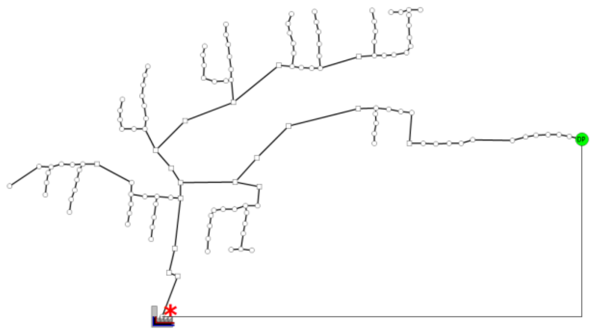

Fig. 4: The considered new built area – DH distribution network.

The annual heat demand for space heating and domestic hot water for the individual houses is shown in table 2. The difference between “Class 2015” and “realistic” is due to an increased and more realistic demand of DHW compared to the expected consumption in 2015. The figures related to “realistic consumption” are used in the analysis.

Table 2: Heat demand per house for the simulated group of houses.

		Heat demand per year		
House	Energy	space heat	DHW	Heat demand
159 m^2	Frame	kWh	kWh	kWh
	Class 2015 frame	30 + 1000/A (kWh/y)		5770
	Realistic consumption	4040	3200	7240

Figure 5 shows the heat capacity demand for the 159 m2 house as a function of hours in the year. The peak

Table 1: Temperature sets for present and future consumer installation

1. Family house year 1970 - 150 m^2, 33 kW DHW capacity, average capacity 6.4kW 1hr/day   DHW pr. year 2300 kWh
Heating is active during 6 months, average heating capacity 3.5 kW 24hr/day
Idle bypass temp. set. = 35°C
For the future situation heating consumption for the house is reduced by a factor 3

	T DHF [°C]	T DHR [°C]	T SF [°C]	T SR [°C]	dTlmn [°C]	Energy/y [kWh]	DH flow [m^3/hr]	Duration [hr/day]	Duration [hr/year]	P av [kW]	Duration [months/y]	T ret. weighted [°C]
Traditional:												
HE	80	40	60	30	14.4	15000	0.075	24	4380	3.5	6	
DHW tap. winter	80	16	50	10	14.9	2300	0.086	1	183	6.4	6	36.4
DHW tap. summer	65	23	50	10	14.0	2300	0.131	1	183	6.4	6	
DHW idle	40	30	-	-	-	-	0.010	23	8395	-	12	
Future:												
HE	55	25	45	23	5.0	5000	0.033	24	4380	1.2	6	
DHW tapping	55	12	45	10	5.0	2300	0.128	1	365	6.4	12	24.3
DHW idle	40	30	-	-	-	-	0.010	23	8395	-	12	

load is cut off in the figure corresponding to 3.4 kW. In order to optimise the network, it is an advantage to raise the supply temperature during peak load.

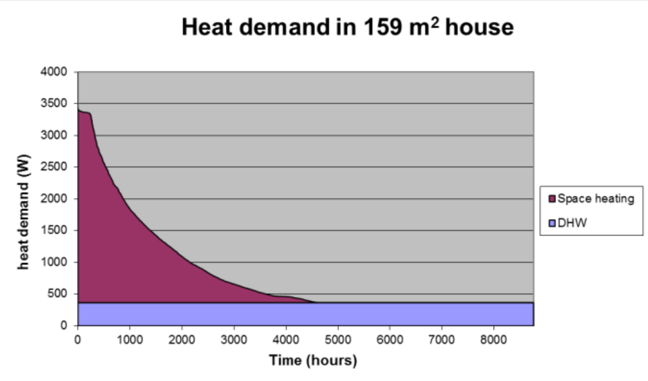

Fig. 5: Heat load demand for the 159 m2 detached house.

The network is dimensioned so that the critical consumer has at least 0.5 bar of pressure difference. The temperature loss in the pipe network is an important issue. During peak load periods the temperature drop in the supply pipes are only a couple of degrees. But in the summer period where the demand is less than 10 % of the peak demand, temperature drops of more than 20°C in the supply pipes are experienced. The network should therefore be designed so that the critical consumer is supplied with a sufficient temperature.

Investment costs

Investment cost for a DH network is dependent on the temperature difference between supply and return in the peak period. Lower supply temperature and lower dT between supply and return requires bigger DH pipes and more flow for delivery of the same amount of heat. The network investment costs are calculated for 4 variants of network supplying the 159 m2 group of one family houses. The investment cost for the traditional 80/40°C system considered is calculated to approx. 513,000 €.The investment costs for a supply system for a 65/25°C in comparison with the traditional supply temperature of 80/40°C is the same. A supply system with the temperature set 55/25°C is some 3-4 % more expensive (approx. 155 € per house) and a system based on 45/25°C will be approx. 9 % more expensive. (approx. 400 € per house).

The correlation between network investment costs and the difference in supply and return temperatures is shown below in figure 6:

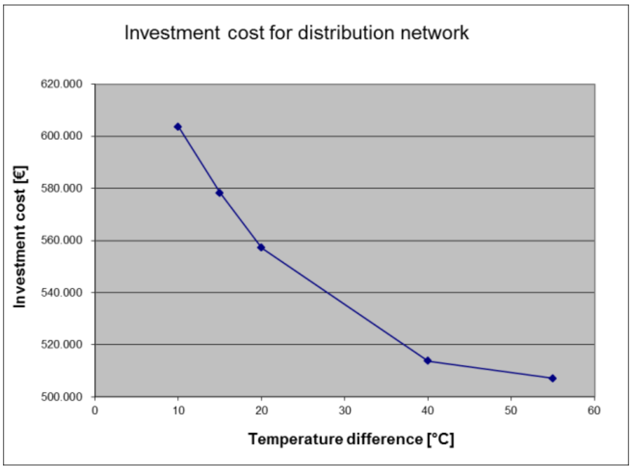

Fig. 6: The network investment cost as a function of the temperature difference between supply and return.

Heat losses and power consumption

The heat loss is dependent on the dimensions of the pipes and temperature levels in the network. As mentioned previously, it is necessary to design a network based on a simulation under peak load and then calculate how this network will perform in terms of heat losses over the year. The analysis is based on heat and peak demand for the group of 159 m2 one family houses. With floor heating in every house it is assumed that the return temperature for space heating is 25°C. This is a realistic value for new low temperature houses with focus on low return temperature. This would, however, not be the same for older floor heating systems. Heat loss on annual basis for a traditional supply (at 80-65°C) system is calculated to be 15-16 %. The similar heat loss for a LTDH system is calculated to be around 8-11 % dependent on the supply temperature 45-65°C and the actual system concept of the consumer installation. See table 3 below.

Table 3 also shows the needed network pump energy for distribution of the DH water in the different alternatives of network. The low temperature supply systems require more pump energy to secure sufficient temperature for the most critical consumer at the far end of the network. Finally the table shows the annual operation cost for each alternative network under the assumed energy prices: district heating price of 46.7 €/MWh and an electricity price of 130 €/MWh. A difference of 17–32 % in yearly operation costs are calculated between the low temperature network concept and the traditional network concept. This corresponds in the case to 1359-2527 € in annual savings for a LTDH network. Per house it amounts to 12-22 €/year. Table 3 does not include the costs of the consumer installation, e.g. the heat pump for temperature boosting.

Table 3: Operating costs for different district heating networks in terms of heat losses and pump energy consumption.

Scenarios		Heat loss in network			Pump energy		Operation cost	Savings
		MWh	%	€	MWh	€	€	%
Traditional network	Supply 80 °C	164,4	16,4	7.722	1,05	142	7.864	0
	Supply 65 °C	143,0	14,6	6.719	1,58	212	6.931	12
LTDH network	Supply 55°C	132,9	13,7	6.243	1,95	262	6.505	17
	Supply 45 °C	104,0	11,0	4.886	3,36	450	5.337	32

Taking the increased costs for consumer installation and network into account the LTDH system cannot be carried on the economic value of the heat loss alone. The LTDH system must furthermore be justified on the value of low district heating temperature level seen from the production side.

IMPACT ON HEAT GENERATION EFFICIENCY DUE TO LOWER TEMPERATURES

As the energy demand for new houses and building decreases the trend in district heating supply is towards lower supply temperature minimising energy losses. In Denmark district heating has a share of more than 60% of the entire heating market. Approximately 80% of the produced district heat is based on combined heat and power facilities. The central power plants have a share of approx. 50% of the total produced district heat. A LTDH system only requires a supply temperature of approximately 40-60°C and has a return temperature of 20-30°C, which in effect influences the CHP operation as the steam can be further expanded in back pressure turbines or in extraction turbines. Further, LTDH temperature sets allow a higher utilisation of the primary energy content of the fuel used. In a case example the electricity production of a back pressure turbine is increased by approx. 15 % at a DH supply temperature of 45°C instead of 80°C. As the value of electricity normally is superior over the value of district heat, it is an economic advantage to increase the electrical efficiency of the CHP operation.

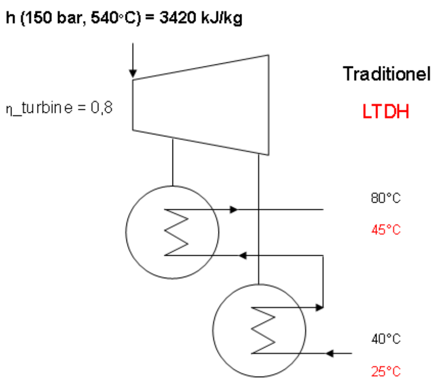

Fig. 7: Example of back pressure turbine for DH supply.

If the district heat is produced in heat only production facilities, the possibility of higher utilisation of the primary fuel is important. Especially the possibility of flue gas condensation of the water vapour considerably increases the overall efficiency of the fuel conversion. This is especially relevant when using natural gas, wet biomass or municipal waste as these fuels have high water content.

It is reasonable to state that a LTDH system increases the primary fuel efficiency in the magnitude of 5-10 % resulting in similar savings for the annual production costs. The considered test house of 159 m2 needs 7.2 MWh/y at an assumed production price of 46.7 €/MWh, resulting in 336 €/y. 5-10 % hereof corresponds to 17-34 €/y per house.

Better integration of solar and geothermal energy resources

The integration of solar and geothermal renewable energy sources into district heating systems will be considerably improved by applying a LTDH system. Large solar thermal plants producing hot water for DH has become widespread in Denmark, mainly due to increased efficiency and beneficial taxation rules. The efficiency of solar panels is highly sensitive to the supply and return temperatures. If the mean water temperature in solar panel is reduced from 60°C to 30°C the efficiency is increase by approx. 55 %.

In relation to geothermal energy, advantages are for example less deep boreholes to achieve a desired temperature and no or very limited absorption heat pump operation is needed. In general, a LTDH system enables a higher degree of utilization of geothermal energy as more locations become suitable.

COST BALANCE FOR REDUCED DH TEMPREATURES

Table 4 includes examples of the cost balance for a family house regarding investments and operational costs when applying LTDH.

Table 4: Simple payback time for applying LTDH, for various temperature sets.

Primary temperature	80°C/40°C	65°C/25°C	55°C/25°C	45°C/25°C	
Increased inv. cost heat exchanger/HP	0	0	250	1600	€/Cons.
Increased inv. cost network	0	0	155	400	€/Cons.
Reduced distribution costs	0	8	12	22	€/Cons. Year
Increased heat generation efficiency	0	10	20	30	€/Cons. Year
Simple pay back time	n.a.	0,0	13	38	Years

Based on this the DH network flow temperature could go down to 55°C. The calculated simple pay back time is 13 years seen from the heating company/society point of view. This shall be seen in relation to the life time of the DH network which is in the range of 50 years. The consumer installation has a typical lifetime of 20 years. In relation to the payback time of 13 years, it has to be mentioned that the future energy price probably will go up and requirements to system energy efficiency will increase towards the future. Reducing the DH flow temperature even further increases the investment costs due to the heat pump for DHW. In this case the simple pay back time is extended considerably. In this regard it has to be mentioned that the heat pump unit will still be attractive to use in the far end of the network where DH supply temperature and pressure is limited. Also where the target is to reuse low temperature renewable sources, this alternative is relevant. At a first look it could be obvious to conclude that the 65°C/25°C DH temperature is optimal, since savings are obtained without any investments. But it should be remembered that energy loss should be reduced and energy conversion efficiency should be increased, to secure future competitive DH solutions. The optimal dT value for the heat exchanger is not exact and depends on a number of boundary conditions. Based on the assumptions above, it's in the range of 5°C. A lower specified dT will drive the heat exchanger cost up (figure 3), and the related reduced distribution costs (table 3) and increased heat generation efficiency will not be able to compensate this. Anyhow for special conditions a lower dT can be optimal as well.

CONCLUSIONS

Based on the assumptions stated in this paper, it's from an economic point beneficial to specify heat exchangers with a low dimensioning dT value, compared to what is recommended in traditional DH nets today. Furthermore it's economical beneficial to apply LTDH, to a certain DH supply temperature level. The example included, states that a flow temperature of 55°C is still economical favourable. Ongoing work and research is investing the profitability of lowering the supply temperature further to 45°C. Regarding system energy efficiency, lower DH supply temperatures are to be preferred.

Traditional DH heat exchangers operate at dT in the range 10-15°C. The future recommendation is a dT value in the area of 5°C. This value is, however, based on some uncertainty and might over time change depending on energy and technology costs. Typically for the future, even lower dT are assumed to be the preferred option, and it fits to the general trend that is historically seen.

For the concept of DH compared to individual heating solutions, it's crucial to stay competitive towards the future reduced heat demands specified in the building energy envelopes. LTDH and heat exchangers operating at low dT is an attractive way for the DH concept to meet this challenge of the future.

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HOW TO MINIMIZE THE TOTAL LIFECYCLE COSTS IN A DH SYSTEM

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ABSTRACT

Object of article is heat loses as key issue of service life cycle costs (LCC) of a pre-insulated pipe system. Heat loses (λ values) for different production methods are presented. Calculation of heat loses for real case comparing 30 years period for conti and traditionally produced pipes show that savings from better pipe insulation is bigger than investment in new pipe system. Logstor daily tests confirm, that λ value from test for 3 m 60/125 mm pipe differs (is lower) than λ value from daily production 12 m. .Heat loses is the most important part of the life time costs for pre insulated pipe system. Evaluation of real heat loses must be taken into account, using test for every dimension 12 m pipe, instead of 3m DN 60 /125 pipe.

What is the LCC for a district heating pipeline:

• Direct investment costs and Annual costs (operating costs). The expected life time for pre insulated pipe system is more than 40 years. According to the experience, life time costs are calculated for a 30 year period.

• Direct investment costs: Pipe material, Pipe installation, Excavation and restoration, Inspection (Purchase costs, components, Installation costs, Costs of planning & commissioning).

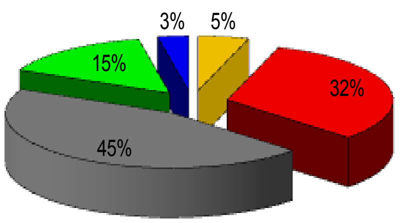


Fig.1 Direct investment costs

• Annual costs (operating costs): Pumping, Heat loss, costs of energy, heat losses, pump costs, costs of maintenance & repairs, costs of poor quality.

LCC for a 30 year period will be split: about 33 % are Direct investment costs, 67 % Annual costs (operating costs).

Only 32 % from direct investment costs are purchase costs for pipes and components. On the other hand, 75% from Annual costs (operating costs) are costs for heat loses.

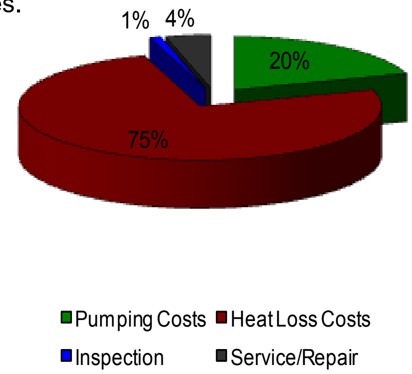


Fig.2 Operating costs

From the figures above follow – the key issue for district heating LCC is heat loses from pre insulated pipeline.

Heat loses depend from pipe dimension, insulation (foam material and thickness), flow and return temperature and soil temperature. According to the EN 253 [1] steel pipe (carrier pipe) diameter and plastic casing outside diameter are standard size, insulation thickness fixed –ser1, ser2, ser3. Does it mean that all pipes with the same dimension, for example DN 60 /125 (ser1) with cyclopentane foam have the same heat loses?

No, because, there are different production methods - traditional and conti (axial conti spiral conti, semi conti). And as a result – LCC will be different for the same project, because of different pipe production method.

The main difference in production methods – different sequence of operations.

Traditional production: 1) steel pipe, 2) HDPE jacket, 3) foaming.

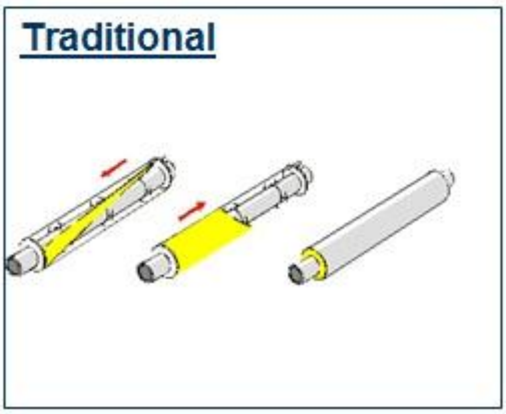
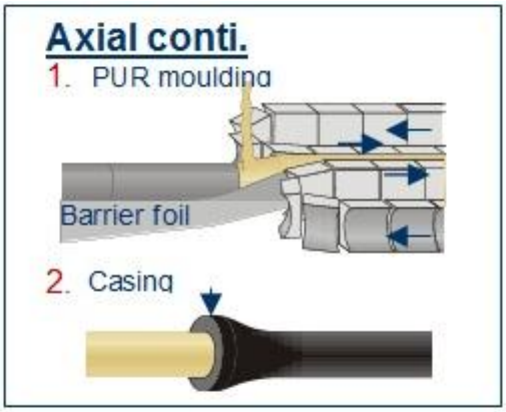


Fig.3. Traditional production method

Conti production: 1) steel pipe, 2) foaming, 3) HDPE jacket.



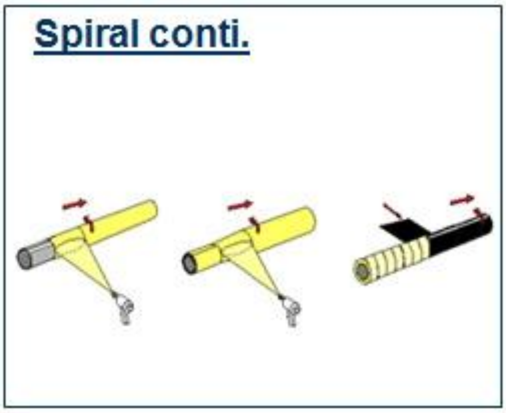


Fig.4. Axial and Spiral conti production method

Due to the different technology conti pipes have lower heat loses than the traditionally produced pipes. We can see from certificates for axial conti λ=0.023 W/mK, for traditionally produced pipes λ=0,026 W/mK.

Samples from Latvia. **1.case.** 500 m pipeline, including pipes 139/225 - 36 m (trench), 114/200 – 24 m, 89/160 – 48 m, 76/140 -138 m, 60/125- 254 m. Total investment for the pre insulated material (conti pipes with diffusion barrier) – 26,000 EUR.

Heat loses were calculated for conti pipes with diffusion barrier and traditionally produced pipes (ser1). In order to make calculations „Logstor calculator" was used

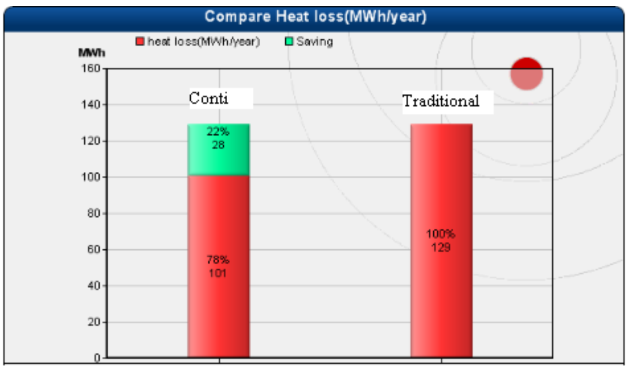


Fig.5. Heat losses 1.case

Annual heat loses from Conti pipes are 28 MWh less than from the traditionally produced pipes, in a 30 year period those are 840 MWh. Fuel price is 40 EUR/MWh

In a 30 year period savings are 336,00 EUR. This means that choice of conti pipes instead of traditionally produced pipes gives savings on heat loses up to 129% from investment in pipe system materials.

2.case. 2064 m pipeline, including pipes 273/450 – 150 m (trench), 200/355 -150 m, 168/280 – 216 m, 139/250 – 528 m, 114/225 – 486 m, 89/180- 342 m, 76/160 – 180 m, 42/125 -12 m. The total investment for the pre insulated material (conti pipes with diffusion barrier) – 199,000 EUR.

Heat loses were calculated for conti pipes with diffusion barrier and traditionally produced pipes (ser1). In order to make calculations „Logstor calculator" was used heat loses for Conti pipes are 81 MWh less than for traditionally produced pipes, in a 30 year period 2,430 MWh.

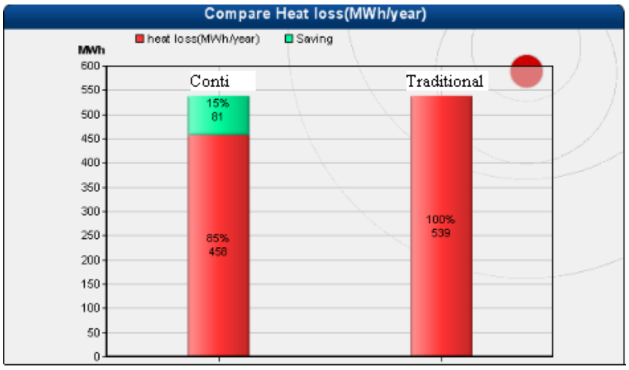


Fig.6. Heat losses 2.case

Fuel price is 40 EUR/MWh, in a 30 year period savings are 97,200 EUR. It means that choice of conti pipes instead of traditionally produced pipes gives savings up to 48.8 % of investment in pipe system materials.

LCC calculation was made for second case based on real tender results (conti pipes). Total investments were 720600 EUR (including 251000 EUR for pre insulated pipe system). Savings for heat loses were calculated for 30 years heat tariff 60 EUR/MWh. Investments for traditionally produced pipes were reduced by 15 %, Total investments was 682800 EUR (including 214000 EUR for pre insulated pipe system).

LCC (30 years) for conti pipes- 1 820 890 EUR, for traditionally produced pipes 1 928 560 EUR. Extra investment 37 000 EUR in conti pipe system gives reduction of LCC by 107670 EUR.

These two real cases show that savings on heat loss difference between conti and traditionally produced pipes could be higher than the investment in new pipe system, and ignorance of this fact will lead to the reduction of efficiency of district heating system and loss of money.

We must take into account, that λ values in certificates from different pipe producers are made for 3m DN 60 pipe with jacket 125 (ser1).

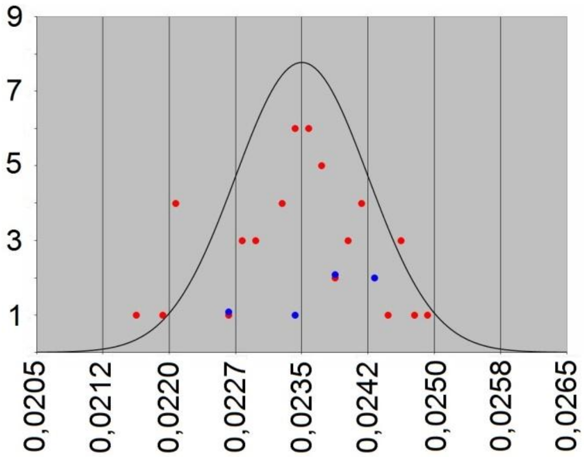


Fig.7 λ values for daily production conti pipe.

For every day production 12 m pipe such average value is not possible. Logstor has tests for daily production 12m DN 60 pipe , average λ value is 0,0272 W/m K (Fig.7). It means that district heating company in real life will have bigger heat loses as they planned based on calculations on 3m pipe certificate value.

If we evaluate pipes with dimension bigger than DN 200/315, there is even more uncertainty.

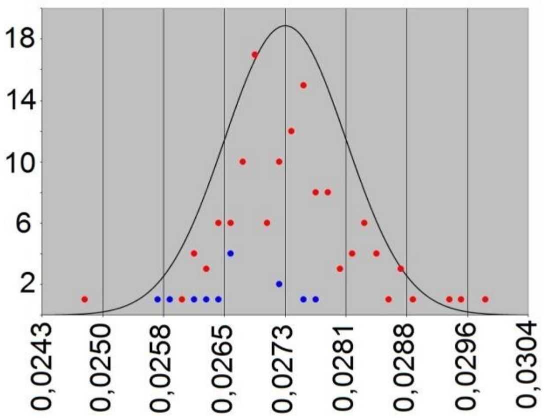


Fig. 8. λ values for daily traditionally produced pipe

According to the EN norms for confirmation of heat loses for DN 800 is used certificate for DN 60 traditional pipe, but Spiral conti smallest dimension is DN 200/355 λ= 0,0249W/mK, and these λ values must compete with traditional 3m pipe DN 60/125 λ=0,026 W/mK.

What to do? Logstor ordered the test for DN 200/355 daily production pipe – spiral conti and traditionally produced pipe - results showed that for conti λ=0,0249W/mK and for traditionally produced pipes λ=0,0266 W/mK. This test confirmed the difference between conti and traditionally produced pipes, bigger than Logstor use for calculations.

Heat loses must be calculated, based on the measurements for daily produced 12m pipe for each dimension. Then the district heating company based on these heat loss calculations can calculate more precise expected savings and life time costs for pipe renovation project. Taking into account the life time costs it is possible to evaluate the level of extra investments in pipe system (conti instead of traditional) to be feasible for exact project. This parameter could be used for evaluation of bids for tenders for renovation of pipeline system. Today many tender conditions are - pipes and installation. In this case the installer will always choose cheaper pipes with higher heat loses. As a result, the end customer does not receive the expected results and extra fuel is being burnt. It means that choice of pipes with reduced heat loses has environmental impact too.

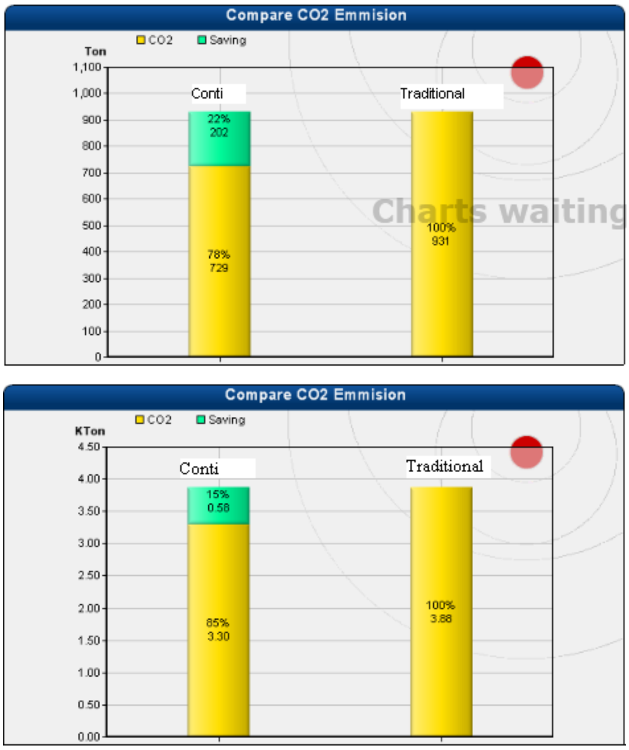


Fig.9. CO2 emissions case 1 and case 2

On the left CO_2 annula emissions for conti pipe on right CO_2 emssions for traditionally produced pipe. For case 1 – annual savings from conti pipes are 202 tons CO_a r (22%) comparing with traditionally produced pipes. For case 2 annual savings from conti pipes are 580 tons CO_a r (15 %) comparing with traditionally produced pipes.

The heatloss difference between conti and traditionally produced pipe is 9-12%, which corresponds to 1% of boiler efficiency. It means that every year 1 % more fuel is used. In 30 years - 30 % from one year consumption. How does this fit to the EU's goal to reduce the CO_2 emission to 20-20-20?

CONCLUSION

1. Heat loses is the most important part of the LCC.

2. If evaluation of real heat loses will be taken into account - it will push installers to choose pre insulated pipes with lower heat loses and better LCC.

3. The EN norms must be changed, taking test for every dimension 12 m pipe, instead of 3m DN 60 /125 pipe.

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Challenges, opportunities and results in DHC-markets

(Cases)

DISTRICT HEATING IN RURAL AREAS IN LOWER SAXONY

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Keywords: Settlement structures, calculated and measured load curves, rural areas

ABSTRACT

Small scale district heating networks are normally supplied by one or at maximum two supply stations. Settlement structures in rural areas in wide parts of Lower Saxony (Federal district in the north of Germany) are very different to settlement structures of cities and villages in the south of Germany. Not only building structures and use of buildings are very different, but also appearance of form of housing schemes. Many of these settlements have only few interconnections between roads. The extreme form of housing schemes has only one single road to which all buildings are directly connected to. These forms of housing schemes causes linear district heating systems.

To enhance security of supply, different heat sources have to be placed along the main roads of villages. For these systems a calculation tool is under development. Before programming this tool, analysis have to be made if standard load curves e.g. from VDI 4655 or BGW P 2007/13 represent behaviour of buildings.

INTRODUCTION

Caused by renewable energy law (EEG), which was concluded in 2000 by German Bundestag, district heating systems in rural areas become more and more popular in Lower Saxony. At the end of 2011 more than 1.300 biogas facilities with more than 650 MW electrical power were situated in Lower Saxony. [1] 70% of these facilities used the heat.

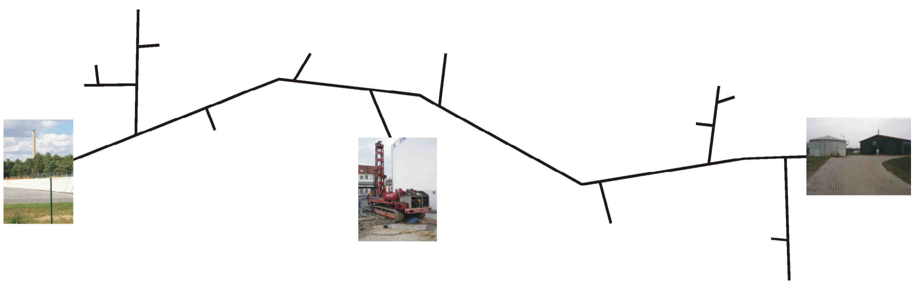

Fig. 1 Structure of a linear district heating system with spatial situated heat sources

The overall grade of thermal use of biogas facilities with heat use is only 55 % [2]. This grade of thermal use is to low for new district heating systems (According to EEG 2012 a grade of at minimum 60% thermal use for biogas facilities with renewable primary products is prescribed [3]). In addition, new district heating systems are facing more and more problems regarding security of supply in settlements with linear structures. Some of these settlements are longer than four kilometres. One of the biggest problems are too low temperatures at the end of row customers in summer, because of heat losses and low flow rate.

To solve problems the idea exists to install different spatially situated heat sources like industrial facilities, biogas facilities, wood chip boilers, solar thermal heat plants or gas boilers as well as long term and short term heat storages along the head pipe. (Fig.1)

But how to calculate system behaviour in an easy way?

Answering this question is the main aim of the research project “Possibilities and boundaries of district heating systems in rural areas taking into account renewable heat sources”. In the project University of Applied Sciences and Arts Hannover, Technische Unversität Braunschweig, Ostfalia – University of Applied Sciences, Borderstep Institute and Fernwärme-Forschungsinstitut are developing a tool for hydraulic and thermal calculation of these small scale district heating systems based on the program “dhemos” developed by Christian Johansson.

HOUSING SCHEMES

At first it is necessary to get information about form of housing schemes, building structures and use of buildings. Villages in Lower Saxony are based on nine different forms of housing schemes. Most of them are only situated in small regions. Some are common in wide areas. Presented are the five most common and interesting types of settlements for district heating systems with spatially situated heat sources:

Scattered Villages

They are the most common villages in Lower Saxony. Most of them are situated in the wide open land with only small hills north of a line between Hannover and Amsterdam. Scattered villages are characterized by a missing center, detached houses a long a few roads with little interconnections. [4],[5],[6],[7]

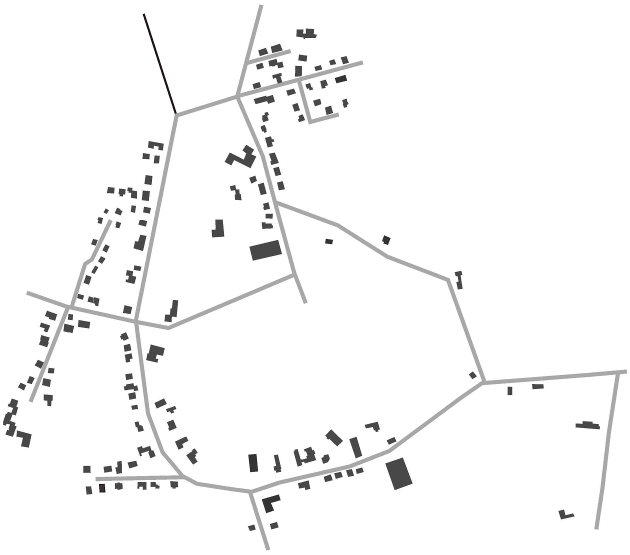

Fig. 2 Example for a scattered village: Heitlingen

In Fig. 2 the large buildings for agricultural use (sheds, repair shops, horse barns e.g.) are dominating the structure of the village by their size. Small buildings are residential buildings by far. Only few buildings are used for public or commercial use.

Hagenhufensiedlung

The Hagenhufensiedlungen are mainly situated in the region of Schaumburg (west of Hannover) and north of Hannover. They are a special planed type of settlements characterized by a single street and mostly buildings are only on one side of this road and a small beck behind the buildings. Later buildings were constructed at the opposite site of the street, too. Originally, the parcel of land of all buildings had the same size. [5],[8]

Fig. 3 Example for a Hagenhufensiedlung: Nordsehl

On the east side of the street (right) buildings for agricultural use dominate the picture. Today many of them are changed into pure residential buildings. On the west side of the street residential buildings and companies (bigger building in south west) are situated.

Fen settlement

Fen settlements are situated in the west and the north of Lower Saxony, near the border to the Netherlands. They are planed along channels for transportation. Most buildings are gable-end onto street. [5],[6]

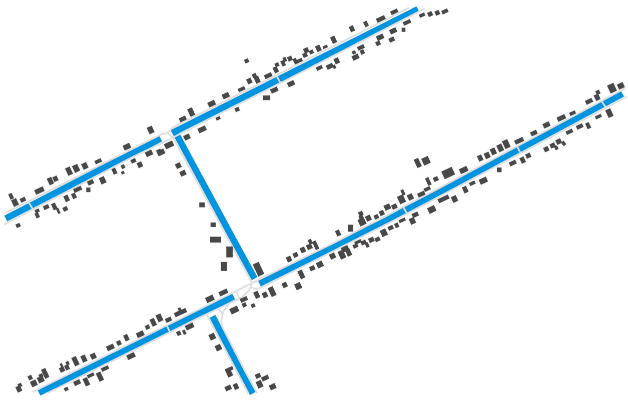

Fig. 4 Example for a fen settlement: Großefehn

Almost all buildings are used for habitation. Only few buildings are also used for commercial, agricultural or industrial purpose.

Row settlement (Hüttensiedlung)

Row settlements were founded by miners in the Harz mountains in the south east of Lower Saxony. The main streets with the houses are parallel to valleys and becks. The main buildings are directly at the streets. The auxiliary buildings are in the back. [4]

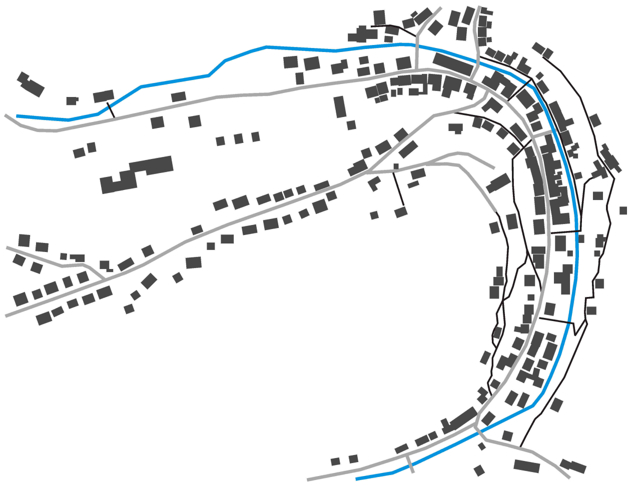

Fig. 4 Example for a row settlement: Wildemann

The buildings are comparatively small and close to each other. Buildings are used for residential, industrial, commercial and public purposes.

Nucleated village

Nucleated villages are the most common form of housing scheme in the area south of Hannover. This hilly landscape is called fertile loess area. Streets are predominant randomly linked. [4],[5],[6],[7]

Fig. 5 Example for a nucleated village: Hohnhorst

Larger buildings are for agricultural, industrial, commercial and public use. Smaller buildings are dominated by residential use.

After second world war most development areas were erected in form of nucleated villages. As result many settlements are a blend of different forms of housing schemes. [5]

THE CUSTOMERS

When forms of housing schemes were identified, identification of buildings and use had to be done.

For rural areas in Lower Saxony nearly one hundred types of buildings and utilisation had been identified. Many of them are described in literature and software including heat load curves. In reality buildings and utilisation are often outside fields of application of these documents. To check applicability, four buildings in a village and some buildings in a city were equipped with heat meters in March 2012. Measured data are compared to data, which were calculated according to VDI 4655 [9] and BGW P 2007/13 [10].

VDI 4655

This guideline was developed for load curves for small scale combined heat and power (CHP) systems in residential buildings. Load curves are available for single family buildings with at maximum 12 inhabitants and multi family buildings with at maximum 40 housing units. The year is divided into 10 typical days (Table 1).

The typical days are defined as follows:

- Overcast: More than 5/8 of the sky is clouded in average at the day
- Clear: 5/8 or less of the sky is clouded in average at the day
- Winter day: Mean temperature of day and 6 days before under 5℃
- Summer day: Mean temperature of day and 6 days before over 15℃

For every day there are load curves based on measurements with heat, tap water and electricity loads for every minute of a day in single family houses and every 15 minutes in multi family houses respectively.

A load curve for a year will be synthesised by assembly of typical days. Thereby the number of each typical day varies with the region, where the calculated CHP-System shall be placed. [9]

Table 1: VDI 4655 – Typical days

Typical days	Description
SWX	Summer, working day
SSX	Summer, Sunday
ÜWH	Transition period, working day, clear
ÜWB	Transition period, working day, overcast
ÜSH	Transition period, Sunday, clear
ÜSB	Transition period, Sunday, overcast
WWH	Winter, working day, clear
WWB	Winter, working day, overcast
WSH	Winter, Sunday, clear
WSB	Winter, Sunday, overcast

BGW P 2007/13

The guideline BGW P 2007/13 was developed for natural gas trading companies. Based on thousands of measured load curves of gas customers, the Technical university Munich developed mathematical correlations for outside temperature, time and heat demand. Data for load curve calculations are available for residential buildings, commercial buildings, small industries and public buildings. All load data apply to weekday, day's medium outdoor temperature and time of day. In contrast to VDI 4655 days in BGW P 2007/13 are from 6.00 a.m. to 6.00 a.m.. [9],[10]

Measured data

At four buildings from a district heating network with overall around 30 heat customers in Heitlingen (Fig. 2), a village north of Hannover, heat load data can be measured. This is a linear district heating network supplied by a biogas facility around 500 m away from the first customer. In two old farm buildings – both are between 70 and 120 years old – with heated residential property and office space overall heat load and heat load for hot tap water generation are measured (buildings 1 and 2). One multi family building, which is older than 200 years, is equipped with heat meters for overall heat load. Measuring hot tap water generation heat demand is not possible at the moment (building 3). All these buildings are equipped with storage charging systems for hot water generation. The fourth building equipped with heat meters in this district heating system is a repair shop for agricultural engineering (building 4). All heat meters collect quantity of heat and water volume as well as supply and return temperature data every 15 minutes.

Additionally nearly 20 multi family buildings of GBH (Gesellschaft für Bauen und Wohnen Hannover) in the north of Hannover have been equipped with heat, pressure and flow measurement systems. This small district heating system shall be used to check load curve differences between similar buildings with different energetic standards. Database for these buildings is too small to present any results at present.

Comparison of calculated and measured data

In our past measuring time (2012-03-08 to 2012-08-02), most frequent typical days with heating demand according to systematic of VDI 4655 were characterized as ÜWH with 40 days of 148. So this typical day will be basis for coming demonstrations. All figures shows the overall load of buildings.

Two days are examples for ÜWH typical days. These are 2012-03-08 and 2012-05-21 (Fig. 6).

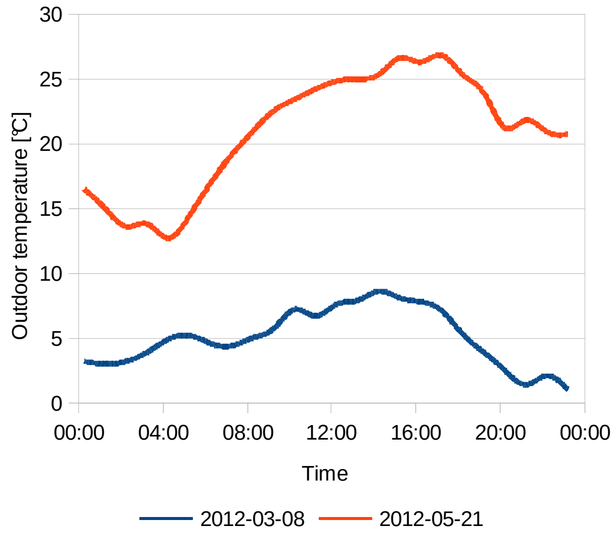

Fig. 6 Example for outdoor temperatures on two ÜWH-days.

At first it is interesting to look for one single building, if calculated values matches measured data. Results are show in figure 7.

It shows, that load curves calculated according to VDI 4655 and BGW P 2007/13 do not match for both days. Peaks of load profiles calculated according to VDI 4655 are nearly at the right time, but they do not show correct quantity. It seems, that the hot tap water storage of this building was loaded when water was used.

Whereas calculated values according to BGW P 2007/13, matches measured days mean load with differences of 23.9 % (2012-03-08) and 24.2% (2012-05-21). Peaks do not match in any case.

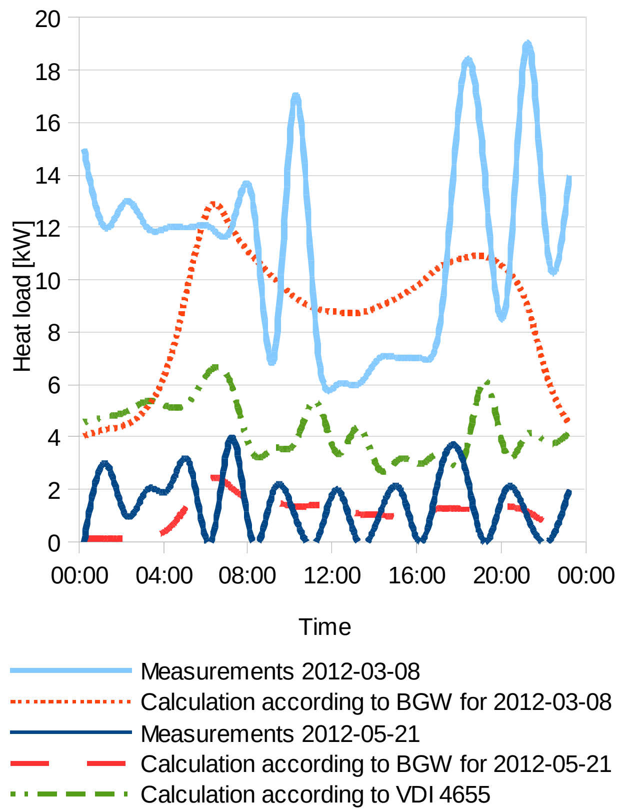

Fig. 7 Comparison of calculated and measured heat loads

When looking on the buildings 1 to 4 as a group in the district heating network, continuation of heat flow is expected. Figure 8 shows the results measured and calculated according to BGW P 2007/13 for 2012-05-21.

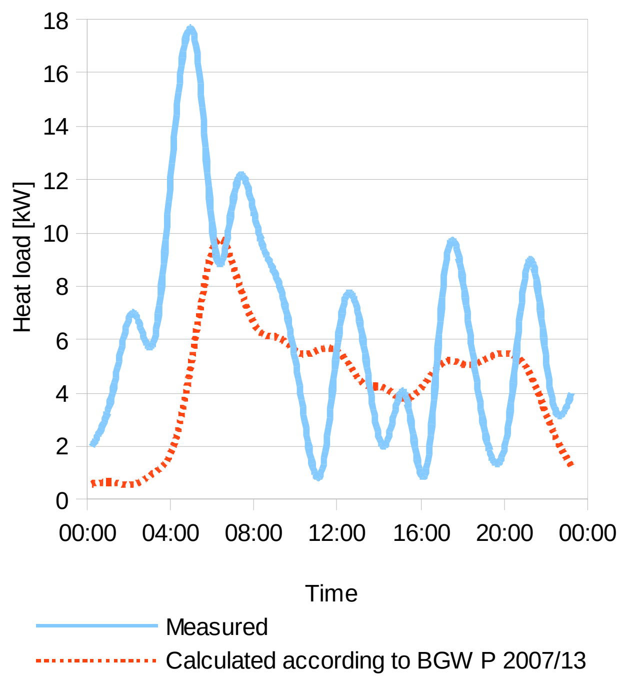

Fig. 8 Comparison of average of measured data and calculated data for buildings 1 to 4

It becomes visible that the calculated load curve has the same trend as from measured data. However, the hourly fluctuation is not calculated.

The last figure (Fig. 9) shows comparison for calculated load curve according to VDI 4655 for buildings 1 to 3 and the averaged measured data over all ÜWH-days.

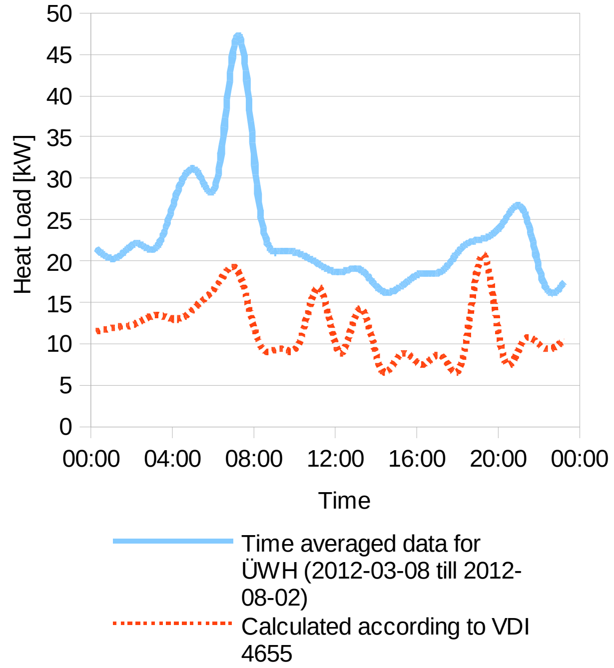

Fig. 9 Comparison of averaged measured data and data from calculations according to VDI 4655, buildings 1 to 3

Calculated and measured data have the same trend over the day. As expected data calculated by VDI 4655 are more fluctuating than averaged measured data, because user behaviour is not the same every day. So averaging reduces peaks. Only peaks in the morning and the evening, when hot tap water is generated and most people are at home, are pregnant.

CONCLUSION

District heating systems in villages in Lower Saxony need new concepts for heat production and storages because of form of housing schemes and load curves. Measured load curves do not fit with the calculated. Maybe changes in control of substations will reduce differences. This must be analysed in the next months.

If fluctuation in heat demand can not be reduced it will be necessary to build spatially situated heat sources and storages close to the main heat customers in the existing district heating system, where our measurements take place. With a central control system for heat sources and substations district heating system efficiency may raise for linear district heating systems also. To check this before constructions start, calculations for different system situations are necessary.

ACKNOWLEDGEMENT

The project “Possibilities and boundaries of district heating systems in rural areas taking into account renewable heat sources” is financed by European Union, ERDF, and the state Lower Saxony. Furthermore the project is supported by Aaron Baitinger Sanitär- und Heizungstechnik, Biogas Heitlingen, Bioenergie Heitlingen, Fels Heizung Sanitär, Hannover Airport, Hille Regelungstechnik, Mieterservice Vahrenheide, on/off engineering and WDV/Molliné.

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MODELING REGIONAL DISTRICT HEATING SYSTEMS – THE CASE OF SOUTH-WESTERN SWEDEN

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Keywords: Regional DH grids, Waste heat utilisation

ABSTRACT

Biomass has become the main fuel for district heating (DH) systems in Sweden and is used both in heat-only boilers and, increasingly, in combined heat and power (CHP) plants. DH contributes also to increased sustainability through the utilization of waste heat (WH) which substitutes for primary energy use. Both the geographical distribution of WH sources and the scale effects of bio CHP plants are driving forces for the merging of DH systems. In this study, we are assessing opportunities for connecting local DH systems by transmission pipelines in the Västra Götaland region of Sweden and the system effects and costs of such investments. The assessment is carried out assisted by the optimizing MARKAL_WS model, in which the municipal DH systems in the region are represented individually as well as their relative geographical distribution. The results indicate that linking of local DH systems into larger regional systems can assist economic and environmental sustainability since it enables utilization of, currently unexploited, industrial waste heat resources. However, the cost-effectiveness of pipeline investments is dependent on the size of the available WH capacity. Furthermore, increased use of WH leads to less electricity generation from CHP in the region.

1. INTRODUCTION

In Sweden, due to the oil crises in the middle of 1970's and a high taxation on oil combined with governmental subsidies for domestic fuels such as peat and biomass (Swedish Governmental Energy Commission, 1995), oil has been almost phased out in the Swedish district heating (DH) sector. Furthermore, the national tradable green certificate system, in which electricity consumers are urged to buy certificates corresponding to a certain quota of their total electricity consumption, encourages investment in biomass-based combined heat and power (CHP) plants as the most cost-effective technology (Bergek and Jacobsson, 2010). Consequently, biomass accounts for a large share of the fuel use in Swedish DH systems and is used both in heat-only boilers and, increasingly, in CHP plants. At the same time, results of various studies have shown that the utilization of waste heat (WH), which substitutes for primary energy use in DH, contributes toward economic and environmental sustainability (e.g. Gebremedhin and Moshfegh, 2004; Karlsson et al., 2009).

Future development of the supply side of Swedish DH systems faces a number of challenges. The value of biomass is likely to increase, and thus the price, as a consequence of more serious climate mitigation, and this will certainly affect the cost-effective utilisation of constrained biomass resources. Already today, in a number of systems, WH from industries and municipal solid waste incineration supplies large amounts of the base load heat but a further increase of the WH supply requires in many cases large grid investment since sources are geographically scattered, and also introduces business uncertainty when DH utilities to a lesser extent can control their heat supplies. The interest for extension of the DH grids through connection of several local systems and industries into a regional grid has thus recently attracted increasing attention.

The purpose of this study is to analyze possibilities and potential system effects of regional integration between several local DH systems and industries. The study evaluates the potential effects of the integration on DH systems and different potential industrial waste heat deliveries in regard to total system cost, environmental impacts including CO_2 emission and resource use, and DH technology choices.

A few studies on the subject of regional integration of DH systems and industries in Sweden have earlier been carried out. For example, Gebremedhin and Moshfegh (2004) studied a locally deregulated heat market in regard to system cost reduction through integration and availability of different actors with various heat supply sources. Karlsson et al. (2009) assessed the economic and environmental potential of connecting industrial plants and local district heating systems to provide a joint DH grid in a regional heat market, in which the region includes three different DH provider companies in three municipalities and three energy intensive industries. In these previous studies, only a limited number of DH systems and industries have been included i.e. three DH systems and three or four industries. Further, both of the mentioned studies apply cost optimizing energy system modeling; however, the investment cost of building new pipelines was not included. In present study, we choose Västra Götaland, a region in the south-western of Sweden, as our case study and include all the local DH systems in the region. Additionally, the investment cost of DH systems' integration pipelines is included in this assessment.

2. METHOD

Since we assess a complex energy system, 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 (Lolou et al., 2004), 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. The model, which represents the energy system of the Västra Götaland region, was developed and applied in Börjesson and Ahlgren (2010; 2012). In the present study, the connection of local DH systems is studied and the system cost is optimized, including perfect foresight, over 30 years. A model discount rate of 5% is used.

MARKAL_WS has a time horizon reaching between 2004 and 2029 and is divided into six 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 this version of the MARKAL_WS model, a better description of the WH capacity from the large industrial chemical cluster in Stenungsund is added. Stenungsund is a municipality with a population of about 10 000 people located about 50 km north of Göteborg, which is the main city in the region with about 550 000 residents. Currently, the chemical industries supply Stenungsund DH system with heat; however, the WH capacity is considerable larger than the demand in Stenungsund (see Hackl et al., 2010). In this model version, we also add investment options for DH transmission pipelines between each of the 37 local DH systems represented in the model. We then assess the effects of different WH capacity levels in the Stenungsund chemical cluster on investments in pipelines and on other cost-effective technology and fuel choices of the region. Each simulated WH capacity level is assumed to be constant throughout the studied time horizon. The WH is assumed to be available for DH without cost, i.e. any monetary transactions between industry and DH companies as payment for the waste heat is considered to be within the system boundaries.

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 DH demand is independent of the price fluctuations. The duration curve of DH is defined by three seasons: summer, winter and spring/autumn (intermediate). There is an unlimited market for electricity generation from CHP plants. The generated electricity is sold at exogenously given market prices which give rise to a lowering of the system cost.

We apply "lumpy" investment option in MARKAL to change exact linear LP model to a mixed-integer programming (MIP) model. With a linear model, technologies can be built at any capacity level (without economies or diseconomies of scale), while with a MIP model selected technologies can only be built at discrete capacity level. In this study, the integration pipelines between different local DH systems are 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.

2.1 INTEGRATION PIPELINES

The possible integration pipelines between local DH systems in the region are described by investment cost, operation and maintenance cost, efficiency and life time. The most significant parameter is the investment cost. In the model, the investment cost of integration pipelines is assumed to be 1000 EUR/m (for simplicity, independent of capacity level). The length of each pipeline is estimated based on distances between the respective cities. Investments in the new integration pipelines can be made from model year 2014. The investment cost is based on data presented by the Swedish DH Association (2007) and data collected through interviews with DH provider companies, which have already invested in such integration pipelines (e.g. Kungälv Energi and E.ON) The pipeline operation and maintenance cost is assumed to be 0.1 EUR/MWh (excluding energy losses) (based on Reidhav and Werner, 2008). In the model, the lifetime of pipelines is 30 years.

2.2 CO_2 TAX AND ENERGY PRICES

In this study, a simplified energy policy situation is simulated and only one policy tool is applied: a cost for CO_2 emissions. This CO_2 tax is defined in the model in an exogenous way, is included in all model scenarios, and is assumed to increase linearly during the studied period from 20 EUR/ton CO_2 in model year 2009 to 80 EUR/ton CO_2 in the model year 2029, i.e. at the end of model time horizon.

The CO_2 cost assumptions as well as fossil prices utilized are based on the 450 scenario in International Energy Agency´s World Energy Outlook (IEA, 2010). Biomass prices are assumed to increase during the studied period due to increased competition. Examples of energy prices used (from 2009→2029, for DH):

- Heavy fuel oil: 28→41 EUR/MWh
- Natural gas (large plants): 21→31 EUR/MWh
- Biomass – wood chips: 20→27 EUR/MWh

The electricity price in Sweden is determined based on marginal production technology of the Nordic electricity system. In this study, marginal production technology and electricity price are assumed to be set by the lowest variable electricity production cost of either coal condensing power plants or natural gas (NG) combined cycle plants.

2.3 MODEL SCENARIOS ASSESSED

In this study, four model scenarios are simulated. Firstly, a base scenario in which no new connections between local DH systems can be built is established; this scenario is referred to as the “without connection” case. However, also this scenario includes three already existing DH systems’ integration pipelines in the region, i.e. Kungälv – Göteborg , Mölndal – Göteborg, and Göteborg – Mölndal with the DH transmission capacities of 19 MW, 30 MW and 40 MW respectively (see also in Results section).

Apart from the base scenario, “without connection”, we study three other scenarios which includes the possibility of building the new integration pipelines. These scenarios are differentiated by three different WH capacity level assumptions for DH deliveries from the chemical industries in Stenungsund. Although there most certainly is, and will be, a large excess capacity of waste heat from this chemical cluster, the precise level is linked to uncertainty. The three WH capacity levels simulated in this study are 75, 150 and 225 MW. The model scenarios are referred to as “WH-75MW”, “WH-150MW” and “WH-225MW” respectively. Consequently, these scenarios investigate the potential for regional DH systems and influence of different WH capacity levels compared to the base case.

3. RESULTS

In this section, the result of the model calculation for the simulated scenarios are presented and compared. Mainly, DH production in the “without connection” case is, in the first part of the studied period, based on bio heat-only boilers (HOBs), NG CHP, municipal waste CHP and heat pumps (HPs), while bio CHP production increases with time and decreases the use of NG CHP, HOBs and HPs. Also, municipal waste CHP is slightly increased during the studied time period, but the amount of available municipal waste constrains further increase (Figure 2 Figure 3).

With the possibility of building new integration pipelines and with a WH capacity level of 75 MW in Stenungsund, the result of the cost-optimized energy system presents that no new pipeline is built in the system. Thus, in regard to primary energy use, technology choice, electricity generation, CO_2 emission and total system cost, in comparison with the base case, the system remains unchanged (Figure 2, Figure 3, Figure 4 and Figure 5).

With the possibility of building new integration pipelines and with a WH level of 150 MW, two new integration pipelines are built in the region: Stenungsund – Kungälv with a DH transmission capacity of 125 MW and Kungälv – Göteborg with a capacity of 124 MW ( ). A new pipeline between Kungälv – Göteborg is added to the existing one since the existing pipeline between Kungälv and Göteborg has only limited capacity of 19 MW.

Figure 1- Västra Götaland region. New and existing integration pipelines

In this scenario ("WH-150MW"), WH from industries in the region accounts for larger share of DH production (Figure 2Figure 3). In comparison with the "without connection" case, biomass and NG is replaced with WH due to lower cost of waste heat for DH utilities. Consequently, electricity generation from biomass based and NG based CHPs decreases by about 19% (Figure 2Figure 3). In this model, CO_2 emission related to primary energy use in industries is not included within the considered system boundaries. With this scenario, CO_2 emission from DH production within the region decreases by 14% since WH replaces a part of the NG primary energy use (Figure 4). However, with an expanded system view for which it is assumed that the generated electricity in DH sector replaces the marginal electricity generation in the Nordic electricity system, the lower electricity generation from CHP in the WH-150MW scenario implies lower CO_2 abatement (reduced "negative" CO_2 emissions) than earlier cases, i.e. "without connection" and "WH75MW" (Figure 4). Total system cost (net of taxes) is reduced (by 15%) and so is the sum of the CO_2 tax (due to less use of NG) (Figure 5). It should be noted that the presented aggregation of the CO_2 taxes implies of cost for the DH sector but revenue for the government.

In scenario "WH-225MW", the same two integration pipelines as in "WH-150MW" are built: Stenungsund-Kungälv and Kungälv-Göteborg; however, in this case with the capacities of 195 MW and 185 MW respectively. In comparison with the "WH-150MW" scenario, more biomass and NG are replaced with WH. Electricity generation from biomass CHP and NG CHP plants, which are the main producers of electricity in the region, decreases by 27% compared to the "without connection" case (Figure 2Figure 3). In comparison with the "without connection" case, CO_2 emissions from DH production within the region decreases by 27% due to the larger share of WH in the heat supply (Figure 4Figure 4). However, with an expanded system perspective taking also effects in the marginal electricity generation into account, the larger use of waste heat and smaller utilization of CHP furthermore reduces the CO_2 abatement effect in this scenario compared to earlier cases (Figure 4Figure 4). Regarding the total system cost and aggregated CO_2 emission taxes, model calculates a reduction of 24% and 6% respectively compared to the "without connection" case (Figure 5).

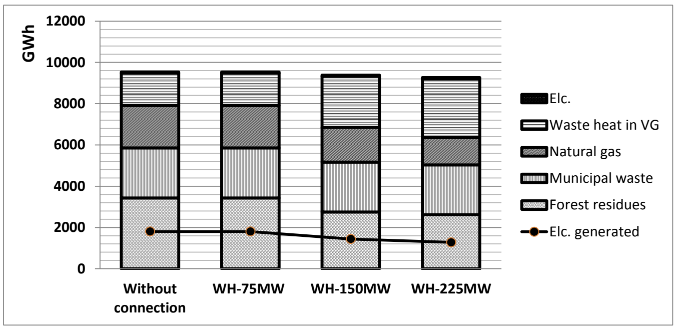

Figure 2- Fuel and electricity use and electricity generation in model year 2019

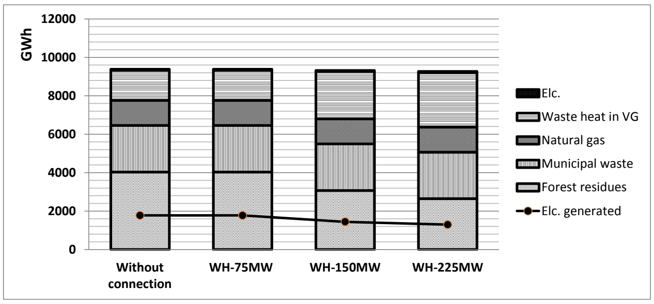

Figure 3- Fuel and electricity use and electricity generation in model year 2024

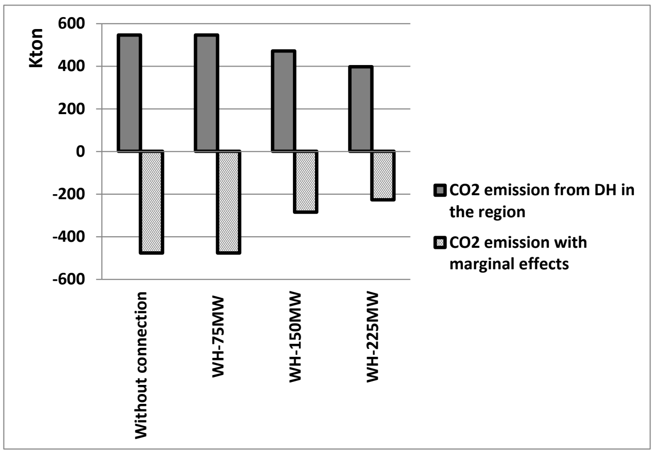

Figure 4- CO_2 emission in model year 2019

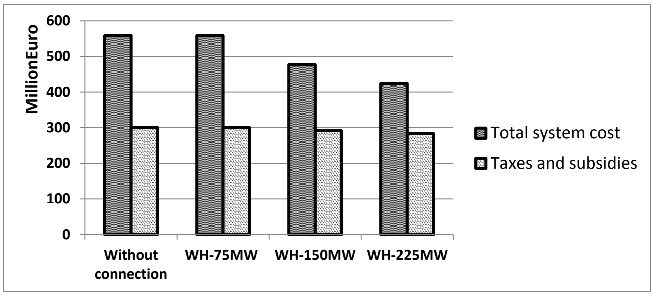

Figure 5- Total cost of DH production (net of taxes) and sum of CO_2 taxes in the region

4. DISCUSSION AND CONCLUSION

In this study, the economic and environmental sustainability of cooperation between a regional DH system and industries is assessed. It is investigated how different levels of WH capacities from industries effects total system costs, technology choices and environmental parameters including CO_2 emissions and fuel use.

In the modeling results, integration of local DH systems and introduction of WH, in excess of 150MW from the chemical industries in the municipality of Stenungsund, reduces the total system cost, which suggests that such actions can improve the cost-competitiveness of DH in comparison with other heating technologies. Additionally, the investment in DH transmission pipelines and the increased use of WH decreases the use of fossil fuels in the DH production of the region significantly. The Swedish DH sector, which is strongly dependent on biomass as fuel, can substitute biomass with WH and benefit economically and environmentally from DH grid connections. However, the utilization of more WH in DH systems also leads to a reduction of electricity generation from biomass-based and NG CHP plants which of course is of importance in a more general energy supply perspective.

The existence of large low-cost heat sources, such as industrial WH, is an important requirement for investments in new integration pipelines between local DH systems to show cost-effectiveness. In this study, by introducing one WH source to the system, two new integration pipelines were added to the system to transfer DH to areas with larger heat demand. Additionally, more WH sources make local DH systems more resilient against economic cycles because local systems can choose between different WH sources.

Through integration of local DH systems into larger regional ones, WH can be used to supply both local and regional heat demand. That is, a regional DH system assists full utilization of available WH as a low cost energy source within the system. In this study, the investment cost of integration pipelines plays an important role in building of a regionally integrated DH system. In several previous studies, this parameter has not been accounted for when the total cost of a regional DH is calculated. One factor in calculation of the investment cost is the distance between local DH systems, which is subject to uncertainties in the sense that the actual best localization of a pipeline will be subject to local conditions. Additionally, in this study the investment cost of the pipelines is constant, independent on their capacity level. In future studies, the investment cost of pipelines might be modeled with better accuracy.

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

ACKNOWLEDGEMENTS

The presented study is part of a larger study in which the sustainability of various future district heating options are assessed using a combination of energy systems assessment and modeling and LCA methodology. The study is financed by FORMAS and E.ON.

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PLANNING OF THE DISTRICT HEATING SYSTEM IN COPENHAGEN FROM AN ECONOMIC PERSPECTIVE COMPARING ENERGY-SAVINGS VERSUS FOSSIL-FREE SUPPLY

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Keywords: Low temperature district heating, Energy renovation, Energy savings, Fossil free energy supply, Costs, Geothermal energy

ABSTRACT

The Danish governmental has an objective of being completely independent of fossil fuels by the year 2050, and the energy supply mix for buildings should be free of fossil fuels by 2035. Therefore, urgent action is needed to meet the requirements for the future energy system. One way of becoming independent of fossil fuels is to energy upgrade the existing building stock and change the energy supply to renewable energy sources. A sustainable way of providing space heating (SH) and domestic hot water (DHW) to buildings in densely populated areas is through the use of district heating (DH). This paper is a theoretical investigation of the DH system in Copenhagen, where heat supply is compared to heat savings in buildings from an economic perspective. Supplying the existing building stock with heat from renewable energy supply technologies e.g. low temperature district heating (LTDH) from geothermal heating plants, may lead to oversized heating plants that are too expensive to build compared to implementing energy savings. Therefore reducing heat demand of existing buildings before investing in supply capacity will save society half the investment, indicating the importance of carrying out energy savings now.

INTRODUCTION

The Danish governmental has an objective of being completely independent of fossil fuels by the year 2050, and the energy supply mix for buildings should be free of fossil fuels by 2035. Therefore, urgent action is needed to meet the requirements for the future energy system. [1],[2]. The solution is to combine energy savings and renewable energy supply in an optimal way. The European building stock accounts for about 40 % of the overall energy use [3]. In order to reduce this energy use there is a need of reducing the energy use of the existing building stock, increase energy efficiency and converting the present heat supply from fossil fuels to renewable energy sources.

The design of new low energy buildings has been in focus throughout the recent years and much research has been carried out in order to design optimized buildings from an energy perspective [4]-[8]. However, only 1% of the building stock today is newly constructed as low-energy buildings, which underlines the importance of looking into the existing building stock, where the potential for energy savings is large [9]-[12]. Investigations have shown that the energy consumption can be reduced with about 50-75%[10]-[14], but it takes significant investment costs to reach very low levels of energy consumption [10]. However, since the existing buildings will remain for many years yet to come, it is an unavoidable factor to deal with

The future energy system will have to be based solely on renewable energy sources, which is a huge challenge for the society. It will have to be based on well coordinated interacting energy supply systems where a list of different renewable energy technologies has to interact and balance in a way that will ensure a system with security of supply.

A sustainable way of providing SH and hot water to the buildings in dense populated areas is by the use of DH [15]. In many countries DH systems are already established, but they, as for the remaining energy supply system, face new challenges in the future. In countries like China, U.S.A, Iceland, and Turkey [16] a large share of the DH supply is based on geothermal, whereas in Denmark, Sweden, and Finland the DH supply mainly comes from combined heat and power generation plants (CHP) [16]. The DH systems will have to be converted from the present supply technologies based on fossil fuels into 100 % renewable energy sources. Different resources such as biomass, geothermal, sun, waste, heat pumps, and surplus heat from the industry and CHP etc. can be considered in regards to convert to a fossil free supply system. In Denmark some CHP plants have been converted into biomass and large solar and geothermal heating plants for DH have already been established. Among newly developed geothermal heating plants in Denmark can be mentioned, Dronninglund, Sønderborg, and Viborg [17].

The DH system currently operates with temperatures of about 80°C/50°C. If the DH system is converted into low-temperature DH (60°C/30°C), the heat-losses from the network will be reduced and the heat supply from renewable sources will be more suitable for the system. The geothermal water under Copenhagen can be drawn at a temperature on 73°C [17], so heat pumps will not be needed to elevate the temperature of the water. This will save on electricity and avoid peak loads in the electrical supply system, which will be more fluctuating and vulnerable to peak loads since it will be based on renewable energy sources, mainly wind power.

This paper investigates different scenarios of the future DH system taken into account energy savings and the conversion of the fossil fuel supply technologies into renewable supply technologies. The approach to the investigation is to state the economical consequences of different energy planning scenarios when it comes to the future DH system. The approach is very general and the objective is to give an overall picture of economical consequences by following different energy planning strategies. Details of the individual heating plants and locations of them are neglected and further detailed investigations will have to be carried out if a complete detailed picture has to be drawn. Furthermore simplified assumptions are made and there are details that will have to be investigated further.

Waste heat from the industry could be used in combination with either geothermal or solar heat, but from [20] the potential has been estimated to be low (3%) in the area of Copenhagen since the industry sector is small, and is therefore neglected in this investigation. This paper looks into the implementation of geothermal supply for the future DH system together with waste for incineration. Solar thermal plants with storage or heat pumps would be other possible future solutions, but are not the focus in this investigation.

THE MODEL

Approach

Due to the planned future energy policy, coal will have to be phased out in 2030 [1]. According to the Heat Plan of Copenhagen [18] coal will already have to be phased out in 2025, which have been the basis of this investigation. Additionally it is assumed that biomass will be available until 2040 after which it will descend to the transportation sector that will have to be fossil free in 2050 [1]. It is assumed that the transportation sector will be willing to pay more for the biomass resource in the future, implying that other renewable energy sources will have to be used. Furthermore research has found that Europe will have a biomass potential of only 15-16% of the total primary energy demand in 2030 [19]. This will result in that biomass will have to be imported from 3rd world's countries, which is not preferable and not considered a long term sustainable solution. The biomass is better used locally in order to develop sustainable energy sectors in 3rd world's countries, and to avoid dependency, which is one of the main concerns today regarding fossil fuels.

In order to use renewable energy sources in an efficient way, LTDH should be considered. LTDH has been object for investigation recently and are among others studied in [21]-[28]. When the heating demand in buildings are decreased to low levels the possibility of LTDH becomes an option, since the need of SH will decrease and the peak loads will to a larger extend be "cut off". It is found from [28] that low temperature DH is possible in most hours of the year in existing buildings. The period with very cold climate conditions require an increase in the temperatures, which is assumed to be possible in the waste incineration plants. Supplying water to the transmissions lines with high temperatures from the incineration plants and mixing it with the colder geothermal water in the local DH plants, it is assumed that the temperatures will be able to cope with the heating demand under cold climate conditions. When LTDH is implemented the problematic of legionella has to be considered regarding the DHW. Studies have shown that the legionella problem can be avoided as long as the temperatures are above 50°C [21], which implies a local boosting of the water temperature in the buildings e.g. by the use of flat stations. Additionally, recent research in Sweden has shown good results by the use of UV-sterilization [29],[30].

Present heat demand and potential for conversion of individual natural gas heated buildings

The present DH network in Copenhagen area consists of three waste incineration plants plus four CHP-plants distributed in a geographical area as shown in Figure 1. The supply area includes the western CHP plants (VEKS) and the central CHP-plants (CTR) in the Copenhagen area. The fundamental basis of this investigation is based on the DH system as it is today, and does not include the entire Copenhagen area at the moment.

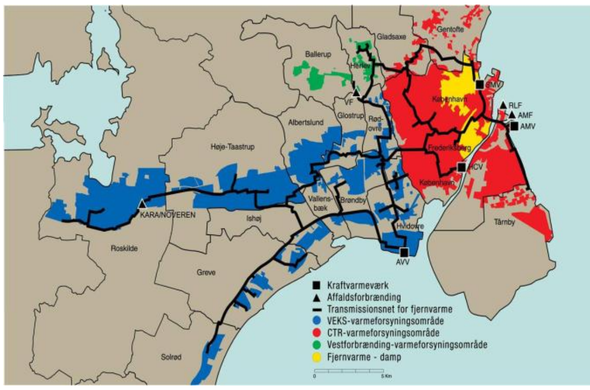

Fig. 1 Map of existing DH network in Copenhagen area. [31]

The total heat demand (2010) of the entire area is 35 PJ/year with a peak load on 2500 MW[31]. The overall net losses are assumed to be 15 % and 8 % of the yearly production with traditional DH and low temperature DH respectively [32],[33]. It is assumed that the DHW demand is 400MW constantly over the year with the exception of the summer period where buildings are expected to use less water due to vacations.

An analysis of the potential of converting individual natural gas users into DH has been carried out [31],[32],[33]. A potential on 10 PJ has been found as a realistic amount within a geographical possible area of conversion [33]. This implies a total yearly consumption on 45 PJ/year and a peak load of about 3200 MW assuming the same increase in percentage from present (2010). Furthermore it is assumed that the DHW-consumption increases with the same tendency as the conversion of the natural gas users into DH takes place.

Energy renovations

As a simplification it has been assumed that a decrease in yearly heat demand on 65%, correspond to a decrease in the power loads on 65%. This simplification is based on simulations made for a low-energy house and an existing building [28], and the ratio of total heat demand over the peak load has been compared. This simplification contains certain errors and will have to be investigated further.

Scenarios

Calculations on three different possible future scenarios are carried out and sensitivity analyzes on the amount of waste for incineration in the future are done. The main calculations are carried out assuming a decrease in the amount of waste on 1/3 in 2070 compared to today.

Reference scenario – No energy renovation but only natural replacement of the existing building mass with new buildings.

This scenario represents a fundamental scenario of what will happen if nothing is done to reduce the heat consumption until 2070. In consequences of that no renovations are done in the existing building mass the buildings will over time dilapidate and be replaced with new buildings. According to [10] a heat reduction of around 50 % corresponds to that the existing buildings will reach an energy level corresponding to what is required from new buildings today in the Danish Building Regulations 2010 [34]. It is assumed that 1% of the existing building mass is replaced with new buildings a year, implying a yearly decrease in the heat demand on 0.5% of the building mass the year concerned.

Scenario 1 – Accelerated energy renovation from 2030-2070

Scenario 1 represents the case where no heat savings are carried out in the near future. The DH supply will be converted from fossil fuels to biomass on the CHP-plants and the prices will remain unchanged. No energy savings are carried out due to pour economy and no legislation or requirements here upon. Only the natural replacement of the building mass with new buildings on 1% per year is undertaken. The biomass will be phased out between 2030 and 2040 after which it will be moved to the transportation sector. Geothermal plants are established in order to cover the remaining nearly unchanged heat demand and the investment in geothermal energy will result in increased prices for DH. Deep energy renovation are carried out and the heat demand decreases with 65 % from 2030-2070, implying a decreased heat supply. The coefficient of utilization will decrease and the prices will rise further.

Scenario 2 – Accelerating energy renovations from today

Scenario 2 represents the case where heat savings are carried out from today. The DH will be converted to biomass and phased out between 2030 and 2040 as for the first scenario, but energy savings are carried out from today until 2040 implying a decrease in the heat demand. The investment in Geothermal heat supply plants are thereby decreased significant.

Economics

In order to calculate the economical consequences for the society for each of the scenarios, simple economical calculations have been carried out. The real interest rate is not considered, which in reality makes the costs higher than indicated here. Estimated costs of investment, maintenance and operating cost are included for geothermal heat and for the DH net. The costs related to the fossil fuels and biomasses are neglected since they are nearly the same in all scenarios. Furthermore it is assumed that the waste in the future will be considered a resource that will be priced, but since the price on heat will be based mainly on the investment in geothermal plants and the coefficient of utilization, the price on waste will be similar. The cost for the reference scenario will be based solely on supply whereas the costs for scenario 1 and 2 furthermore are based on the energy renovation, implying that they will be added to the supply price.

Geothermal - Capital investment cost

The investment cost for geothermal is estimated to be 1.6 mil €/MW for a geothermal plant on 135 MW [18],[31],[37]. Around half of the capacity (70MW) comes from geothermal heat. From other sources [35],[36] an investment cost on 1.7 mil €/MW is found. Assuming LTDH implying that there will be no need of heat pumps the investment in geothermal is assumed to be approximately
$2.7\ \text{mil}\ €/\text{MW}.\quad (1.6\ \text{mil}\ €/\text{MW} \cdot 2 = 3.2\ \text{mil DKK/MW}.$ The cost will be around the double, but due to economy of scale it is assumed to be slightly lower $\approx 2.7\ \text{mil DKK/MW}$).

Geothermal - Operating and maintenance cost

The price for operation and maintenance cost (O&M) is difficult to estimate since it varies depending on various factors and conditions. The O&M-cost is assumed to be 6.3 €/MWh, based on [37].

DH network – Capital investment in new capacity

According to [37] the investment cost for installing new pipelines in a new DH area with a yearly heat demand on 38,000 MWh is about 10.7 mil €, resulting in a unit price on 282 €/MWh. This fixed asset investment is very sensitive to both the density and the accessibility of the area. Hence a unit price of 302€/MWh is assumed [37].

DH-network - Operating and maintenance cost

The O&M cost is assumed to be 2 €/MWh [36].

Energy renovation costs

According to [10] which is based on the entire building stock in Denmark (dwellings) the cost of saving 102 PJ/year corresponding to energy savings on 65% is 51 Mil €. This result in a unit price per saved petajoule of 8.3 Mil €/PJ, based on saving in 60 years.

Assumed lifetimes

Geothermal:	40 years
DH network:	60 years
Renovations of dwellings:	60 years

Costs

The investment cost for geothermal is found based on the needed capacity in the different scenarios, and O&M-costs are found based on the total geothermal heat production during the period in question (40 years). The investment cost for the DH network is based on the potential for converting natural gas costumers into DH corresponding to 10 PJ. O&M-cost

is calculated based on the total heat production throughout the period in question (60 years). The total costs are:

$$\mathrm{Costs_{Total}} = \mathrm{Invest_{Geo}} + \mathrm{O\&M_{Geo}} + \mathrm{Invest_{DH}} + \mathrm{O\&M_{DH}}$$

The unit price for supply energy is calculated as:

$$\mathrm{Unit\ Cost_{Supply}} = \frac{\mathrm{Cost_{Total}}}{\mathrm{Production_{Total\_Geo}}}$$

The total costs for the supply throughout the entire period in question are:

$$\mathrm{Total\ Cost_{Supply}} = \mathrm{Unit\ Cost_{Supply}} \cdot \mathrm{Production_{Total\_DH}}$$

In scenario 1 and 2 the total cost for supply is dependent on the decrease in heat demand, implying that the cost for carrying out energy renovation has to be added to the supply price:

$$\mathrm{Cost_{Savings}} = \mathrm{US} \cdot \mathrm{ES}$$

US is cost of saving one unit of energy
ES is the energy savings in the period in question

Table 1 shows the economical calculations for each scenario.

RESULTS AND DISCUSSION

Reference scenario

The reference scenario represents the case where no accelerated energy renovations are carried out. Figure 2 shows the peak load and the distribution of resources. The priority of the utilization of the resources is: 1. Waste for incineration; 2.Geothermal; 3. Biomass; 4. Fossil fuels. As seen from the figure the heat demand is increasing until 2035, due to the conversion of natural gas areas to DH. Simultaneously the existing building mass is replaced with new buildings decreasing the heat demand with 0.5% per year. The figure shows that it is needed to invest in a capacity of 2,800MW geothermal heat.

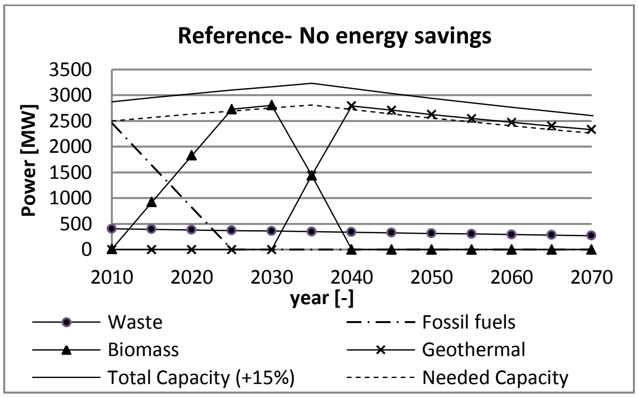

Fig. 2 Peak load for the reference scenario, where no accelerated energy renovations are carried out.

The yearly production of the different supply technologies until 2070 are seen in figure 3. As seen the geothermal heat production is peaking in 2040 with 32 PJ after which it decreases with 13% up until 2070. The total geothermal production in the entire period is 1100 PJ.

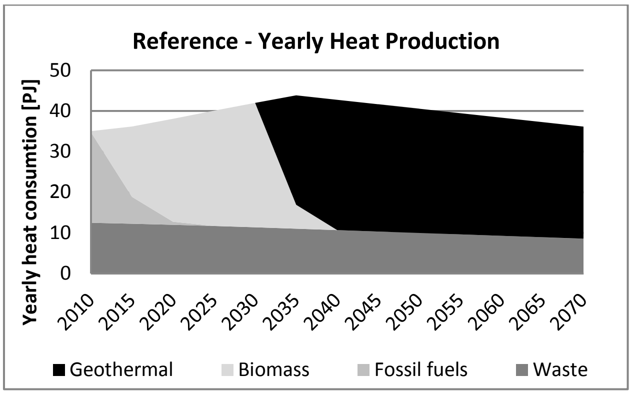

Fig. 3 Yearly heat production for the reference scenario, where no accelerated energy renovations are carried out.

Scenario 1

Scenario 1 represents the case where accelerated energy renovations are carried out from 2030. Figure 4 shows the peak load and the distribution of the supply technologies. As seen from the figure the heat demand is likewise the reference scenario peaking in 2030 after which it decreases. The investment in geothermal capacity is seen to be 2,500 MW, which is slightly lower compared to the reference scenario due to the accelerating energy renovations.

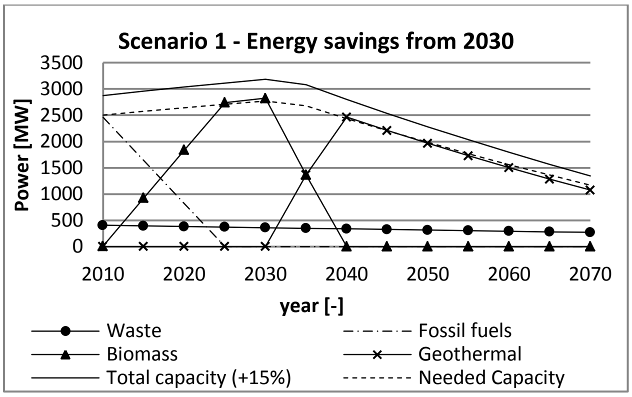

Fig. 4 Peak load for scenario 1 – accelerating energy renovations from 2030.

Figure 5 shows the yearly production of the different supply technologies from 2010-2070. The geothermal production peaks in 2040 with 28 PJ. Due to the accelerating energy renovations the heat demand decreases from 2030 up until 2070 resulting in the coefficient of utilization drops significantly. The production of geothermal heat decreases with 60 % up until 2070 and the total geothermal heat production within the entire period is 780 PJ.

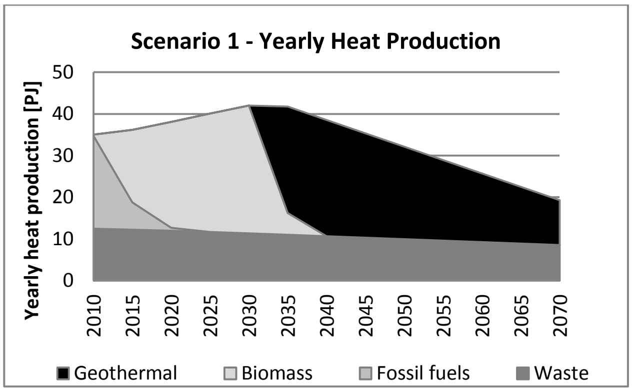

Fig. 5 Yearly heat production for scenario 1 - accelerating energy renovations from 2030.

Scenario 2

Scenario 2 represents the case where accelerated energy renovations are implemented already from today. Figure 6 shows the peak load and distribution of the different supply technologies. The total heat demand is decreasing throughout the entire period in question despite the conversion of the 10PJ. This implies that the investment in geothermal capacity is reduced to 1,200 MW corresponding to a reduction of 60% compared to the reference scenario, and 45% compared to scenario 1.

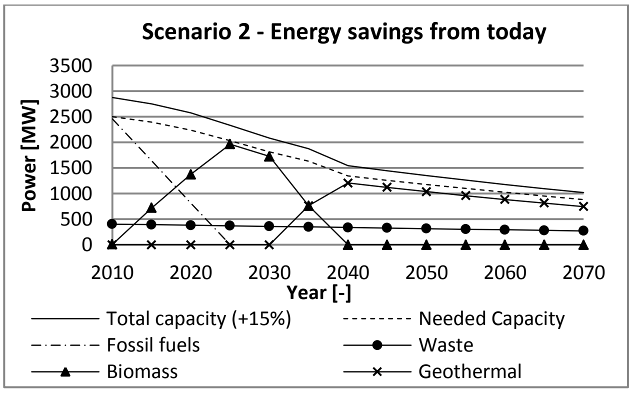

Fig. 6 Peak load for Scenario 2 – accelerated energy renovations from today.

Figure 7 shows the yearly heat production of the different supply technologies until 2070. As seen the geothermal heat production peaks with 16 PJ, which is 50% less compared to the reference scenario and 43% less compared to scenario 1. The geothermal production decreases with around 30% by 2070 compared to the year of peak. The total geothermal heat production throughout the entire period is 484 PJ.

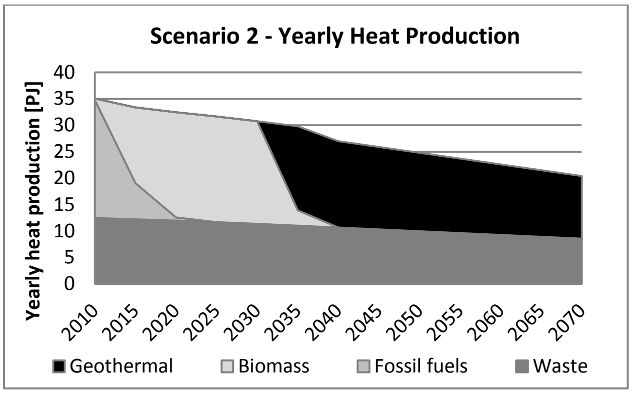

Fig. 7 Yearly heat production for Scenario 2– accelerated energy renovations from today.

ECONOMY

Table 1 shows the estimated costs for each of the scenarios. The total cost for the society is about 25 billion € if no accelerated energy renovations are carried out, but future investment exclusively focus on supplying heat in order to meet the future heat demand. If the accelerated energy renovations are implemented when investment in supply capacity already has taken place (scenario 1) it is seen that it is more costly for the society with about 3 billion € compared to the reference scenario, implying a total price on about 28 billion €. In this scenario the heat demand are reduced after the investment implying that the coefficient of utilization is decreased significant, which is very costly. On the other hand, it is seen that if accelerated energy renovations are implemented already from today (Scenario 2), resulting in a reduced heat demand when the investment in supply capacity takes place, it will save the society for about 1 billion € compared to the reference scenario and about 4 billion € compared to scenario 1.

This stresses the importance in carrying our energy renovation at the right time and thereby reducing the heat demand before investment in supply capacity takes place. As seen supplying heat to an unchanged heat demand compared to implementing energy renovations from today seems to not have significant different consequences. But reducing heat demand seems to be slightly more cost optimal for the society and furthermore, it should be taken into consideration that the peak load will be reduced, creating more stable supply conditions, which is very valuable in the future energy system. Furthermore it will ensure an added value of the building stock.

Table 1 The total cost for each scenarios

		Reference	Scenario 1	Scenario 2
Geothermal				
Unit cost for fixed asset investment	[mil €/MW]	2.68	2.68	2.68
Capacity	[MW]	2793	2464	1207
Total cost for fixed asset investment	[mil €]	7498	6614	3241
Unit cost for O&M	[mil €/MW]	2	2	2
Total O&M - costs	[mil €	1937	1463	947
DH-net				
Unit cost for fixed asset investment	[€/MW]	302	302	302
Converted potential (10PJ)	[MWh]	2777778	2777778	2777778
Cost for expansion of DH-net	[mil €]	839	839	839
Unit cost for O&M	[mil €/PJ]	0.56	0.56	0.56
Total O&M - costs	[mil DKK]	1341	1192	933
Heat production				
Total DH -production in 60 years	[PJ]	2379	2114	1656
Geothermal production in 40 years	[PJ]	1110	838	543
Total costs	[mil €]	11616	10108	5960
Unit cost for supply	[mil €/PJ]	10.46	12.06	10.98
Total supply costs in 60 years	[mil €]	24886	25487	18185
Renovation				
PJ saved by energy renovating (65%)	[PJ]	-	265	723
Unit cost for savings	[mil €/PJ]	-	8	8
Cost for energy renovation	[mil €]	-	2205	6021
Total cost	[Bil €]	25	28	24

SENSITIVITY ANALYSIS

Waste for incineration

A sensitively analysis is carried out analyzing the consequences of increasing amounts of waste for incineration. All assumptions are unchanged except that the amount of waste is reduced with 1/3 up until 2070 compared to the initial conditions. This results in less investment in geothermal capacity. In reality this will require an investment cost in new incineration capacity, which has not been included in the calculations and reservations should be made here upon. The three scenarios already described are investigated. Figure 8 shows the cost for each scenario.

Geothermal heat as first priority

Furthermore a sensitivity analysis of the consequences for using geothermal heat as first priority compared to waste for incineration has been done. This implies that by 2040 there is no more waste utilized in the DH system and can likewise be seen as the scenario where the amount of waste is reduced, because the energy contained in the waste is utilized for other purposes resulting in a minimum contribution to the heat production. The three scenarios already described are investigated, and figure 8 shows the cost for each of the scenarios.

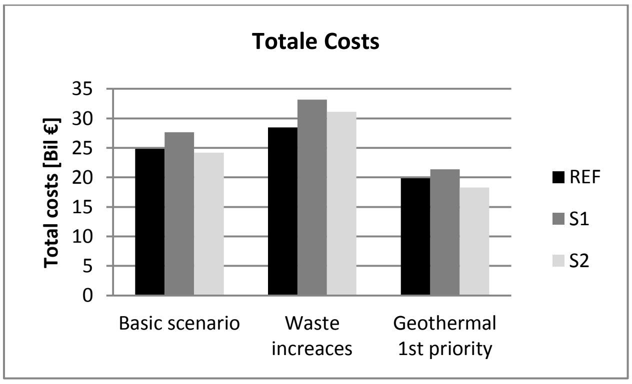

Fig. 8 Comparison between the three scenarios by different assumptions

Figure 8 shows a comparison between the different scenarios and the different sensitivity conditions. As seen scenario 2 represents the cheapest solution for both the basic analysis and the sensitivity analysis of geothermal heat as first priority. In the sensitivity analysis where the waste amounts are increased it is seen that the cheapest solution seems to be the supply-solution. It is expected that the amount of waste is decreased in the future, due to more efficient sorting and more efficient utilization of the energy content for other purposes, implying that either the basic scenario or the geothermal scenario most likely becomes more realistic. As seen from the figure the solution with the geothermal as first priority is generally cheaper than the others, due to the fact that the geothermal plants have a higher degree of utilization, which makes it more economically beneficial.

CONCLUSIONS

A simple and very general model analyzing different future energy planning scenarios regarding DH in Copenhagen has been carried out. Furthermore sensitivity analyses of what will happen if the amounts of waste for incineration changes have been done, using different preconditions. It has been found that from an overall economical perspective it is cost beneficial to invest in energy renovations in order to reduced the heat demand before investing in new renewable energy supply technologies for the future DH-system. This will save around half the investment cost in new supply technologies. If the heat demand is reduced after the supply-investment it will be very costly for the society since much capacity will not be utilized. The economical consequences of only focusing on supplying heat for an unchanged demand versus reducing heat demand through energy renovations starting from today, seems to be quite similar. From this investigation it seems to be slightly cheaper and more beneficial to carry out energy renovations, also taken into account the security of supply. Reducing the heat demand results in smaller peak loads and more stable conditions, which is an advantage for the future energy system based on renewable energy resources. This investigation is based on different assumptions that will have to be investigated further, implying certain uncertainties. Though, the conclusion drawn from this investigation indicates that it is important to reduce heat consumption before investing in new capacity.

ACKNOWLEDGEMENT

This project has been financed by Gate 21 – Plan C, and all of the participants in the project team have contributed significantly to the making of this paper.

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PERFORMANCE AND PROFITABILITY PERSPECTIVES OF A CO_2 BASED DISTRICT ENERGY NETWORK IN GENEVA'S CITY CENTER

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Keywords: District Heating, District Cooling, Refrigerant, CO_2, Decentralization, Heat Pump, Thermoeconomics

ABSTRACT

A new type of district energy network capable of providing simultaneously heating and cooling is being investigated. It is based on the use of CO_2 as a heat transfer fluid by taking advantage of the latent heat of vaporization, to store and transfer heat across the network. The goal of the present study is to determine the performance of a CO_2 network when applied to a real urban area. It focuses first on determining the requirements for the various thermal energy services for a part of Geneva's city centre. The energy consumption is first computed for the energy conversion technologies now in place in this area - namely fuel boilers and vapour compression chillers. Then the new energy consumption is computed if a CO_2 network were used instead of the existing technology. Finally a profitability analysis of the CO_2 network variant is done accounting for investment, energy purchasing, equipments replacement, operation, and maintenance costs.

For an interest rate of 6% and a price of the delivered heating/cooling energy at 0.13 CHF per kWh, a net present value of 82.8 million CHF after 40 years is achieved, while the break-even is reached after 5 years of operation.

INTRODUCTION

District heating and cooling networks have been used to deliver energy in urban areas for many decades. Generally, these networks rely on centralized and efficient energy conversion technologies supplying heating and/or cooling to the users through a water loop. In most of the cases, the supply temperature of such a network is selected according to the most demanding consumer connected. Thus all the other users are supplied at a temperature beyond their need – often far beyond their need. Furthermore, when heating and cooling have to be supplied, two independent water loops are needed. Finally, most of the time, heat discharged by the cooling users in the district cooling network is not transferred to the district heating network, and thus not recovered.

A new type of district energy network is being investigated. It is based on the use of CO_2 as a heat transfer fluid. It uses the latent heat of vaporization, instead of sensible heat, to store and transfer heat. The pressure of the network is selected such that evaporation/condensation takes place at around 12 to 14 °C. This level of temperature allows free cooling to be used for most of the cooling applications, while decentralized heat pumps transfer heat, from the network to each heating user, at the required temperature level. Furthermore only two pipes are required by the network, thus allowing the recovery of waste heat from the cooling users to be recovered by the heating users. Obviously, the heat required by the heating users may, most of the time, not be strictly equal to the waste heat discharged by the cooling users. Hence, a central plant is needed such that the required amount of heat can be taken from/released into the environment.

Fig 1 provides a schematic view of a CO_2 network. A more detailed description of the concept is done by Weber and Favrat in [2]. A presentation of a list of possible energy services and associated conversion technologies that can be included in a CO_2 network was done by Henchoz et al. in [4].

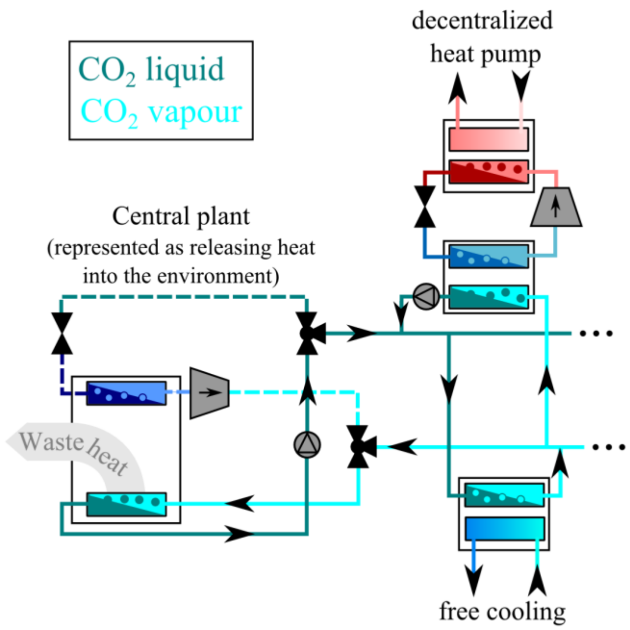

Fig. 1 Schematic representation of a CO_2 based district energy network.

AREA STUDIED

It was chosen to study the area of “Rues Basses” in Geneva. Data such as the energy reference area (ERA) and buildings affectation was made available to the authors by Geneva’s cantonal office for energy [12]. Fig 2 shows a map of the area studied. The area was divided in 32 groups of buildings for which the 3 possible affectations were considered:

- Commercial buildings
- Office buildings
- Residential buildings

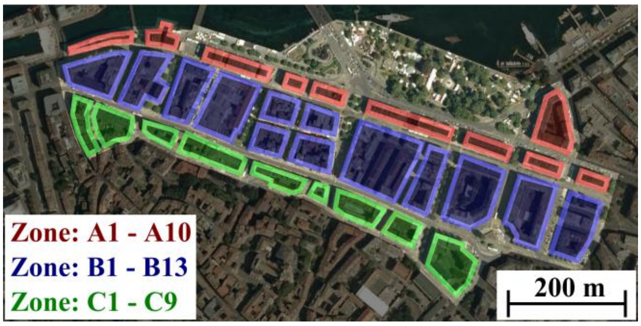

Fig. 2 Map of the area considered, depicting the subdivision in 32 zones [12].

Table 1 shows the ERA for the groups of buildings depicted in Fig 2. For readability reasons, the detailed data for each group is not presented. However, all the computations were done with this subdivision in 32 zones, such as to keep as much information as possible on the spatial distribution of the various physical quantities.

Table 1

	ERA = Energy Reference Area [m²]		
Zone	Commercial	Offices	Residential
A1 –A10	20’700	89’200	17’700
B1 – B13	97’000	260’700	51’500
C1 – C9	40’400	62’600	48’100
A1 – C9	158’100	412’400	117’300
Total: 687’800			

According to the the scanE the ERA of the above mentioned categories can be subdivided in two subcategories as presented in Table 2.

Table 2

	Subcategories	
Commercial	Shopping mall	Restaurant
	90%	10%
Offices	Individual office	Open space
	50%	50%
Residential	Post1990 residential	Pre1990 residential
	20%	80%

THERMAL ENERGY NEEDS

The various energy services considered in this study are the following:

- Space heating
- Air conditioning
- Hot water preparation
- Refrigeration
- Server cooling

For the six subcategories of Table 2, the yearly energy required for the various services was taken from [5] and [6]. Notice that since the buildings in the area considered are old, the SIA document of 1988 [5] seemed to be reasonable. For each subcategory it was chosen to account at maximum for two energy services in heating, respectively cooling, one being a function of the outside air temperature and the other being constant throughout the year. The services considered as well as the corresponding yearly energy per m² of ERA are shown in Table 3.

In order to be able to evaluate the energy quantities on a monthly basis, especially the effects of the seasonal variations on space heating and air conditioning the following approach was used:

$$Q_{ERA} = \frac{UA}{ERA} \cdot \int (T_{room} - T_{atmospheric})dt \qquad (1)$$

Where Q_{ERA} is the yearly energy per m² of ERA, *UA* the heat transfer coefficient through the building envelope. The integral can be replaced by the yearly heating, respectively cooling degree days. Hence the coefficient of loss becomes:

$$\frac{UA}{ERA} = \frac{1000}{24} \cdot \frac{Q_{ERA}}{YDD} \qquad (2)$$

The annual values for Geneva are 2300 °C days in heating and 600 °C days for cooling. The degree days where obtained from monthly data for the atmospheric temperature available at [7]. The values for the various loss coefficients are shown in Table 3.

Table 3

Category	**Services**	**Yearly energy** [kWh/m^{2}yr]	**Loss coef.** [W/m^2°C]
Shopping mall	Space heating	124.1	2.26
	Hot water prep.	7.9	
	Air conditioning	70.0	4.84
	Refrigeration	30.0	
Restaurant	Space heating	66.0	1.20
	Hot water prep.	66.0	
	Refrigeration	10.0	
Individual office	Space heating	55.0	1.00
	Air conditioning	72.0	4.97
	Server cooling	8.0	
Open space	Space heating	55.0	1.00
	Air conditioning	45.0	3.11
	Server cooling	45.0	
Post1990 residential	Space heating	37.5	0.68
	Hot water prep.	12.5	
Pre1990 residential	Space heating	70.8	2.17
	Hot water prep.	21.2	

The total thermal energy required annually is 107’494 MWh. 54% of which are for heating and 46% for cooling. Fig 3 shows the energy required for each service along the year on a monthly basis. The heating peak occurs in January for an average load of 15.5 MW, the max over min heating requirement is 31.6. The cooling peak occurs in August with an average load of 16.1 MW and the max over min ratio is 9.4.

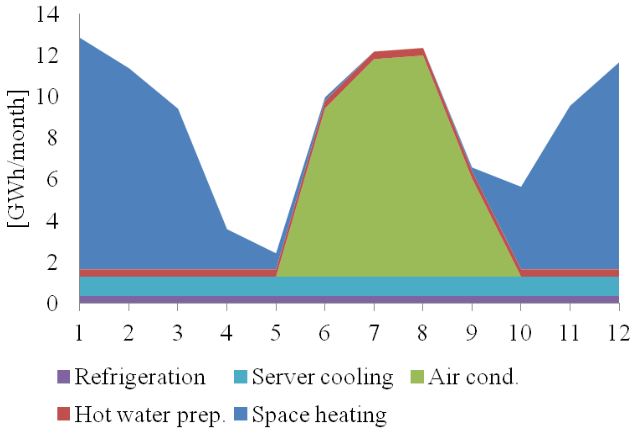

Fig. 3 Monthly energy required for the various services considered.

CURRENT ENERGY CONVERSION TECHNOLOGY

The current supply of energy in the studied area is considered to be exclusively relying on fuel boilers for space heating and hot water preparation, while air cooled vapour compression chillers provide the cooling service . The boilers are considered to operate following a pulse width modulation by alternating between full load and idle periods of variable duration. The design atmospheric temperature was set to -6°C [5]. The part load energy effectiveness of the boilers is then computed as follow:

$$\varepsilon = \left(\frac{1}{\varepsilon_n} + \frac{\lambda_0}{\tau} - \lambda_0 \right)^{-1} \qquad (3)$$

Where ε_n is the effectiveness [1] at nominal load and λ_0 the residual consumption at idling condition, as a percentage of the delivered nominal load.

The vapour compression chillers performance is approached by considering ideal Carnot heat-pump cycles, with constant exergy efficiency. Because air-cooled condensers are considered, the parasitic power consumption of the fans was accounted for. Hence, the electric power required is computed as follow:

$$\dot{E} = \dot{E}_{cycle} + \dot{E}_{fans} \qquad (4)$$

With

$$\dot{E}_{cycle} = \frac{\dot{Q}_{evap}}{\eta} \frac{T_{cond}}{T_{evap}} \left(1 - \frac{T_{evap}}{T_{cond}} \right) \qquad (5)$$

Where Q_{evap} is the heat load, η the exergy efficiency, T_{cond} the condenser temperature and T_{evap} the evaporator temperature. The two temperatures are given by:

$$T_{cond} = T_{atmospheric} + \Delta T_{air} + \Delta T_{\min} \qquad (6)$$

$$T_{evap} = T_{service} - \Delta T_{\min} \qquad (7)$$

The parasitic power consumed by the fans at the condenser is given by equation (8), according to [3]:

$$\dot{E}_{fans} = \frac{0.605 \cdot \left(\dot{Q}_{evap} + \dot{E}_{cycle}\right)}{\left(\Delta T_{air} + \Delta T_{\min}\right)^{0.9937}} \quad (8)$$

In the expressions (6),(7) and (8), ΔT_{air} is the temperature increase when the cooling air passes through the condenser and ΔT_{min} is the minimum approach of temperature.

The various parameters used for computing the consumption of the current energy conversion technology are listed in Table 4.

Table 4

Parameters		Value
Boilers	ε_n	0.90
	λ_0	0.02
Chillers	η	0.35
	ΔT_{air}	12°C
	ΔT_{min}	2.5°C
$T_{service}$	Air conditioning	18°C
	Refrigeration	5°C
	Server cooling	21°C

The monthly energy consumption was computed for the 32 groups of building. The annual total amount is 77'576 MWh, 84.6% of which is fuel oil and 15.4% electricity. The maximum monthly averaged load occurs in January for the boilers at 17.43 MW, the max over min ratio being 31.9. For the chillers, the maximum monthly averaged electric load occurs in August at 4.38 MW. As for air cooled compression chillers, a decrease in the atmospheric temperature has a strong positive effect on the power consumption; the max over min ratio is 30.7, which is much higher than the min-max cooling load factor. The monthly consumption for the different services is shown at Fig. 4. Notice that the type of energy consumed is mentioned for each service.

The yearly effectiveness in heating, for the considered area and the current energy conversion technology is 0.88. The yearly effectiveness in cooling is 4.15.

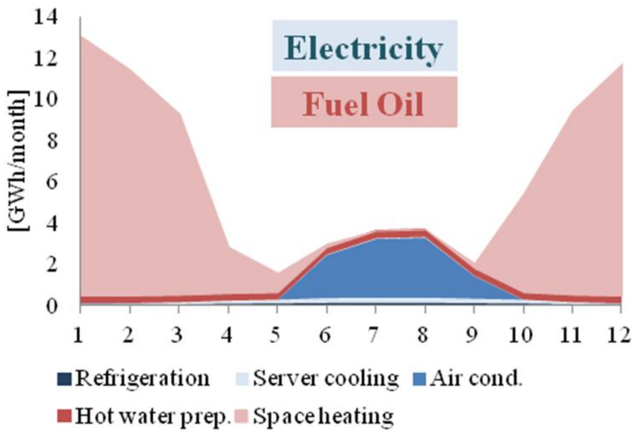

Fig. 4 Monthly energy consumption of the boilers and air-cooled vapour compression chillers by energy service.

CO_2 NETWORK

In order to evaluate the performance of the CO_2 network, in a realistic test case, such a network is imagined such as a replacing technology for the area of "Rues Basses". All the services considered previously have to be supplied by the network. Fig. 5 shows the configuration of the two main lines, as well as the location of the central plant. Each line is constituted of two pipes, one containing CO_2 in a liquid state and the other containing CO_2 in a vapour state. Both are very close to the saturation, which is set at 12°C (47.3 bar). As the area considered is located very close to the lake, the central plant is assumed to be taking heat from, respectively releasing heat in it. The lines are respectively 903 m and 940 m long. The total length of the network is 3'686 m.

Fig. 5 Configuration of the CO_2 imagined for the current study.

The decentralized conversion technologies chosen to supply the various services at the user end are the following:

- Intermediate heat pumps for space heating and hot water preparation. (Heat from the CO_2 condensation is transferred to the refrigerant through an evaporator-condenser.)
- Free cooling for air conditioning and server cooling. A pressure differential of 1 bar is

maintained between liquid and vapour lines such that the CO_2 flows freely in the evaporator.

- CO_2 vapour compression chillers for refrigeration. Liquid CO_2 is expanded to the required saturation temperature and evaporated; the vapour produced is then recompressed to the network.

The electric energy required for the decentralized heat-pumps is evaluated with the same method than in the previous section for the vapour compression chillers. Obviously in this case there are no parasitic power consumption caused by the air cooling. The required temperatures for the services are the same except for space heating. Since the effectivness of heat-pumps depends strongly on the level at which heat is delivered, the following heating curve was supposed (the buildings are assumed to have a renovated envelope) [6].

$$T_{service} = 55 - 1.47 \cdot (T_{atmospheric} + 6) \qquad \forall T_{atmospheric} \leq 16.4°C \tag{9}$$

The temperature at condenser and evaporator becomes respectively:

$$T_{cond} = T_{service} + \Delta T_{\min} \tag{10}$$

$$T_{evap} = T_{network} - \Delta T_{\min} \tag{11}$$

In the equation above $T_{network}$ is the saturation temperature of CO_2.

The electric energy required for the central plant when operated as a heat pump is evaluated similarly, the temperature T_{cond} and T_{evap} are defined by:

$$T_{cond} = T_{network} \tag{12}$$

$$T_{evap} = T_{lake} - \Delta T_{water} - \Delta T_{\min} \tag{13}$$

In (13) ΔT_{water} is the temperature decrease of the water flowing through the evaporator, and T_{lake} the temperature of the water at evaporator's inlet.

Knowing the energy required for each service, the latent heat of vaporization Δh_{vap} of the CO_2 at $T_{network}$ and with the conversion technologies defined above, it was possible to evaluate the massflow of CO_2 liquid, consumed by each of the 32 groups of buildings:

$$\dot{m}_{liquid} = \frac{\dot{Q}_{evap} - \dot{Q}_{cond}}{\Delta h_{vap}}$$
$$\dot{Q}_{evap} = \dot{Q}_{AirCond} + \dot{Q}_{Server} + \dot{Q}_{refrig.} + \dot{E}_{refrig.} \tag{14}$$
$$\dot{Q}_{cond} = \dot{Q}_{heating} - \dot{E}_{heating} + \dot{Q}_{HotWater} - \dot{E}_{HotWater}$$

The massflow of vapour is simply the opposite of the massflow computed with equation (14).

By mass balance, the massflow along the liquid and vapour lines could be computed. The pressure drop was computed for each segment with Churchill's correlation.

The electric energy required for the circulation pumps at the central plant was evaluated as follow:

$$\dot{E}_{PumpCentrd} = \frac{1}{\eta_{pump}} \left(\sum_{i=1}^{n} \dot{m}_i \frac{\Delta P_i}{\rho_{liq}} + \sum_{k=1}^{n} \dot{m}_k \frac{\Delta P_k}{\rho_{vap}} \right) \tag{15}$$

Where the two terms on the right hand side are the sum of the pumping losses on each segment for the liquid and vapour lines respectively. Obviously η_{pump} is the efficiency of the circulation pumps. There were 18 segments considered; their length corresponding to the distance from one group of buildings to another. Notice that some of the closest groups were lumped together such as to reduce the number of segments and that the massflows coming from the groups B1 to B13 were splitted equally between the two branches of the network.

As mentioned earlier the liquid line is at a higher pressure than the vapour line thus enabling free cooling but implying an additional pumping power consumption for all the heating users. The expression is the following:

$$\dot{E}_{PumpUsers} = \frac{1}{\eta_{pump}} \frac{\Delta P_{vap-liq}}{\rho_{liq}} \sum_{i=1}^{n} \dot{m}_i \tag{16}$$

Where the sum denotes the total massflow of CO_2 pumped from the vapour line to the liquid line by the heating users.

The total pumping power for the network is the sum of equations (15) and (16).

The values for the various parameters used for computing the CO_2 network's energy consumption are listed in Table 5 while Table 6 shows the value of the various parameters used for the computation of the pressure drop in the network's piping.

Table 5

Parameter		Value
$\eta_{central}$	Central efficiency	0.55
η_{HP}	Users heat pumps efficiency	0.45
η_{pump}	Circulation pumps efficiency	0.8
ΔT_{min}	Minimum approach of temperature	1°C
ΔT_{water}	Temperature decrease of the water	4°C
T_{lake}	Inlet temperature of the water	7.5°C
$T_{network}$	Network's temperature	12°C
Δh_{vap}	Latent heat of vaporization at $T_{network}$	189.3 kJ kg^{-1}
$\Delta P_{vap-liq}$	Pressure differential vapour - liquid	1 bar

Table 6

Parameter		Value
φ_{liq}	Diameter of the liquid lines	100 mm
φ_{vap}	Diameter of the vapour lines	200 mm
ρ_{liq}	Density of the liquid	846 kg m^{-3}
ρ_{vap}	Density of the vapour	144.7 kg m^{-3}
μ_{liq}	Dynamic viscosity of the liquid	79.3 μN s m^{-2}
μ_{vap}	Dynamic viscosity of the vapour	16.4 μN s m^{-2}
$T_{network}$	Network's temperature	12°C
k_{pipe}	Roughness of the pipes	0.3 mm

The CO_2 network studied shows an annual energy (electricity) consumption of 16'765 MWh. The monthly averaged electric power peaks in January at 4.77 MW. The maximum over minimum ratio is 24.8. The share represented by the network utility – namely the central plant consumption and the pumping energy – amounts to 25.7% annually. Fig. 6 shows the energy consumed on a monthly basis for the energy services provided as well as for the central plant and for the circulation pumps. Note that air conditioning and server cooling do not appear, this is explained by the fact that free cooling causes no direct energy consumption. However, air conditioning is the main reason why the pumping energy has its peak in the summer period. During the months of July and August the share of pumping energy represents more than 50% of the total network's consumption.

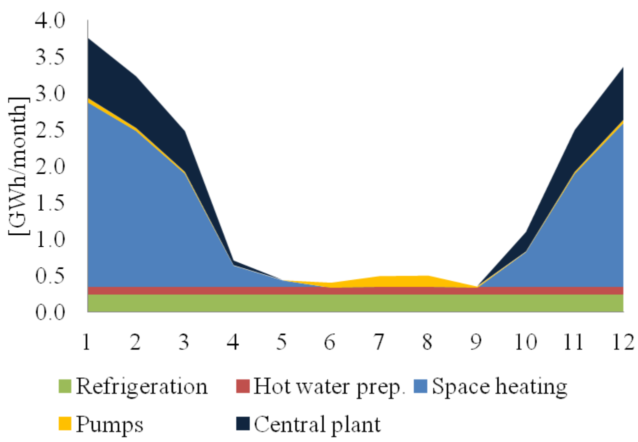

Fig. 6 Monthly energy (electricity) consumption of the CO_2 network studied.

The yearly effectiveness in heating, for the considered area and with the CO_2 network as energy conversion technology is 3.61. The yearly effectiveness in cooling is 124. The share of the pumping energy due to cooling and heating is 68.1 % and 31.2% respectively.

Compared to the current technology in place, the CO_2 network allows for a reduction of 78.4% in energy consumption. Such a reduction is achieved by order of importance through:

- A more efficient heating due to the use of a combination of centralized and decentralized heat-pumps.
- The replacement of all the vapour compression chillers by free cooling systems for the services of air conditioning and server cooling.
- The waste heat recovery from the cooling users allowing for the central plant not to consume electricity for heat pumping from May to September.

Finally, the greenhouse gases emission reduction is at the minimum 52% and can go up to almost 100% depending on the type of electricity bought from the grid.

EVALUATION OF THE INVESTMENT REQUIRED

In order to study the profitability of the CO_2 network presented, it is necessary to evaluate the investment required. It was chosen to divide the system into two main cost categories – the piping and the equipments.

The cost of the piping has been considered as the sum of the pipes cost and the excavation cost. A 2.5 multiplication factor is used to account for the extra cost for excavation in urban area.

The different elements considered for the investment cost related to the equipments are:

- The decentralized heat pumps
- The central plant, with the heat-exchanger and the compressor.
- The network regulations, including circulation pumps, control valves and programmable logic controllers (PLC).
- The plate heat exchangers at the cooling users.

The various cost functions used are presented in Table 7. The source for the cost function of the pipes is [2].

The decentralized heat-pumps cost function was fitted from data of two different manufacturers totalling 52 water-water heat-pumps. For the heat pumps used for hot water preparation, the function was fitted from 12 heat pumps of the same two manufacturers. In the latter case the cost of a hot water buffer tank was taken into account. For this study, it was decided that the biggest heat pump available would correspond to the biggest of the 52, respectively 12 heat pumps of the survey.

The cost function for the central plant heat exchanger and compressor are both from [3]. It is assumed that the heat exchanger of the central plant can operate indistinctly as an evaporator or a condenser, the area chosen to compute the cost is the biggest one. The overall heat transfer coefficient assumed is 1000 W m^{-2} K^{-1}. In the present case the maximum load in condensation is around 16 MW under a log mean temperature difference (LMTD) of 2.33°C, while in evaporation it is only 9.3 MW under a LMTD of 2.49°C. Hence, the size needed is constraint by the condensation and the required heat transfer area is 6'900 m^2.

The cost function for the main circulation pump (central) is from [3]. A fixed cost per unit purchased is assumed for the decentralized circulation pumps, the regulation valves and the PLCs.

The plate heat exchangers cost correlation was fitted from data coming from a call for 4 different CO_2 evaporators and condensers. Based on the maximum volume flowrate in commercially available CO_2 plate heat exchangers, it was found that the maximum heat load per exchanger is around 67 kW under the temperature differences they are operated in the CO_2 network presently studied.

A multiplication factor of 2.65 was applied to the purchasing cost in order to obtain the installed cost.

The detail of the investment required for the network is presented in Table 8

Table 7

Cost function	X [unit]	Unit / Max size
$C_{Pipe} = 7.33\ X + 767$	φ [mm]	CHF m^{-1}
$C_{Excav} = 1.66\ X + 237$	φ [mm]	CHF m^{-1}
$C_{HeatPump} = 1'488\ X + 6'813$	$\dot{E}$ [kW]	CHF / 25.8 kW
$C_{HotWatHeatPump} = 1'853\ X + 9'391$	$\dot{E}$ [kW]	CHF / 15.5 kW
$C_{CentralHEX} = 513\ X^{0.82} + 5'700$	A [m^2]	CHF / 10^4 m^2
$C_{CentralComp} = 10'260\ X^{0.6} + 22'800$	$\dot{E}$ [kW]	CHF
$C_{CentralPump} = 50'160\ X^{0.9} + 35'340$	$\dot{V}$ [$m^3 s^{-1}$]	CHF
$C_{UserPump} = 2'000$	-	CHF
$C_{Valve} = 600$	-	CHF
$C_{PLC} = 1'000$	-	CHF
$C_{CoolingHEX} = 627\ X^{0.57}$	A [m^2]	CHF / 67 kW_{th}

Table 8

Piping	Pipes	6'881 kCHF
	Excavation	4'476 kCHF
	Total piping	**11'356 kCHF**
Decentralized heat pumps		**6'296 kCHF**
Central plant	Compressor	718 kCHF
	Heat exchanger	727 kCHF
	Total central plant	**1'445 kCHF**
Network regulation	Central plant circulation pump	39 kCHF
	Decentralized circulation pumps	376 kCHF
	Control valves	182 kCHF
	PLCs	284 kCHF
	Total regulation	**880 kCHF**
Cooling users heat exchangers		**340 kCHF**
Total purchasing cost		**20'318 kCHF**
Bare module factor (not applied on the piping cost)		**2.65**
Total installed cost		**35'104 kCHF**

PROFITABILITY OF THE CO_2 NETWORK STUDIED

In this section, the profitability of the network studied is assessed. The performance indicator chosen is the Net Present Value (NPV). It consists in transferring the different future cash flows with a fixed interest rate so as to be able to compare these future amounts of money with today's investment.

In this study the NPV for every year of operation year is computed taking into account:

- The initial investment
- The revenues from heat and cold sales
- The cost of buying electricity from the grid
- The cost of replacing the equipments
- The cost of operation
- The cost of maintenance

Purchasing cost and installed cost are discussed in the previous section. The cost of engineering is considered to be 18% of the total installed cost. Hence the total initial investment for the network is 41.422 Mio. CHF.

The price of the kWh of heating respectively cooling supplied to the users is set at 0.13 CHF kWh^{-1}. The price of electricity from the grid is 0.22 CHF kWh^{-1}. According to [8, 9] the electricity price rose in average of 1.2% per year, between 1980 and 2010. A similar rate of increase was taken into account in the present study for both the electricity bought from the grid and the thermal energy billed to the customers.

For the current analysis, it was decided to consider an overall lifetime of 40 years. It corresponds to the lifetime of pipes. Nevertheless the lifetime considered for the rest of the equipments was only 15 years: Thus, two replacements of the equipments were taken into account in the NPV computation. The engineering overhead of 18% was also included in the equipments replacement cost. A 3.5% annual increase of the equipment cost is considered, corresponding roughly to the rate of increase of the *Chemical Engineering Plant Cost Index* between 1950 and 2010.

The cost of operation is assumed to be constituted mainly by manpower. It has been assumed that three equivalent full time jobs are required for operating the network. The manpower rate is 65.2 CHF h^{-1} and increases of 1.2% per year which, according to [10], corresponds to the value for the industries of production and distribution of energy. Every full time job is considered equal to 1927 h yr^{-1} [11].

The annual maintenance cost considered was 4% of the installed cost for the decentralized heat pumps and 1.5% for the piping. A 1.2% annual increase of the maintenance cost was considered, assuming that the maintenance cost is mostly driven by the cost of related manpower.

Finally the interest rate used for the NPV computation was 6%.

The evolution of the NPV over the lifetime of 40 years is shown at Fig. 7.

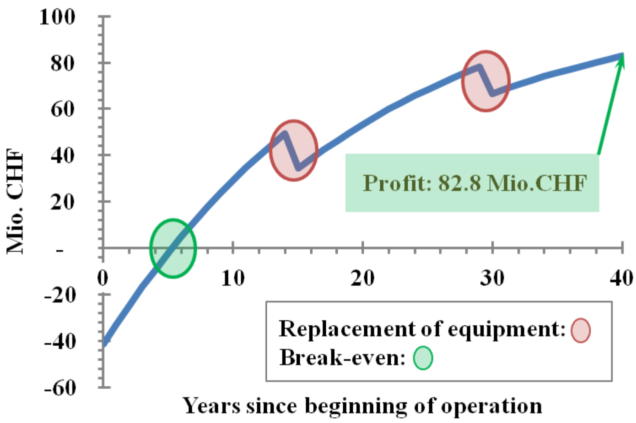

Fig. 7 Evolution of the net present value of the CO_2 network studied along its lifetime. (40 years, 6% interest, price of heat/cold: 0.13 CHF kWh^{-1})

The main results of the profitability analysis are the following:

- The break-even point is reached short after 5 years of operation.
- The profit generated amounts to 82.8 Mio. CHF present value.
- The cost of production of a kWh of service delivered (price for NPV = 0 after 40 years) is 0.087 CHF kWh^{-1}.
- The contribution to the total cost is distributed as follow:

1. Electricity from the grid: 39.6%
2. Total initial investment: 25.0%
3. Replacement of equipment: 20.0%
4. Maintenance: 11.3%
5. Operation: 4.10%

CONCLUSION

Based on the energy reference area and the affection of the buildings in the area of “Rues Basses” in Geneva, the required monthly energy was evaluated for space heating, hot water preparation, air conditioning, refrigeration and server cooling. It led to an annual demand of 107’494 MWH, 54% of which is heating and 46% cooling.

The energy consumed was evaluated considering decentralized fuel boilers and vapour compression chillers as energy conversion technologies. It showed an annual consumption of 77’576 MWh of energy, 84.6% of which is fuel oil and 15.4% electricity.

A CO_2 network was then considered to replace the former technology. The resulting network represents a total of 3’686 m of piping; its annual electric energy consumption is 16’765 MWh representing 78% less than for the conversion system based on boilers and vapour compression chillers. Moreover the greenhouse gases emissions reduction is at least 52% and can reach almost 100%, depending on the type of electricity bought from the grid.

An evaluation of the investment required for the network led to a cost for the piping of 11.3 Mio. CHF and 8.9 Mio. CHF for the rest of the equipment. The total initial investment including installation cost and engineering is 41.4 Mio. CHF.

A profitability analysis based on the net present value of the system was carried out. It accounted for investment, energy sale and purchase, equipment replacement, operation and maintenance. The interest rate considered was 6% and the price of heating/cooling service 0.13 CHF kWh^{-1}. The profitability analysis showed that the break-even point would be reached after 5 years of operation and the profit generated would reach 82.8 Mio. CHF present value, for a lifetime of 40 years.

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DHC13, the 13th International Symposium on District Heating and Cooling
September 3rd to September 4th, 2012, Copenhagen, Denmark

ECONOMIC CHALLENGES FOR THE DISTRICT HEATING INDUSTRY IN GERMANY

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Keywords: Scenario 2050, market development, district heating in Germany

ABSTRACT

The German energy turnaround does not only focus on electricity but has a second main subject: renewable heat from the sun, from biogas co-generation and from geothermal sources. The goal of the energy turnaround is ambitious and the district heating sector is facing a number of challenges. The district heating chain with its planners, suppliers, operators and heat customers has been analyzed to check for its readiness to put the energy turnaround into practice.

An economic scenario is outlined describing a possible development path for the German district heating sector. More than 50% of the households must be supplied by district heating by 2050, if the current scenarios of the German government shall become reality. But still, the development is very much focussed on exploiting only some of the necessary heat sources. Solar heat, geothermal heat and waste heat are only seldom used for district heating. Some technologies like seasonal storage are not ready for the market yet. But many different heat sources will be needed to realize a sustainable heat supply.

Politics as well as the firms and associations of the district heating sector must act, since important interim targets should be met until 2020.

INTRODUCTION

In 2012, the backbone of district heating in Germany consists of 1.360 district heating networks run by about 200 members of AGFW [1] supplying 1 TWh/a to 325.000 buildings. The large networks amount to about 21.700 km of piping [2]. The national statistics [1][3] documents about 4.8 million households using district heating, which represent about 13% of all households. The existing networks have been continuously built over the last 50 years and are generally quite big.

Following recent legislation initiatives this backbone has been complemented by additional networks, which were funded on the basis of mainly two stimulus programs, the Combined Heat and Power Generation Act in 2008 and the Renewable Energy Heat Act in 2009, until 2010 about 2.200 km additional district heating networks have been built [2] [4]. But the structure of these networks is considerably different. Within the program to fund district heating based on renewable energy sources, about 1.500 short networks have been built in 2009 and 2010. On average, the networks are only 680 m long and serve 8 to 9 buildings. While the networks of AGFW transport 4,9 GWh/a per km, networks funded by the Renewable Energy Heat Act transport only 520 MWh/a per km. Networks funded by the Combined Heat and Power Generation Act transport about 760 MWh/a per km. It is obvious, that a structural difference exists which will bear on the further development of district heating in Germany.

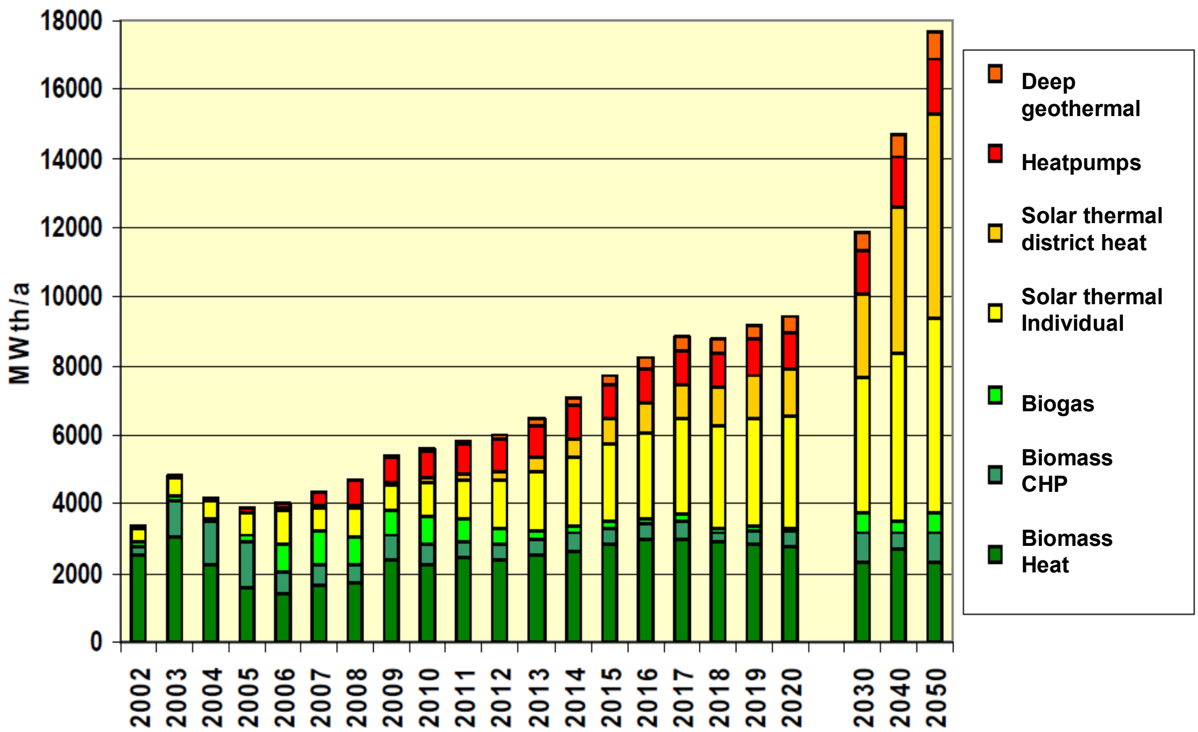
This paper will first outline the heat supply scenarios of the German government. On the basis of these scenarios, a possible future development of district heating will be outlined and the number and size of networks will be roughly estimated. Finally, the strengths and weaknesses of the sector will be focussed and possible actions of politics and economic actors will be described.

HEAT SUPPLY SCENARIOS FOR GERMANY

According to a study for the German Ministry for the Environment, district heating will become the dominant heat supply technology for renewable heat until 2050 with a share of heat supplied of 54% [5]. Since fossil fuels as heat sources will primarily be processed in cogeneration plants and distributed by district heating, an overall share of about 55% of the heat will be distributed through heating networks.

Although today there is a strong focus on new renewable district heating powered by biogas and wood, these goals can only be achieved if additional heat sources are successfully deployed. In the view of the study, the main contribution will come from solar district heating and geothermal heat, which both should start growing within the next few years (Fig 1).

It must be mentioned that in the view of other institutes employed by other ministries, the expectations of Germanys energy future are somewhat different. The scenarios developed to underpin the federal Governments energy concept contrarily envisage a reduced amount of heat distributed by district heating [5] because they assume the energy efficiency of buildings to rise steadily. Thus nearly no additional district heating would be built. It remains the secret of



the authors how the fantastic amount of 150 TWh/a of usable heat from new "carbon capture and storage" coal cogeneration plants will be supplied to the user: If not as e-mail attachment, the construction of new district heating systems will be necessary as well.

Either way, both scenarios require more than half of the households in Germany to be connected to a district heating system. Additionally, two technologies must be ready for series production by 2020. These technologies are:

1. Seasonal storage: Nearly 4 TWh/a solar heat shall be distributed through district heating by 2020, more than 40 TWh/a by 2050 [5]. This assumes working seasonal storage facilities with a reasonable efficiency. Seasonal storage would also be helpful in exploiting waste heat of cogeneration or industry as far as this is produced during summer. It is puzzling that the report doesn't even mention the term "seasonal storage" at all.
2. Deep geothermal heat: Heat pumps are perfect to serve single objects. Heat supply for geothermal driven district heating will most probably need deep wells supplying a heat capacity of 10 MW and more. To date, only a handful of deep geothermal heat projects is realized each year [4].
3. Cold district heating: To exploit low-exergy sources like waste heat from data centres or unconventional sources like old mines, it will be

To achieve the goals of the Federal Ministry for the Environment, a strong development of the number of district heating networks, supplied houses and supplied households is unavoidable. And the necessary complementary technologies must be brought to their respective maturity phase.

If one takes the goal of supplying 55% of the German apartments by district heating in 2050 for granted it is possible to construct a picture of the number of buildings which in that case must be supplied. The following table draws on the German national statistics of buildings and estimates a higher density of district heating in cities (urban districts). The connection rate is lowest in cities single family houses (25%) and highest in multihousehold buildings in cities (85%) (Table 1).

In 2012, the number of apartments supplied is about 4.8 million; the number of buildings is very likely not higher than 700.000 because there is a high concentration of district heating in urban multihousehold buildings.

Within the next 38 years, about 6.8 million buildings must be connected additionally to district heating to achieve the goal of the Federal Ministry for the Environment.

Looking on urban [1] as well as rural district heating systems one finds, that a piping of around 60 m is necessary to connect one building. Since the density of connected buildings has to rise sharply, it is estimated that in the future scenario only 40 m are sufficient for this purpose. Overall, a length of 272.000 km of piping networks will have to be installed to meet the goal.

Table 1 Number of buildings and apartments supplied by district heating to achieve a connection rate of 55%

in thousands	Single family houses	Semi-detached houses	Multihousehold buildings	Total
Urban districts	1.811	539	1.328	13.627
Rural districts	9.557	3.049	1.743	25.762
				39.390
Connection rate in %				
Urban districts	25,00%	40,00%	85,00%	
Rural districts	35,00%	45,00%	60,00%	
Apartments with district heating				
Urban districts	452	215	1.129	10.011
Rural districts	3.345	1.372	1.045	12.153
Total connected apartments				22.164
Total connected buildings	3.798	1.587	2.175	7.560

On the basis of data on rural district heating systems we found, that an investment of about 20.000 € to 30.000 € per building is in most projects sufficient to construct the district heating network. Since in cities, the average length of piping might be a bit shorter, but more streets, footpaths and underground installations present obstacles for heat pipes, we assume that the investment does not differ significantly in cities. But again, following the idea of a higher density of connected buildings, we assume that about 18.000 € per building will be sufficient. Overall, an investment of about 122 billion € will be necessary in the forthcoming 38 years, about 3 billion € each year. This is about a 700% increase compared to investments of the energy industry in the supply of heat and cold of 470 mil. € in 2009 [9].

Additionally, the building of thousands of seasonal storage units, deep geothermal wells and solar collector fields will foster turnover of sustainable businesses in the heat market, drawing on the other hand the turnover from oil and gas central heating units to a close.

OBSTACLES TO DISTRICT HEATING

The wide diffusion of district heating and the construction of thousands of networks face some quite severe obstacles. Concerning heat customers, they not only fear to be dependent on the network or don't trust unknown network operators; they also do not understand a full cost accounting comparison of oil or gas central heating and district heating. The operators in turn often do not offer a pricing model which is easy to understand and in favour of the customer. But the heat customer is after all not the main obstacle. Other obstacles are found in politics, local government and planning as well as in the lack of operators which are interested in the exploration of new heat sources and new district heating networks.

HEAT AND THE GERMAN ENERGY TURNAROUND

Generally, the German energy turnaround follows the idea to transform the whole energy system. A huge step forward in efficiency, a fast phasing out of nuclear energy and the substitution of fossil energy sources by renewables are the cornerstones of the concept. The transformation shall take place in the markets for electricity, for heat as well as for transport fuels. But in practice, the main effort is invested in the electricity sector. Concerning heat, the two central goals of the German federal government are to increase the rate of thermal refurbishment to 2% of the buildings per year and to enhance the rate of heat produced from renewable sources [7]. In practice, two acts were adopted: the Combined Heat and Power Generation Act in 2008 and the Renewable Energy Heat Act in 2009. On the basis of both acts funding schemes for district heating networks were developed.

The outcome of these funding schemes is limited. First, as outlined above, the new district heating networks are comparatively short and they only provide heat to a low number of consumers. Compared to the logical target to build 272.000 km of networks and supply district heating to additional 6.8 million buildings the outcome is obviously much too small.

But the outcome is also technically limited to concepts based on fossil fuels, biogas cogeneration and biomass boilers [2] [4]. But within the next 20 years, the biomass resources will be employed close to their theoretical maximum, while the resources to extract geothermal heat or solar heat remain largely untouched [6]. Only very few projects based on these sources are realized. And waste heat of industrial production or data centres also remains an untapped potential, while studies show a considerable heat potential of over 100 TWh per year [8].

German policy should urgently act, to foster the diversity of renewable and other unconventional heat sources used for district heating. It should be ensured, that funding also stimulates district heating business models based on solar and geothermal sources as well as waste heat.

Looking on the result of the funding, there also seems to be a lack of business models which lead to the construction of medium or large district heating networks. Last but not least, the link to spatial planning is missing. Waste heat, geothermal heat or sufficient area to install a solar collector field and a big seasonal heat storage are not available everywhere. If we want to tap these potentials, we must ensure that district heating is constructed in districts which allow for the use of these sources.

THE DISTRICT HEATING SECTOR

To date, the district heating sector is small. A couple of hundred network operators and some dozen planning bureaus and specialized producers of piping and components are nearly all there is. In the last five years, some hundreds of so called bio-energy villages and energy cooperatives have been founded by engaged individuals, but most of them are focussed on operating just their communities' network. Bigger network operators on the other hand are mostly interested to incrementally condense and enlarge their existing networks, not in exploring and realizing new district heating networks. Who then shall actually do the job of planning and constructing district heating networks to the amount of over 100 billion € in 40 years?

Who shall actually supply the large seasonal heat storage units, which doubtless will be needed?

Who shall convince millions of heat customers to use district heating, just because they live close to a waste heat source or close to a promising geothermal well?

All of this points to a clear lack of entrepreneurship around district heating.

While the German Renewable Energy Federation BEE (Bundesverband Erneuerbare Energie e.V.) has become a strong political force with active lobbying and in many ways active support by NGOs and the media, the business associations of the district heating sector are less politically active and in our opinion do not exploit the opportunities as far as they should.

CONCLUSION

District heating is a cornerstone of a sustainable heat concept in a modern society. The German energy turnaround lacks much clarity and effort as far as heat supply is concerned. Thermal refurbishment of buildings and cogeneration of biogas and biomass will not do the job of a sustainable heat supply alone. More renewable heat sources have to be tapped and complementing technologies like seasonal heat storage must be ready for series production in 2020.

The potential market is large and business opportunities are plentiful. The government has already set some promising signals to foster development. But the companies of the district heating sector and their associations should be more active to demand the next necessary steps and to enhance public discussion about sustainable heat supply.

ACKNOWLEDGEMENT

This work is funded by the Lower-Saxonian Ministry for Science and Culture and the European Regional Development Fund.

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ESTIMATION OF WASTE HEAT RECOVERY AND TRADE POTENTIAL FOR INDUSTRY SECTION IN KOREA

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Keywords: Industry energy in Korea, waste heat, heat recovery potential

ABSTRACT

Waste heat recovery potential in the industry section of Korea is surveyed to provide basic data for efficient energy utilization planning. The waste heat from industrial sectors of food processing, textile, paper and wood products, chemical plant, metal processing, ceramic industry, and miscellaneous plants are collected through a national wide survey sponsored by KEMCO (Korea Energy Management Corporation). We found that about 53% of the waste heat originates from chemical plants and almost 30% from metal processing. A great majority (83%) of the waste heat is ejected in the form of flue or exhaust gas. We also collected the amount and the states (pressure and temperature) of steam that is traded among factories. We expect that the collected data will be useful for guiding the direction of project planning and energy policies for district heating.

INTRODUCTION

It is known that industrial energy consumption accounts for about one third of the total energy consumption in the world [1]. As an industrialized country Korea is no exception. Dependence on overseas oil and gas poses a lingering threat to the continuous development of economy for a long time. As of 2011, 253 million TOE (or 96.5 % of total energy consumption of 263 billion TOE) of energy is imported to Korea [2]. Without doubt, we need to make every effort to maximize the utilization of the available energy resources, and the industrial sector is one of the areas with great potential for success.

In this study, we tried to survey how much energy is consumed and wasted in each sector of industry in an effort to collect data for various policy planning and engineering design in the future. With the aid of KEMCO, our team surveyed wide ranges of industry, and the results are reported in this paper.

WASTE HEAT RECOVERY POTENTIAL

Based on energy consumption provided by KEMCO, we estimated the amount of waste energy from industry. The results are summarized in Table 1.

Table 1. National estimated waste process heat

Industry	**Energy purchase (A) (TOE)**	**Recovery potential (B) (TOE)**	**Ratio B / A**
Food	1,612,000	157,766	0.097
Textile	3,504,000	612,752	0.174
paper/wood	2,226,000	153,744	0.069
chem/petro	36,227,000	4,414,425	0.121
metal	21,926,000	2,985,623	0.136
ceramic	5,637,000	87,375	0.016
Others	6,658,000	757,444	0.114
Sum	77,790,000	9,169,129	0.117

The combined waste energy (or the recovery potential) for our nation reaches about 11.7% of all the energy consumed by industry. Comparing with 9.63% for Japan, this number is about 20% higher. Fig. 1 shows the relative importance of each sector of industry in waste heat amounts.

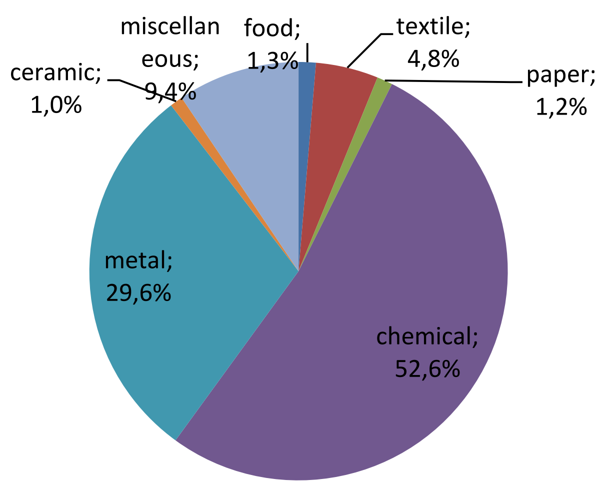

Fig. 1. Composition of waste heat by sectors

As heavy and chemical industries are the main stream of Korean industry waste heat from chemical plants and metal forming is dominant.

From a technological standpoint, the forms of waste energy and temperature ranges are important. In Fig. 2, composition of the waste energy forms are presented. Most of the waste energy is exhausted in the form of hot gas.

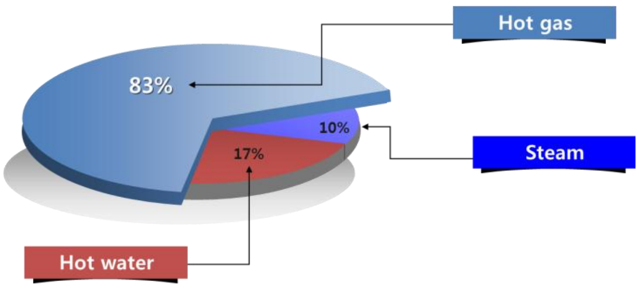

Fig 2. Forms of waste energy

Fig 3 shows the temperature distribution for wasted steam. The temperature ranges are good enough to build heat exchangers for space heating and hot-water supply. Depending on the characteristics of processes exhausted gas may be utilized for subsequent processes. Most of the wasted heat also can easily be used as heat sources for absorption chillers or adsorption chillers during summer seasons.

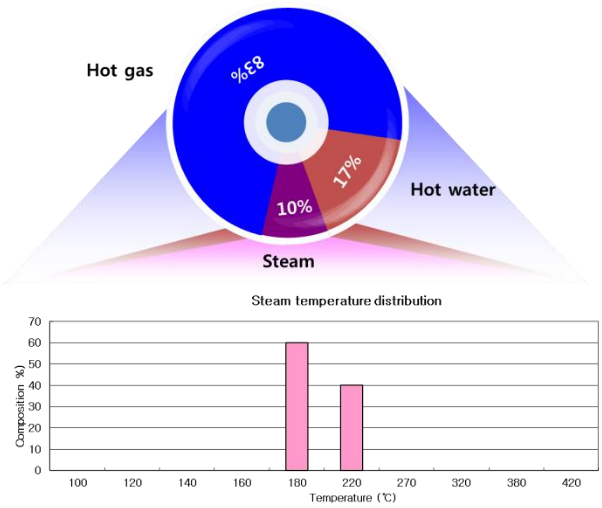

Fig. 3. Temperature ranges for wasted hot gas

The temperature ranges for wasted hot-water are relatively low and direct use as hot-water for space heating is advisable. During summer seasons, hot water may drive single-effect absorption chillers or multiple effect ones with added heat from other heat sources such as gas-fired heaters.

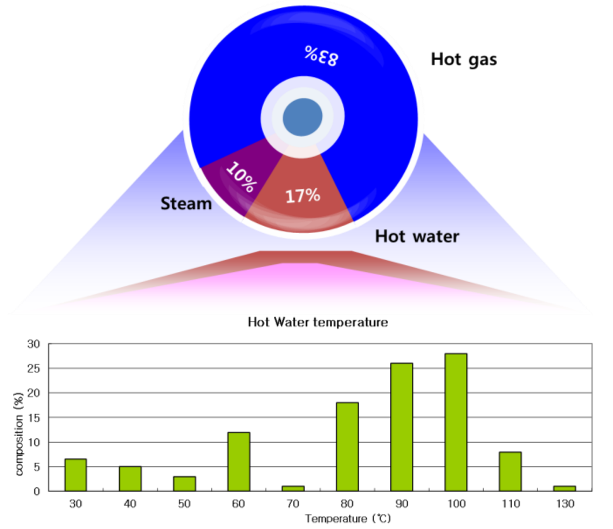

Fig. 4. Temperature ranges for hot water

Fig. 5 shows the temperature distribution for the wasted hot gases. Here, we can see a great potential of recovered heat due to high values of exergy. The potential includes power generation at the temperature levels of recovered heat. With modern technologies such as organic Rankine cycle, a large portion of the wasted heat by hot gas can be easily exploited. Another possibility for using high temperature recovered heat is to use as process energy at slightly lower temperatures. In this case, we will need to develop efficient heat marketing or trading systems and programs by combining heat suppliers and users in an integrated way.

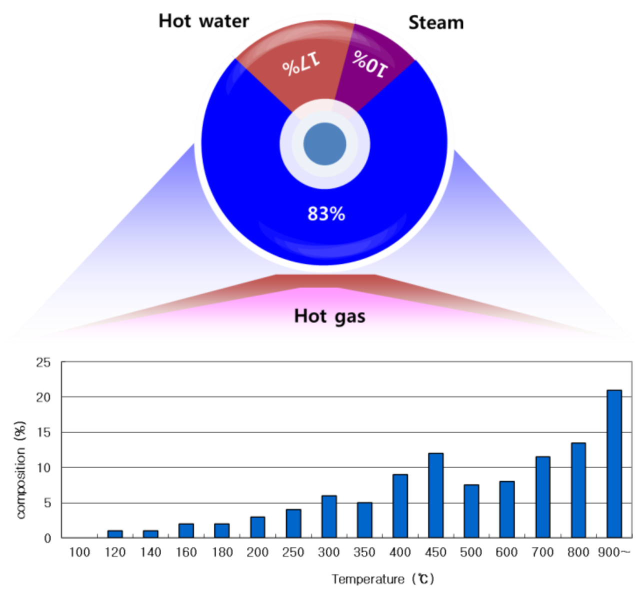

Fig. 5. Temperature ranges for wasted steam

DISTRICT HEATING BUSINESS IN KOREA

District heating companies

District heating business is prolific as summarized in Table 2. Currently, 27 companies are in business all around the country, and the number of companies are on the rise.

Table 2. Number of district heating companies in Korea

year	No of companies
2001	20
2002	20
2003	21
2004	21
2005	21
2006	21
2007	20
2008	24
2009	25
2010	27

The amount of the annual total sales by all companies are summarized in Table 3.

Table 3. Annual energy sales by district heating companies

year	heat sale (Tcal/yr)	electricity sale (GWh/y)
2001	31,422	13,214
2002	29,080	12,950
2003	30,540	13,487
2004	30,869	12,651
2005	30,099	11,851
2006	30,559	12,284
2007	31,722	12,652
2008	30,416	12,339
2009	31,012	14,098
2010	37,358	15,554

The distribution of heat and electricity production by the individual companies is plotted in Fig. 6. Even though the general trend is that companies with larger power production also produce more heat, the correlation between the amount of power production and heat production is weak.

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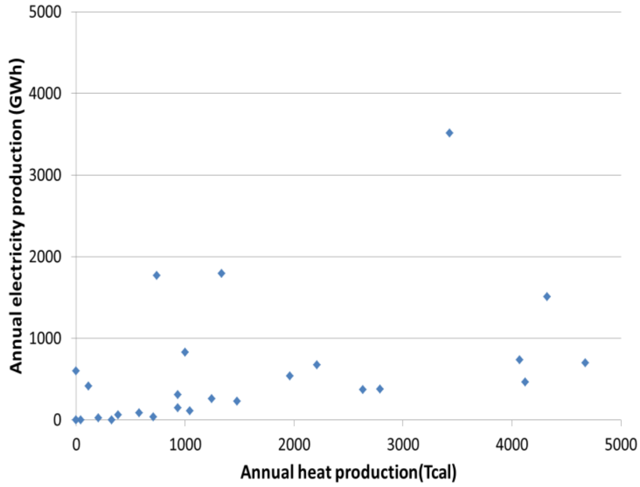

Fig. 6 Distribution of Example for Symposium Template

Fig. 7 describes electrical power generation by the individual companies. Contributions from gas turbine generators (GTG), combined heat and power plants (CHP), and the amount from local utility company is presented. Both quantity and source of power generation are diverse depending on the location and size of the companies. In Fig. 8, profiles for electricity sales are plotted. Produced electricity is sold to the utility company and local users, or consumed locally by the district heating companies. Comparing with Fig. 7, there are strong relations between the amounts of electricity produced and that sold.

Fig. 9 shows the distribution of the heat production by the individual companies. In addition to CHP (boiler of after turbine), the companies produce heat by various methods such as heat only boilers (HOB), through processes, and nearby incinerators. It turned out that heat is coming from other companies through trade agreement. Fig. 10 shows how the produced heat is consumed. Heat is supplied to public buildings, commercial sectors, factories, and residential area. Portions of the produced heat is consumed locally by the district heating company or exported to other district heating companies.

Fig. 11 shows the distribution of the amounts of energy sources consumed to produce the electricity and heat. While most of the companies consume most of the fuel to run the CHP systems, there are three district heating companies that run only boilers to supply heat without producing electricity. This is a rare form of district heating adapted to special situations associated with the operation of the system or constraints imposed by local environment.

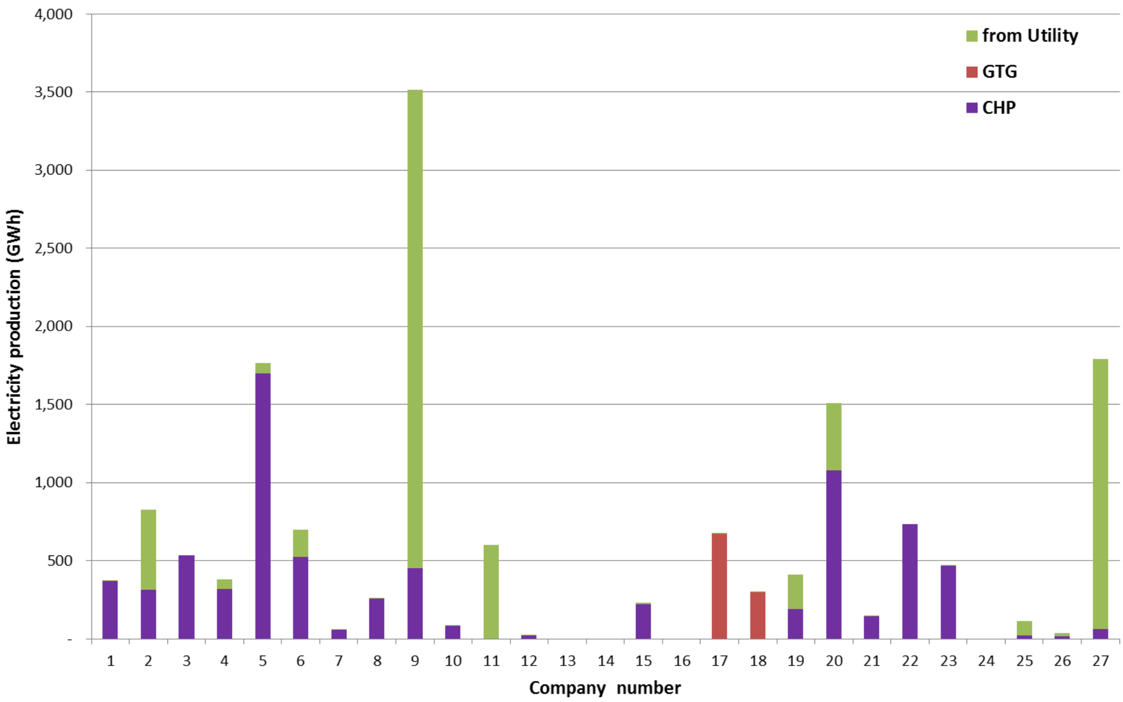

Fig. 7. Electrical Power production profile

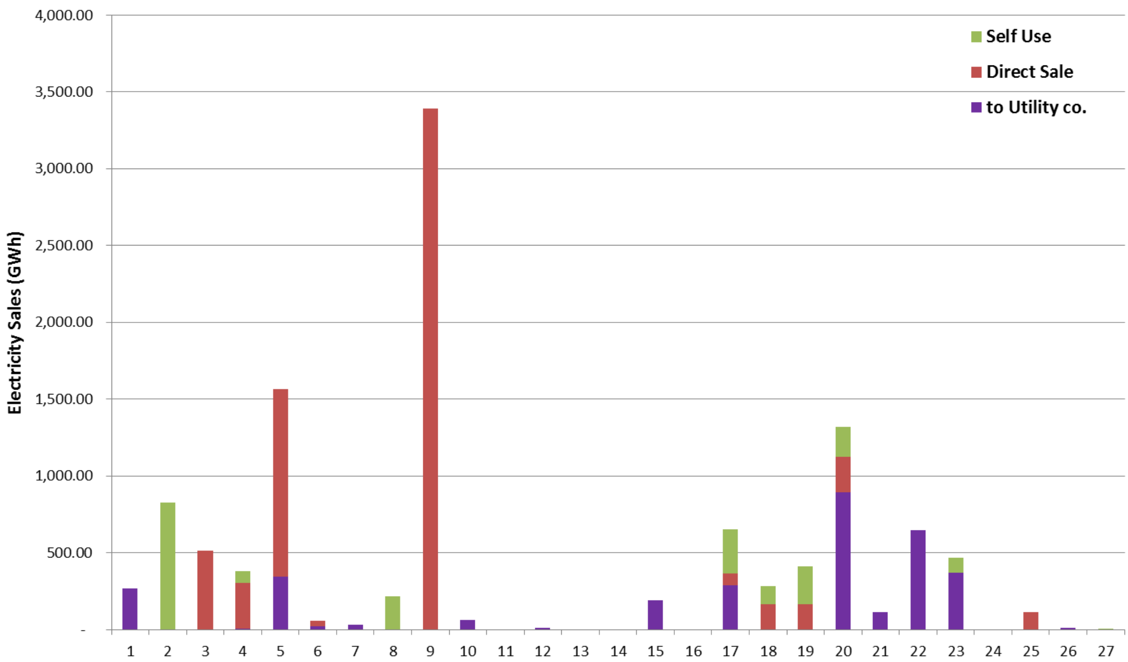

Fig. 8 Electricity sales profile for each company

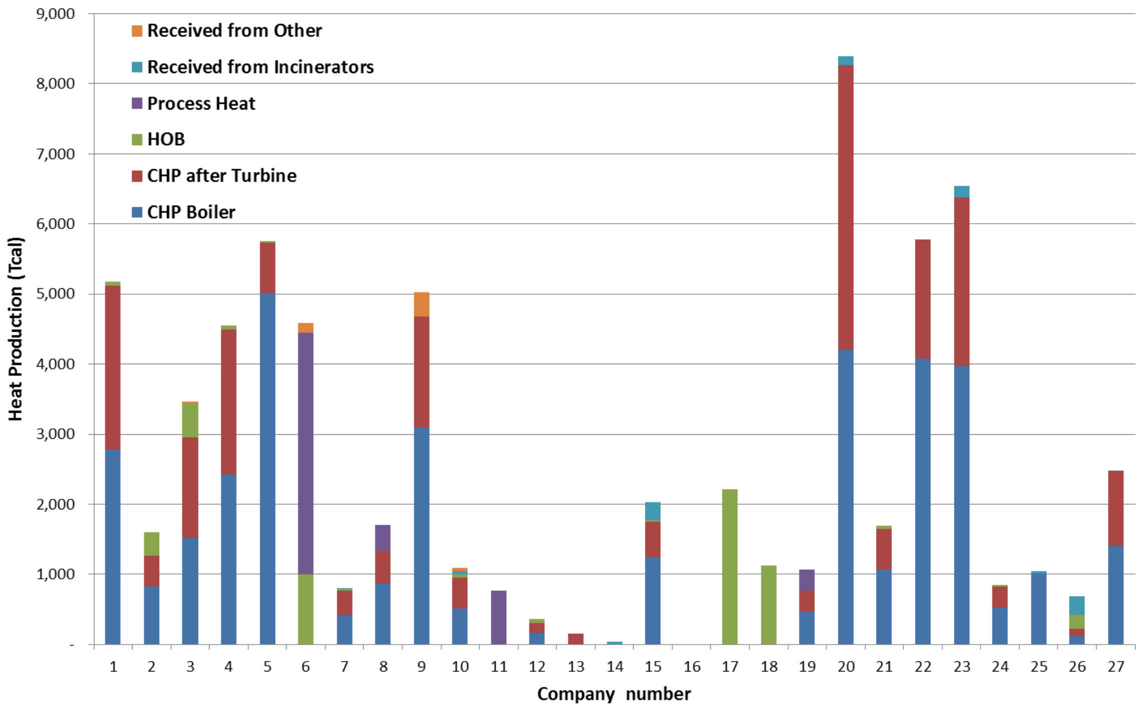

Fig. 9. Heat production profile for each company

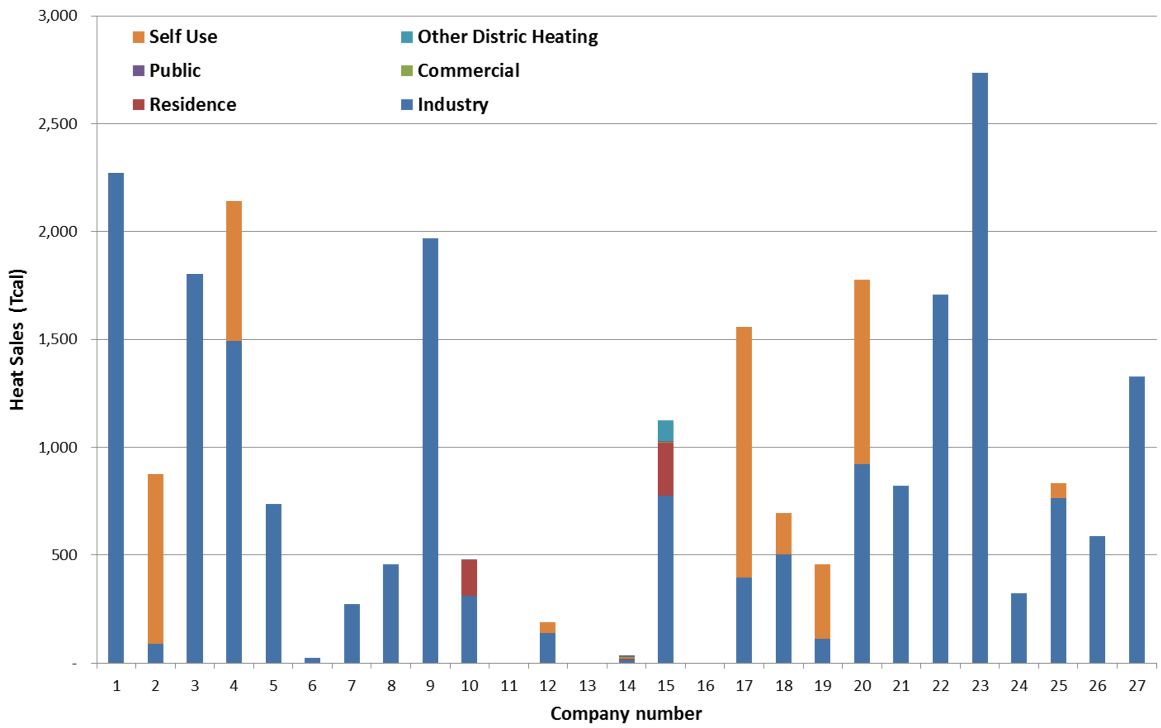

Fig. 10. Heat sales profile for each company

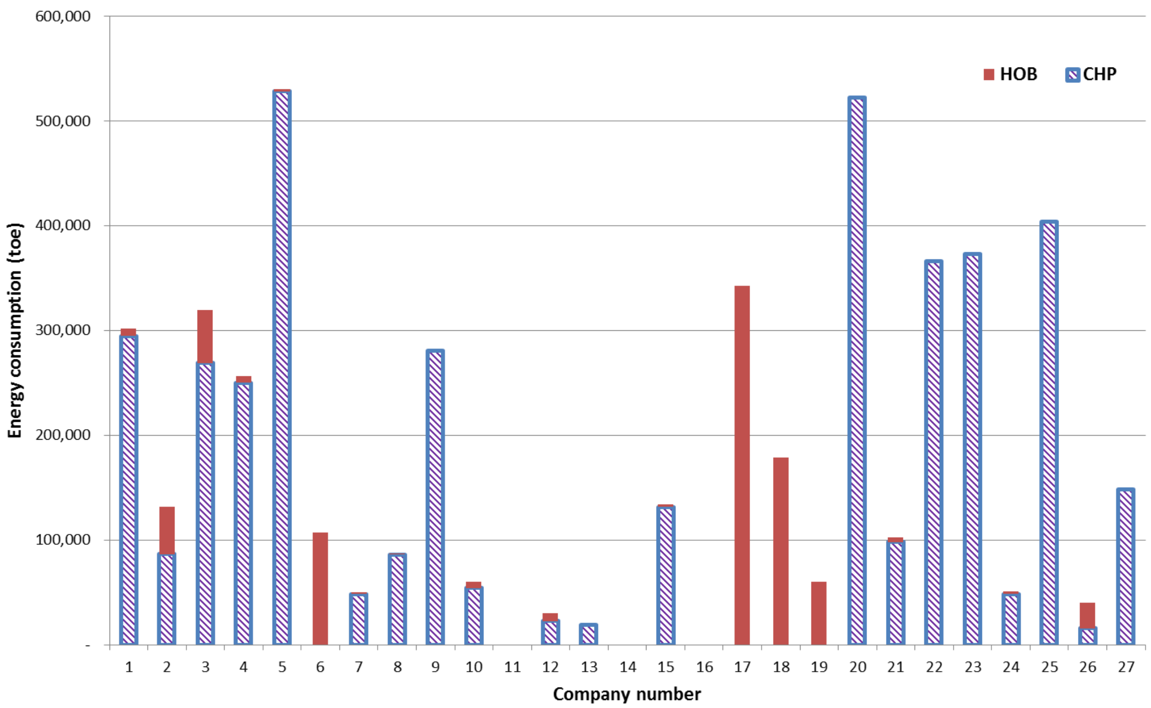

Fig. 11. Energy consumption profile for each company

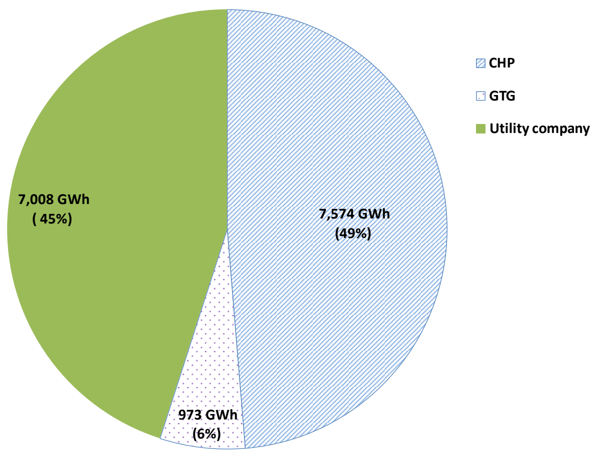

Fig. 12. Power production profile by source

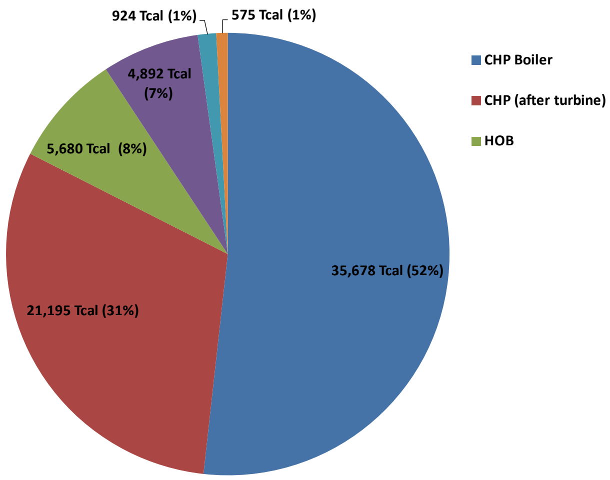

Fig. 13. Power production profile

Figs. 12 and 13 summarize the total amounts of energy sources to produce the electricity and heat by all of the district heating companies.

CONCLUSION

Through the survey of this study, we found that there is a great deal of energy recovery potential from various sectors of industry in Korea. In particular, waste energy in the form of hot gas has the best potential due to the abundance of resources and inherent high quality associated with elevated temperatures. We expect that though intelligent planning and integrated management on a national-wide scale, the full potential of the wasted energy can be realized and help alleviate energy and environmental problems.

Our survey on district heating company reveals underlying characteristics of the energy production and resource consumption. The results suggested the direction of national energy policy surrounding the district heating business in Korea. They also hinted at the effects and consequences of well-planned system and policies[3].

ACKNOWLEDGEMENT

This study was supported by a research fund from KEMCO (Korea Energy Management Corporation).

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GIS BASED ANALYSIS OF FUTURE DISTRICT HEATING POTENTIAL IN DENMARK

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Keywords: GIS, district heating, long-run marginal costs, renewable energy

ABSTRACT

The physical placement of buildings is important when determining the future potential for district heating (DH). Good locations for DH are mainly determined by having a large heat demand within a certain area combined with an access to local resources.

In Denmark, the placement of buildings and their heat demand has in recent years been assessed in a heat atlas including all buildings in Denmark. The focus in this article is to further develop a method for assessing the costs associated with supplying these buildings with DH.

The analysis takes departure in the existing DH areas in Denmark. By finding the heat production cost within these areas, and adding transmission and distribution costs, the economic feasibility of supplying areas with DH is found.

The result of the analysis is that the DH potential differs from area to area. In many areas it is economically feasible to expand DH, while in others production costs and grid losses should be reduced for DH expansions to be feasible. Including transmission and distribution costs into the calculation, gives an idea about where the boundaries for DH are. These boundaries are not static, but changes under different conditions.

INTRODUCTION

The focus on energy conservation measures is increasing both in EU policy and national legislation like the Danish. Several reports state that a 50% reduction in space heat demand is required to meet the future renewable energy targets [1, 2, 3]. In Denmark 61.3% of the 2.75 million Danish heat installations are district heating (DH) [4]. In general district heating is economically feasible when the heat generation and distribution costs are lower than the cost of the individual local heat generation [5]. In a recent Swedish study [6] the competitiveness of DH has been examined in regard to the costs associated with distribution, which is the main aspect that separates DH from individual heating.

In Heat Plan Denmark from 2008 [7], the potential for expanding DH into natural gas areas have been addressed [8]. For DH to be feasible, the local conditions are important, where the feasibility is mainly determined by having a densely populated area and access to local resources. This has led to a focus on potentials for DH in Europe [9] where the potentials are examined on the more detailed NUTS3 level, instead of the usual national level.

With the increasing focus on the importance of local conditions for heat planning and with advances in geographic information systems (GIS) and computer technology, the focus on utilizing GIS in heat planning is also increasing. For instance in larger cities like London and Paris who have developed maps of their heat demands [10, 11]. This is a very basic way to use GIS, where the heat demands are simply mapped but not used for any actual planning or analyses. In other studies the mapping of heat demands is only the first step, while the second step is to use the mapping to look into potentials for DH and CHPs. This is for instance the case for Great Britain where a map for combined heat and power development has been developed [12]. Another example is from the Swedish DH association who in 2003 made a study of connecting different DH areas [13]. A German example [14] shows a tool for creating grid based maps of heat supply in cities, which further on can be used to assess the feasibility of DH. Another example of a grid based analysis is from [15] where the heat density is used to find new areas close to an existing DH grid. A Danish example is the heat atlas developed in [16]. The heat atlas is very detailed, having heat demands on address level, but has not yet been used to examine the expansion of DH areas into areas without collective heat supply.

By using the Danish heat atlas together with cost models for DH propagation in a GIS model, the present article is a first attempt to include local conditions for DH in a national analysis for Denmark.

SCOPE OF THE STUDY

The main focus of the article is defined by the following research questions:

- How can a GIS model be constructed to include local conditions for district heating?
- Where is it under current conditions feasible to supply buildings with district heating?
- Where is district heating feasible if space heat demands are reduced?

The study is delimited to focus on socio-economic costs for DH propagation. Socio-economic costs exclude costs that are based on political agreements like taxes, subsidies or local tariff structures. The reason for using socio-economic costs is that large infrastructure projects, like DH, needs to be based on long-term planning that ensures that the projects are beneficial for society in a longer perspective. This is also why the Danish heat supply law [17] states that

DH companies have to carry out a socio-economic calculation for all expansion plans. Therefore, neither business- nor private economic considerations have been taken into account in this article. Also the focus is so far only on current costs and technologies, not taking e.g. increasing fuel prices into consideration. All the costs are from national documents, meaning that local variations are not considered.

METHODS AND DATA COLLECITON

The heat atlas is based on data from the Danish Buildings Register (BBR) and a methodology from the Danish Building Research Institute (SBi) for calculating the heat demand of buildings based on age, type and usage, the latter is described in detail in [18].

An essential part, when examining DH propagation, is not only to focus on each individual building, but to examine areas of buildings which are geographically close to each other, so that the benefits of heat dense areas will be considered. Since the information from the heat atlas is on the individual address level, the information needs to be summarized in larger areas. This can be done in several ways, but to represent the physical reality best, built up areas from the Danish Common Public Geodatabase (FOT) [19] is used. In FOT the built up areas are mapped as four categories: dense city, multi-storey buildings, low buildings and industry. By using these areas, the heat demands and associated areas are close to buildings plots, not including park areas, roads etc. Additionally data from the Danish Address and Road Database (DAV) is used.

The source for information on all Danish DH areas is a data extract from the Danish Energy Agency's energy producer count from 2009 [20], which includes information on all heat and electricity producers in Denmark.

COST MODELS FOR DISTRICT HEATING

The following subsections describe the cost models for DH used in a GIS model to examine the DH potential in Denmark. The costs are divided into production costs, transmission costs and distribution costs. Altogether these costs define the total cost of supplying an area with DH. All costs are given as long-run marginal costs, which includes investment costs, operation costs and fuel costs, but also enables a comparison between technologies with different lifespans.

Production cost

The first model assesses the production costs of existing DH systems in Denmark. The cost related to production within DH (excluding transmission and distribution costs) mainly consists of investment costs in production capacity, fuel costs and operation and maintenance costs. In Denmark all electricity and heat producers report their energy production and fuel consumption to the Danish Energy Agency in an annual producers count [20]. By joining the information from the producers count with a map of DH areas, it is possible to assess the local costs. A national map of DH areas has not been maintained around 2003, therefore the areas used in this study are based on information from [21]. In the present study the costs used are based on two documents: the preconditions for socio-economic costs [22] and the energy technology data sheet [23], both made by the Danish Energy Agency. Using these two sources for all production costs standardizes the costs and excludes local differences in costs. The negative aspect of this choice is that in some places the costs will differ so much from the actual costs that the calculations would not give the same results as doing more specific analyses. One reason for these differences is that the costs of local resources often depend on specific agreements among the suppliers and the DH companies, which naturally gives variations in costs. Finding local variations in costs would certainly have been more precise, but would take a long time to carry out. On the other hand the positive sides of using these two sources are that the calculations are more transparent and give certain coherence in the calculations. Also they make it possible to include a variety of fuels and technologies in the calculations, without spending time on getting local data. The costs in the model are calculated separately for fuel costs and cost related to investments in production capacity and operation and maintenance (O&M).

Fuel costs

The fuel costs for each DH area are found by multiplying the annual fuel consumption for each production unit with the fuel costs. Afterwards the costs are allocated between produced heat and electricity. In general allocation methods are subjective and therefore two methods are used in the model, to give an insight into the importance of this allocation, both are based on [24] from the Danish TSO. The first method used for the allocation is the called the energy content method, and uses the formula:

$$\frac{\mathrm{Q}_{production}}{\mathrm{P}_{production}+\mathrm{Q}_{production}} \cdot \mathrm{Fuel}_{consumption} \tag{1}$$

The second allocation method is the energy quality method, see formula 2. This is a modified version of the energy content method, where based on experience the allocation model uses 1 kWh heat to substitute 0.15 kWh electricity.

$$\frac{\mathrm{Q}_{production} \cdot 0.15}{\mathrm{P}_{production}+(\mathrm{Q}_{production} \cdot 0.15)} \cdot \mathrm{Fuel}_{consumption} \tag{2}$$

The energy quality method allocates a larger share of the costs to the electricity side than the energy content method, which means that this method is more positive towards DH. After the allocation the total annual fuel cost assigned to the heat side is summarized for each DH area. Finally the total annual fuel cost for each DH area is divided by the total annual heat delivery giving a EUR/GJ price for each area. By using both produced and delivered heat in the fuel cost calculation, the grid loss is indirectly included in the fuel cost. The following section describes the second part of the heat production cost model, which is the cost of annual investments and O&M.

Investment and O&M cost

In Denmark a variety of different technologies are used for DH production. All of these technologies have different costs associated with investments and operation of the plants. Therefore, it is necessary to assess these costs and as mentioned above, the Danish Energy Agency produces a technology catalogue approximately every year, where information about different present and future technologies is collected. This information includes a description of the technology, technical data about efficiencies and expected lifetime of a plant, but it also includes information on the economics, where investment costs and O&M costs are the main categories.

All in all 32 different categories for technologies are used to assess the cost of annual investments in capacity and operation and maintenance. Since the process of assigning these categories has to be carried out manually, it is chosen to focus only on the main producers within each area. Therefore, the backup units and peak-load units are excluded from the cost calculation. In total there are 1710 production units included in the producer count, after excluding presumed peak- load units with less than 438 full-load hours per year this is down to 842 units. For each of these 842 units one of the 32 categories has been assigned manually by looking at the primary fuel use, the name of the production unit and the capacity of the unit. This makes it possible to assign annual costs for each of the plants according to the prices from the Danish Energy Agency. The benefit of this procedure is that the costs are transparent and comparable, and can easily be updated in future versions of the model, on the other hand the downside is again that the local variations are not included.

In general the costs can be split into two categories, the fixed costs and the variable costs. The fixed costs consist of annual investment costs and O&M costs which are not determined by the plant operation of the plant. The variable costs on the other hand are mainly O&M costs which are associated with the utilization of the plant. Therefore, the fixed costs are determined by the production capacity of the plant and the variable costs are determined by the annual energy production. To arrive at a marginal production cost, it is necessary to find the annual fixed costs by using equation 3. The calculation is carried out using the lifetime of each technology and a discount rate of 6%. The lifetimes vary between 10 and 40 years, depending on the technology.

$$a \cdot I = I \cdot \frac{i}{1-(1+i)^{-n}} \tag{3}$$

Since many plants produce both heat and electricity, the allocation models presented in the previous section are both used to assign a share of the total annual cost to the heat.

Total heat production cost

An overview of the resulting heat costs is shown in Figure 1 which shows the total long-run marginal production costs including fixed costs, variable costs and fuel costs all based on the year 2009.

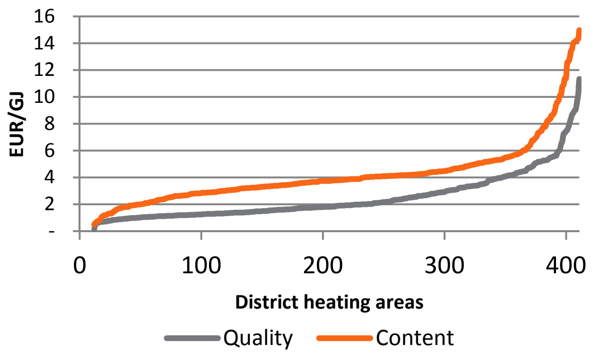

Figure 1: Long-run marginal cost for heat production in DH areas

As seen in Figure 1, the choice of allocation method is important when assigning costs to DH. If only the energy quality method is used, the costs associated with heat production will be very low, while on the other hand using the energy content method the costs will be higher.

Transmission cost

To avoid placing transmission pipes in restricted areas, the pipes follow the road network in the GIS model. In reality transmission pipes would not always follow the roads, so in some cases the length found in the model is a conservative estimate. By using a network analyst tool in GIS, the transmission pipe length to the closest DH area for 150,156 built up areas outside DH is found. To be able to carry out the analysis all the areas have been defined as points by using a polygon to point tool. After finding the length of the pipes the needed capacity of the pipes are found. This is done by dividing the annual energy demand in the area, given in MWh per year, by 3000 full-load hours, giving the need for capacity in MW. To find the cost of establishing the transmission line, a cost in EUR per meter is used, see Table 1. The calculations of capacities are based on a temperature difference of 55°C and the water flow in the table.

Table 1: Total cost of transmission pipes including projecting, field work, pipe work, materials and digging, based on [25] graph C.

Dimension DN	Water flow m/s	Capacity MW	Cost EUR/m
32	0.9	0.2	195
40	1.0	0.3	206
50	1.2	0.6	220
65	1.4	1.2	240
80	1.6	1.9	261
100	1.8	3.6	288
125	2.0	6.1	323
150	2.2	9.8	357
200	2.5	20	426
300	2.7	45	564
400	2.8	75	701
500	2.9	125	839
600	3.0	190	976

To find the total cost of each transmission line, the length and cost per meter is multiplied for all transmission lines. Finally, the transmission cost is annualized by using equation 3 with a lifetime of 30 years and discount rate 6%. Afterwards the total cost is divided by the heat demand in each area to give the annual EUR/GJ cost for transmission to the area.

Distribution cost

While the previous section determined the cost of building transmission lines between areas, this section assesses the heat distribution costs within each area. According to [6] the distribution cost consists of four categories:

- Distribution capital cost
- Heat loss cost
- Pressure loss cost
- Service and maintenance cost

The main cost category is the distribution capital cost which will be the focus in this section. The heat loss costs are included in the heat production cost model described in the production cost section. The distribution capital cost is the investment cost of constructing the DH network. In [6] the expression for distribution capital cost is reformulated in the following way:

$$C_d = \frac{a \cdot I}{\left(\frac{Q_s}{L}\right)} = \frac{a \cdot (C_1 + C_2 \cdot d_a)}{p \cdot \alpha \cdot q \cdot w} \tag{4}$$

C_d is the annual distribution capital cost, which consist of the annual investment divided with the linear heat density. The linear heat density has historically been used to measure the effectiveness of existing DH systems based on empirical evidence. The linear heat density is expressed as Qs/L or the annual sold heat divided with the total trench length of DH system. In equation 4 the linear heat density is reformulated to consist of four parameters where p is the capita/m^2 land area, a is the m^2/capita building area, q is the annual demand in GJ/m^2 building area and w is the effective width. The first two parameters are known as the plot ratio. When the plot ratio is known, the expression can be reduced to equation 5, where e is the plot ratio.

$$C_d = \frac{a \cdot (C_1 + C_2 \cdot d_a)}{e \cdot q \cdot w} \tag{5}$$

The effective width is a measurement for pipes required per land area. As the concept is used in [6] the data is based on a database including overall information about urban areas, which means that it is an aggregated model of areas. By aggregating the information from the heat atlas to areas from FOT, a more detailed model of distribution cost can be constructed.

The heat atlas and the FOT data are the only inputs for the distribution cost model. The main parameters used are the heat demand and the building area. These are used to find the three parameters used for calculating the linear heat density. The first is the specific heat demand, which is the heat demand divided with the building area, which gives the GJ/m2. The second is the plot ratio, which is the building area divided by land area. The third is the effective width which uses the plot ratio as the input parameter. In previous Swedish studies [6] and [26] the effective width has been examined, but since the present model is used for Danish conditions, data from the DH company in Aarhus has been collected, see Figure 2.

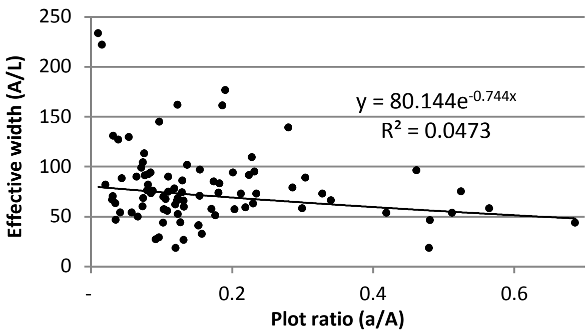

Figure 2: Effective width based on 88 DH areas in Aarhus

Based on Figure 2 the effective width can be found by using the formula:

$$w = 80.144 \cdot e^{-0.744 \cdot plot\ ratio} \tag{6}$$

Formula 6 is close to the correlation in the before mentioned Swedish studies. However, it must be underlined that the correlation between the plot ratio and effective width is very weak, so it should only be seen as a weak tendency towards a lower effective width with an increasing plot ratio. The formula is only applicable for plot ratios below 0.7, so in the model for areas with a plot ratio above 0.7 the effective width has been assumed to be 50 meters.

ANALYSIS OF DISTRICT HEATING POTENTIAL

By using the GIS model, developed in the previous section, the potential for expanding DH is examined. In general this is done by finding the cost of supplying all areas with DH that are not supplied with DH today. Instead of comparing the cost of the DH supply to the existing heat supply, it is compared to the least expensive individual supply option, which in the case of Denmark is a ground source heat pump. This is both to simplify the calculations and to secure that DH is not chosen in areas where heat pumps might be a more feasible solution. Since there are uncertainties associated with the cost calculation for DH, the heat pump cost is reduced with 10% to exclude areas that are too close to the individual supply cost. The heat pump costs consist of investment costs, O&M costs and electricity consumption cost. The heat pumps are assumed to have an average COP of 3.29, a lifetime of 20 years and the electricity price is set to 65 EUR/MWh [23, 22]. This result in a long-run marginal cost of 22.65 EUR/GJ, reduced by 10% the cost is 20.39 EUR/GJ, which is used as the limit for when DH is considered feasible.

The analysis consists of two different scenarios:

1. Current heat consumption in buildings
2. Reduced heat consumption in buildings

Both of these scenarios are based on the current supply in DH areas and the current costs of fuels and technologies. The goal with the second scenario is to show the feasibly of DH if DH areas do not change. The heat consumption is in average reduced by 75% in the second scenario, which is technically possible according to [18].

RESULTS

Since the model operates on a very detailed level it is not possible to show the map output for the whole of Denmark, even though the analysis is carried out for all DH areas in Denmark. However, Figure 3 shows an example of the output of the model, where the existing DH area is depicted with grey and the built area outside DH is depicted with red. By comparing the cost of supplying each of the red areas with DH to the cost of supplying them with individual heat pumps the blue areas are found. The blue areas show the areas where DH is feasible compared to heat pumps. There are different potentials depending on the cost allocation method used, where the light blue areas are the energy content method, which allocates more of the investment costs to the heat side, while the dark blue areas are the energy quality method which allocates most of the costs to the electricity side. This also means that all the light blue areas are also included as the potential in the energy quality method. There are some general tendencies to draw from the example, first of all that dense areas close to the DH area are mostly feasible and secondly that the areas need to be

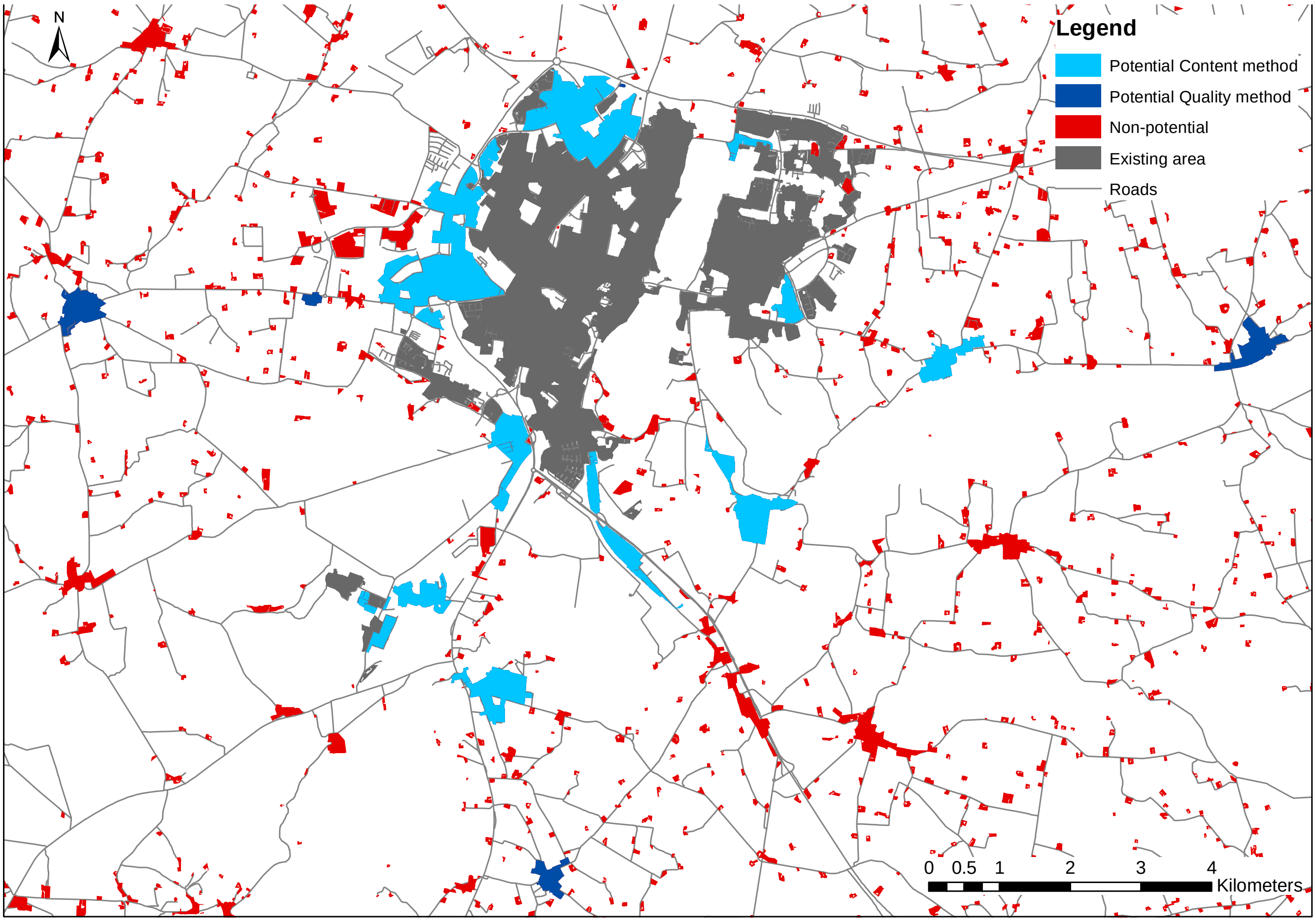

Figure 3: Example of output from GIS-model

larger when further away from the DH area. This supports the basic assumptions of the economics of DH propagation. The heat demands within each area cannot be seen from the map, but in general larger areas have larger demands.

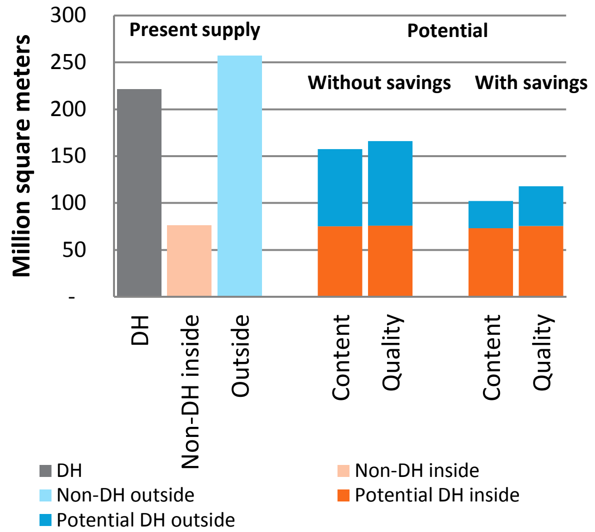

Figure 4: Total potential given in million m^2 built area

In Figure 4 the overall result of the model is shown. It shows that without savings there is quite a large possibility to expand DH in Denmark. Depending on the allocation method the potential inside is around 70 million m^2 of buildings, and the potential area outside DH areas is around 80 million m^2. In the scenario with heat savings the potential decreases, mostly in areas outside DH.

Examining these potentials individually for each DH area, shows that there are large variations between areas, see Figure 5.

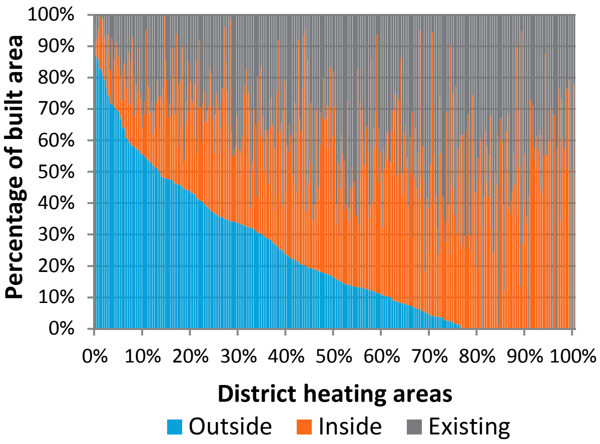

Figure 5: Building area distribution for each DH area (Energy Quality Method)

In 15% of the areas more than half of the built area is outside the existing areas, while in 22% of the areas the DH is not expanded beyond its current area. In most DH areas it is feasible to connect buildings inside.

These results reflect that the difference in the geographic distribution of the heat demands and the difference in costs are important in relation to the potential.

Figure 6 shows a graph of the heat demands of all areas outside DH sorted by the total cost from lowest to highest. As the long-run marginal cost of individual ground source heat pumps are assumed to be 22.65 EUR/GJ, the figure show that around 50% of the heat demand outside DH is more costly to supply than the individual alternative.

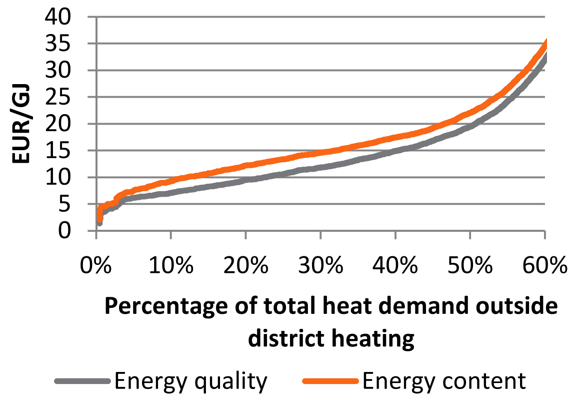

Figure 6: Total costs for potentials outside DH

In Figure 7 the costs are divided between production, distribution and transmission, for the potential areas outside DH and based on the current heat consumption. In general the transmission costs are in all cost categories, with most areas below 4 EUR/GJ. The main part of distribution costs are in the range 2-8 EUR/GJ and the production costs are mainly below 8 EUR/GJ.

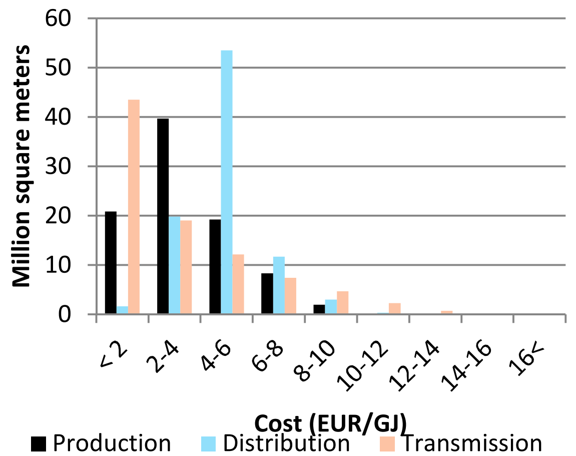

Figure 7: Potential outside (energy quality method and no heat savings)

DISCUSSION

The main focus of the article is to develop a method for calculating the DH potential by including all the major cost categories of supplying buildings with DH. In its current version the model can only be used as a screening tool and not as a tool for local planning. Due to the data inputs the results cannot be extracted on e.g. municipal level and used in concrete decisions. However, with local data inputs the methodology used in the model could be used for these purposes.

The inputs for the model are mainly heat demands, building areas and costs regarding the heat supply. The building related inputs are based on the BBR register, which includes several errors [27]. It is however, the most complete data on buildings for Denmark. The inputs regarding costs are based on a generalization of costs, meaning that there are no local variations in fuel costs or production capacity costs, or the other variable costs. This makes the costs transparent but also gives uncertainties compared to the actual costs in each area. The existing maps of DH areas in Denmark are outdated due to a lack of updating. Therefore, the geographic boundaries used in this study are based on combined information from several sources. This gives uncertainties in the model, but is necessary to be able to analyse the potential. The mapping of DH areas should have high priority in the future, since it is essential for estimating the propagation costs.

In Denmark the Danish Energy Regulatory Authority registers consumer costs in all DH areas, these costs are not very transparent, but could be used if the model should be used for private economic purposes. However, a private economic analysis has a different purpose than the present study and would most likely not include the benefits of supplying heat dense areas, when the costs are not allocated between production, transmission and distribution. An important cost that the model does not include is the cost of maintaining the existing DH grid. It could be added to the heat production cost in an area, but would require more detailed data on each DH area. Also the costs for increasing the production capacity in areas where the existing production units cannot cover the demand associated with an expansion, is not included. This means that in areas where the potential is much larger than the existing supply capacity, the cost could be higher than in areas where the expansion can be covered by the existing capacity. This should be included in further studies, since it is an essential part of calculating the feasibility of expanding DH areas.

The results of the analysis show that even though a large share of the Danish buildings stock is supplied by DH, there is a potential to expand even further. In the scenarios based on the current heat consumption, it is feasible to expand the DH areas from 40% to 68-70% of the total heated area. In the scenarios with a reduced heat demand, the feasible share drops to 58-61%. This indicates that unless DH areas improve, the potential feasible share for DH will be reduced with the improvements in the buildings stock. There are many options for DH areas to adjust to this new situation. One option is to change from expensive fossil fuels to less expensive renewable energy sources. This is a development that can be seen in many areas already, where more and more areas are building solar thermal collectors to reduce the natural gas production. Another way to adjust to the new situation would be to improve the efficiency in the system by reducing grid losses and lowering supply temperatures.

In the scenarios different allocation methods have been used for allocating the costs between heat and electricity production. These methods influence the results and therefore the choice of method should be considered carefully in areas where the costs are close to the individual supply cost. If more detailed information about the production units is accessible, it should be considered to use an allocation method based on the market prices of electricity.

What separates this study from many previous studies is the choice to separate DH costs into three categories. From the analysis it is clear, that this is an important distinction to make, so that areas with high heat densities and low distribution costs, and areas with a short distance to supply areas and low transmission costs, are more feasible than other areas. If the focus is only on the existing heat price, these benefits are not included, and it is very likely that DH propagation will not be considered even though it is socio-economically feasible.

CONCLUSION

This article examines how a heat atlas of Denmark can be used in combination with a GIS model of DH costs, to assess the potential for DH propagation. The cost models for DH are designed to include local variations and are based on long-run marginal costs. By separating the costs into three main categories; heat production, heat transmission and heat distribution, the total cost of supplying areas that are not connected to DH is found. This gives a model where local variations are included, meaning that the expansion potential differs from area to area depending on production costs and the geographic placement of the heat demands. In the model the current supply is used as the basis for finding the potentials.

The DH potential is examined in four scenarios, two based on the current heat demands and two on a reduced heat demand. In the present Danish system DH covers 40% of the total built area. The scenarios with current demands show a potential for increasing this area by 13-14% inside and additionally 15-16% outside, depending on the allocation method used. So in the most positive scenario, it gives a DH potential of 70% of the total built up area in Denmark. In the scenarios with decreased demands the potential is between 13-14% inside and 5-8% outside, giving a potential between 58-61%. This shows several things, first of all that there is an expansion potential in all scenarios, secondly that the allocation method is important, and finally that if DH areas wants to keep the heat market share they should improve the system by changing fuels and minimizing grid losses.

The results also show that including local variations are necessary to give the full picture of DH costs, it is not enough to base heat supply decisions in heat dense areas on separate buildings. This is mainly due to the fact that the costs related to heat distribution is reduced in areas with a high heat density. Therefore, in general heat supply decisions should be based on the spatial placement of the heat demands and the characteristics of the local DH area.

ACKNOWLEDGEMENT

Professor Sven Werner from Halmstad University for assistance in cost calculations for DH. AffaldVarme Aarhus for delivering data on their DH grid for the effective width calculation.

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MAPPING LOCAL EUROPEAN HEAT RESOURCES – A SPATIAL APPROACH TO IDENTIFY FAVOURABLE SYNERGY REGIONS FOR DISTRICT HEATING

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Keywords: Local heat resources, excess heat recovery, district heating, GIS analysis, heat synergy opportunity zones

ABSTRACT

A major setback in standard generic energy modelling is that national conditions constitute the basis for analysis. By such an approach, heat and energy assets, demands, and distribution structures are viewed from an aggregated perspective not permitting insight into unique local circumstances and conditions. As a consequence, genuinely local synergy opportunities, e.g. recovery and utilisation of excess heat from various activities and sources by distribution in district heating systems, are often ignored or overlooked in generic forecasts.

The ambitious European targets to increase energy efficiency in future power and heat distribution and use acts as a force to address local conditions in a more systematic and thorough sense than previously elaborated. Increased utilisation of local heat assets and recovered excess heat from local activities, to provide space and tap water heating in residential and service sectors, can replace and thus substitute large shares of natural gas and electricity currently being used to satisfy low temperature heat demands. Spatial screening and identification of local conditions throughout Europe, by use of NUTS3 regions as analytical level of reference, can disclose favourable synergy regions by combining information on local heat assets and demands, and hence provide additional and pivotal information to energy modellers.

In this study, local conditions such as excess heat from thermal power generation plants, Waste-to-Energy incineration facilities, energy intensive industrial processes, and renewable heat assets (geothermal and solar), are depicted together with heat demand concentrations, using GIS based spatial information, to visualise the possibilities of mapping local European heat resources.

INTRODUCTION

A tendency in generic energy modelling is that national conditions constitute the analytical level of reference [1], [2]. As a consequence, forecasts relying on generic energy model outputs tend not to integrate sub-national, or local, conditions and possibilities when projecting future energy scenarios, thus not considering conditions relevant for expansions of district heating systems [3], [4]. Generic energy models are further often based on current energy technologies, business-as-usual scenarios, and market equilibrium solutions, why possibilities for radical technological changes seldom are recognised.

Another tendency visible in generic energy model forecasts, perhaps reflecting traditional perspectives on heat supply for district heating systems, is a continued and static comprehension of district heat being strictly associated with fossil heat supply technologies, and hence not a major contributor in the decarbonisation of the European energy system [5], [6]. In essence, such views fail to recognize the important role of district heating systems as energy efficiency infrastructures, by their ability to recover and distribute excess heat, as well as to realise the dynamic range of possible future heat supply for modern district heating technology.

Both of these tendencies are subject for reconsideration as recent and ambitious European targets to increase energy efficiency in future power and heat distribution and use [7], [8], [9], acts as a force to address local conditions in a more systematic and thorough sense than previously elaborated. The main reason for this is simply that only local conditions disclose obtainable synergies between local heat assets and prevailing heat demands – only at local levels can excess heat from thermal power generation and energy intensive industrial activities, as well as heat from local heat resources, be utilised by recovery and distribution in district heating systems.

During the spring of 2012, a cooperate group of researchers from the Department of Development and Planning at Aalborg University in Denmark and from the School of Business and Engineering at Halmstad University in Sweden, set out to counteract these tendencies by investigating possibilities to develop a new holistic approach in energy modelling. The work process, initiated during 2011 by Euroheat & Power through the DHC+ Technology Platform, aimed at uniting a top-down energy modelling perspective with unique input data from a bottom-up mapping of local European heat resources and conditions. The approach, methodology, and results from this work, the Heat Roadmap Europe 2050 - First pre-study for EU27 [10], was published in early June, 2012.

In its full extent, the Heat Roadmap Europe 2050 project is thought to be absorbed within the Intelligent Energy Europe Programme, and eventually disseminated and integrated on a practical level in the forthcoming energy efficiency endeavours of Europe. A key priority area in this respect will be the importance of communicating local European heat synergy opportunities, and possibilities with district heating solutions, to urban and regional energy planners and analysts throughout the continent. The main aim of this paper is thus to precede this general ambition by communicating some core findings and conditions from the bottom-up mapping part of the first pre-study in the Heat Roadmap Europe 2050 project.

METHODOLOGY

The methodological approach of the Heat Roadmap Europe 2050 project, principally a combination of energy modelling and mapping of local conditions, is not completely new. The same fundamental idea was used previously in the Heat Plan Denmark projects (Varmeplan Danmark) of 2008 [11] and 2010 [12], where local information data with high geographical resolution was used for mapping national local potentials and costs of district heating expansions. Although the main target area for the analysis in the Heat Roadmap Europe 2050 project is the total area of the European Union, with its 27 member states (EU27), a deliberate break-up of national boundaries into NUTS3 regions have been made to disaggregate the analytical reference level.

NUTS3 regions, being the third and least aggregated level of "Nomenclature of Statistical Territorial Units", i.e. administrative regions, of Europe, are available for 34 European countries with 1461 defined NUTS3 regions, among which 1303 regions are found among EU27 Member States [13]. Population counts vary considerably in each NUTS3 region, although a threshold average range from 150000 to 800000 residents has been defined by NUTS regulation. Still, about 100 NUTS3 regions have more than one million inhabitants and, in some rare instances, population counts escalate to two to six millions. An additional bonus by using the predefined entities of NUTS3 regions as analytical reference level, apart from the local perspective, is that several other statistical variables are easily available from the Eurostat databases.

Thus relating all data and gathered information to NUTS3 regions, the work of mapping local European heat resources and conditions in the first pre-study of the Heat Roadmap Europe 2050 project was performed in accordance with a logical sequence, where (i) spread of urban fabric, (ii) residential and service sector low temperature heat demands, (iii) excess heat activities, (iv) local heat resources, and (v) European district heating systems, were to be identified. In this paper, the gathered data from pursuing this sequence is presented in order of appearance and, basically, in the form of maps.

In the first pre-study project, additionally, a series of concepts describing levels of available excess heat within each NUTS3 region was considered, among which the "excess heat ratio" (sum of available excess heat divided by total heat demands) was elaborated as a measure to identify European excess heat hot spots. Due partly to principal issues of concept definition and partly to some inconsistencies found in input data with regards to thermal power generation activities (which are further described in sub-section Excess heat activities below) this conceptual approach could not be fully completed within the project time span. The project work group decided instead to focus primarily on concept development and consolidation of input data before commencing further calculations of excess heat ratios.

For this reason partly, but also to add an extra dimension to this paper, a spatial analysis based on information on European district heating systems and assessed city heat demands is performed herein to introduce the related concept of "heat synergy opportunity zones" (HSOZ). In contrast to the excess heat ratio concept, which basically derive synergy opportunity identification from the locations and magnitudes of excess heat activities, this approach reversely indicate locations for future European excess heat recovery and local heat resource utilisation by referring directly to the current spread of European district heating systems.

Since all gathered local data and subsequent analyses in the mapping of local conditions part of the Heat Roadmap Europe 2050 first pre-study project was associated to geo-references and further processed by means of GIS software, a brief introduction to the concept of spatial information and GIS analysis is given in the following.

Spatial information and GIS analysis

Parallel to the rapid development of personal computer processor capacities during the last three decades, Geographic Information System (GIS) analysis has earned increased recognition as a powerful format for geographical and spatial studies. Compared to most other database applications, which might contain geographical information in the form of street addresses, zip codes etcetera, all information in GIS databases is linked to a geo-reference (coordinates) [14], which enables unlimited association of additional data and statistics to any spatially defined location.

Key features of GIS analysis can shortly be described as increased possibilities to integrate data and perform analysis in ways that exceed those of manual methods. GIS analyses allow modelling, querying, and mapping, of large quantities of spatial information, and – perhaps most importantly – offers cartography as an optional output interface. Visual representation of spatial information is highly communicative and represents an easily comprehendible form of analysis and result dissemination.

Today, GIS analysis is widely used in a multitude of fields (e.g. science, government, business, intelligence, and industry). Developments in Internet interactivity have also increasingly given the general public access to database information, as in the case of the recently published UK National Heat Map [15], the UK CHP Development Map [16], and the wiki portal Enipedia [17]. At the Enipedia webpage, which connects to other databases online and interfaces with Google Earth, interactive map representations of e.g. European power plants and other energy infrastructures are only a few clicks away.

In relation to district heating and excess heat recovery, the idea of using GIS based spatial analysis to identify heat synergy opportunities was used in Sweden already in 2003 to identify more aggregated heat loads for higher utilisation of industrial excess heat and combined heat and power [18]. A similar project in the UK, which later provided knowledge for the UK National Heat and CHP Development Maps mentioned above, gathered spatial information about industrial heat loads [19]. Similar approaches has also been used to give an overview of the European power plant infrastructure [20], and to assess viable district heating transmission distances between excess heat activities and cities in the German federal state of Bavaria [21], [22].

GIS software products generally consist of toolboxes with a wide range of commands by which data processing can be performed. Specially designed for different purposes, commands are often sorted under major headings such as analysis tools, cartography tools, data management tools etcetera. The Environmental Systems Research Institute Inc. (ESRI), of Redlands, California [23], offers a suite of GIS software products, commonly named ArcGIS, which comprises extensive command toolboxes including also e.g. geocoding and spatial statistics tools. In this study, the ESRI ArcGIS 9 desktop version (ArcMap 9.3.1) has been used [24].

Heat synergy opportunity zones

The main aim of the mapping part in the Heat Roadmap Europe 2050 project is to combine spatial information and statistical data for European excess heat activities and local heat resources with corresponding information on city heat demands and existing district heating systems. Ultimately, the project aims at identifying, mapping, and evaluating NUTS3 regions – or clusters of NUTS3 regions – with favourable conditions for excess heat recovery and local heat resource utilisation by means of distribution in existing or new district heating systems.

In the limited context of this study, the concept of heat synergy opportunity zones is introduced as a midway indicatory of favourable synergy regions for district heating in Europe. The basic idea to identify these heat synergy opportunity zones is to exploit the exclusive information on European district heating cities, assembled in the Halmstad University District Heating and Cooling (HUDHC) database, since the presence of district heating systems is a precondition for large-scale distribution of recovered excess heat and utilised local heat resources.

From the city centre of each recorded EU27 city with one or more existing district heating systems (totalling at 3233 as of June 2012, see also Table 2), a radius, representing viable transmission distance by reflecting the magnitude of city low temperature heat demands in residential and service sectors, is calculated to define the size of a circular heat synergy opportunity zone emanating from the city. A general presumption of 100 kilometres viable transmission distance at a heat demand of 3.6 PJ is applied, although a transmission distance of 30 kilometres (corresponding to a heat demand of 1.08 PJ) has been set as a maximum transmission distance in this analysis.

By this approach, which is executed by use of the ArcGIS toolbox proximity command "buffer" on the associated data for each city in the HUDHC database, a city specific viable transmission distance is found according to equation 1:

$$f(x) = \begin{cases} \frac{x}{3.6} * 100 & x \leq 1.08\,PJ \\ 30 & x > 1.08\,PJ \end{cases} \quad \text{[km]} \qquad (1)$$

The function value, f(x), symbolises the transmission distance, and the function argument, x, represents the heat demand. The 30 kilometre limit is motivated partly with reference to current applications and Swedish experience [25], [26], and partly to avoid overestimations. Unique low temperature heat demands in city residential and service sectors are assessed by multiplying specific EU27 Member state heat demands for low temperature heating purposes, as detailed in Table 1, by total population counts in each district heating city.

In a second and third step, the ArcGIS toolbox analysis command "clip" is used, firstly to relate each heat synergy opportunity zone of the generated buffer layer to the NUTS3 region in which it is located, and secondly to identify excess heat activities located within the perimeters of each zone. In the context of this study, all excess heat activities found to be located within calculated heat synergy opportunity zones are identified and told, although not evaluated in terms of available excess heat volumes or potential excess heat deliveries to city district heating systems. The presentation of European heat synergy opportunity zones serves thus the purposes of merely introducing the concept in itself, and to visualise the possibilities in GIS analysis.

DATA

In this section, gathered data used for mapping of local conditions in the first Heat Roadmap Europe 2050 pre-study is presented together with some additional projections based on subsequent analyses of the information. As mentioned above, local conditions data was assembled in accordance with a logical sequence consisting of five main categories, which are all included in the following sub-sections, and mainly collected from public databases and sources. Data source references, applied assumptions, and performed processing of gathered data, are given and briefly described in each sub-section accordingly.

Urban fabric

As a first field of understanding, the spread of European urban fabric has close relevance to the use of district heating, since high population densities in city areas generate correspondingly high heat densities. When considering the fundamental dependency on sufficiently high linear heat densities for feasible heat distribution, conventional 3rd generation district heating technology can principally be perceived as an urban occurrence. According to United Nations World Urbanization Prospects [27], about 73% of all EU27 residents lived in urban areas in 2010, indicating that the major part of residential and service sector low temperature heat demands are located in urban and city areas. Forecasts for the future further indicate that urban population fractions in EU27 will continue to increase.

To reveal the geographical concentration of residential and service sector heat demands in urban areas, the

European Environment Agency database; Corine land cover 2000 [28], was used in the pre-study project. Extractable from this database, the spatial distribution of European urban fabric, sorted under the three categories of (i) continuous urban fabric, (ii) discontinuous urban fabric, and (iii) industrial and commercial areas, provided information on total urban fabric land areas within each NUTS3 region. Urban area fractions for all European NUTS3 regions, calculated by dividing the total sum of urban fabric land area by the corresponding total NUTS3 region land area, are presented in Fig. 1.

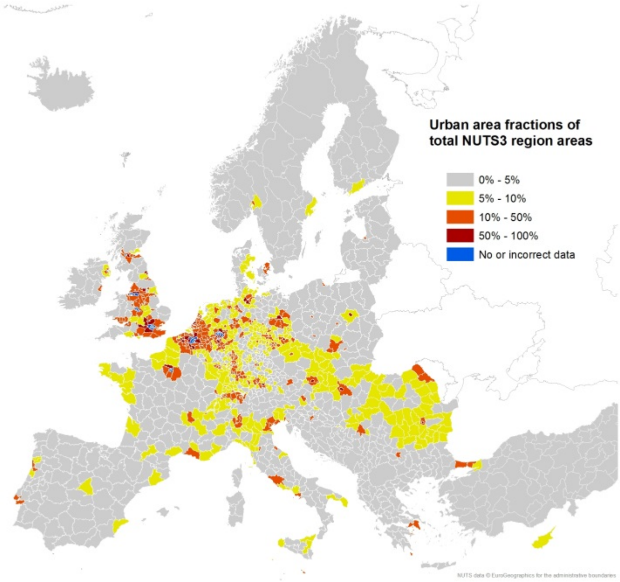

Fig. 1. Urban area fractions of total NUTS3 region land areas for all European NUTS3 regions. Sources: [28], [29].

The possibility to identify proportional fractions of urban land areas within each NUTS3 region land area, discretely discloses the locations of European population and heat density concentrations. This possibility is thought to prove even more useful in the extension of Heat Roadmap Europe 2050 project, as the results will be disseminated to regional energy planners and local authorities. When sub-penetrating the NUTS3 region level to out-line e.g. feasible transmission distances from available heat sources to existing and future district heating systems *in situ*, high resolution information on land cover types and urban fabric distribution can provide pivotal spatial guidance. By thus offering geographical support when identifying and analysing future European heat synergy opportunities, the Corine land cover 2000 database constitutes a corner-stone in the tool-package of the Heat Roadmap Europe 2050 project.

Heat demands in residential and service sectors

A key parameter in the future Heat Roadmap Europe 2050 project will be to produce reliable assessments of heat demands for space heating and hot water preparation in each NUTS3 region, since these heat demands constitute the main target for district heat distribution. In the full extension of the project, these assessments are ideally to be made at disaggregated levels utilising local heat use data. In the limited time realm of the first pre-study (January to April, 2012), the 2008 net EU27 heat demand for space and tap water heating in residential and service sectors was approximated to 11.5 EJ, according to a previous analysis performed by Persson and Werner in [30], where data from [31] and [32] was used.

From a parallel study [33], in which the anticipated 2008 net EU27 heat demand from [30] was calculated and specified for each respective EU27 Member State, total national low temperature heat demands in residential and service sectors was found and subsequently divided by total national population counts for 2009 [34] to produce average EU27 Member State specific heat demands, as presented in Table 1. Eventually, to produce assessments of unique residential and service sector heat demands for each NUTS3 region, average EU27 Member State specific heat demands were related to population counts within each NUTS3 region in respective Member State. By this procedure, naturally, unique NUTS3 region heat demands were generalised, although not as bluntly as would have been the case if a EU27 average specific heat demand value would have been applied uniformly.

Table 1. Estimated low temperature heat demands in residential and service sectors in EU27 Member States, 2008. Sources: [30], [33], [34]

	$Q_{Res\&serv}$ [EJ/a]	P_{Tot} [kn]	$q_{Res\&serv}$ [GJ/na]
Austria	0.247	8355	30
Belgium	0.343	10753	32
Bulgaria	0.064	7607	8
Cyprus	0.010	797	13
Czech Republic	0.236	10468	23
Denmark	0.183	5511	33
Estonia	0.039	1340	29
Finland	0.196	5326	37
France	1.702	64350	26
Germany	2.733	82002	33
Greece	0.162	11260	14
Hungary	0.220	10031	22
Ireland	0.119	4450	27
Italy	1.099	60045	18
Latvia	0.060	2261	26
Lithuania	0.057	3350	17
Luxembourg	0.019	494	39
Malta	0.002	414	4
Netherlands	0.503	16486	31
Poland	0.709	38136	19
Portugal	0.105	10627	10
Romania	0.293	21499	14
Slovakia	0.109	5412	20
Slovenia	0.039	2032	19
Spain	0.520	45828	11
Sweden	0.258	9256	28
United Kingdom	1.473	61595	24
EU27	**11.50**	**499687**	**23**

When projected on the European map, as in Fig. 2, it can be seen that assessed spatial specific annual NUTS3 region residential and service sector low temperature heat demands of magnitudes from below 2 TJ per square kilometre and year up to 5 TJ per square kilometre and year dominate the continent. In absolute terms, annual residential and service sector heat demands exceed 20 PJ for a total of 91 NUTS3 regions (in 13 instances above 50 PJ), reaching a maximum of 144 PJ in the city of Berlin, Germany. Common for most high heat demand NUTS3 regions is their hosting of major high population cities, which explains a marked coherence with high urban area fraction NUTS3 regions, as depicted in Fig. 1.

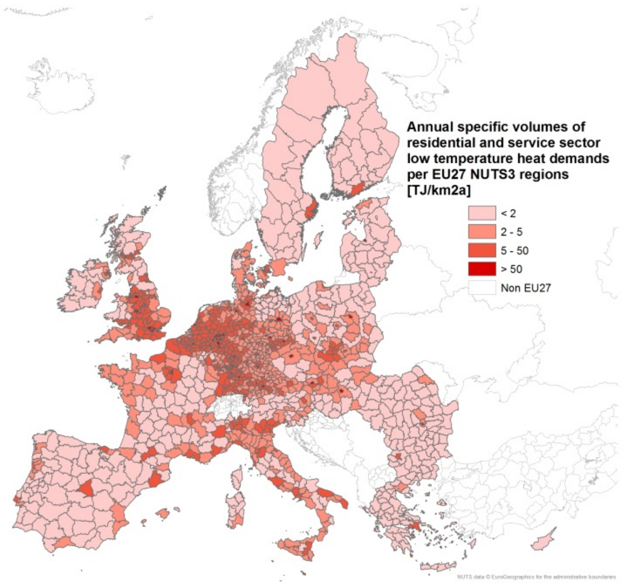

Fig. 2. Assessed spatial specific annual volumes of residential and service sector low temperature heat demands per NUTS3 region in EU27. Sources: [30], [33], [34].

Excess heat activities

From the 2008 EU27 energy balance, reported by the International Energy Agency [31], it can be derived that district heat supplies satisfied approximately only 12% of total end use low temperature heat demands in residential and service sectors. The major part was instead satisfied by heat supplies from natural gas (45%), petroleum products (19%), and electricity (12%), all together contributing with approximately 76%. Persson and Werner have further shown in [30] that a total primary energy volume of 28.0 EJ was supplied into European thermal power generation during the same year. From this primary energy supply, 10.4 EJ of electricity was generated, while only 1.8 EJ – from a total rejected excess heat volume of 17.6 EJ – was recovered for heating purposes by district heat distribution.

If seen from such a perspective and considering current conditions, Europe is in possession of a vast but poorly utilised heat resource contained in the rejected excess heat from thermal power generation and energy intensive industrial processes. In the Heat Roadmap Europe 2050 project, as well as in several formal communications from the European Commission [7], [35], this condition has been recognised as a key area for future energy efficiency improvements. The mapping of local conditions part of the first pre-study hereby focused on identifying the locations of current excess heat streams to be found mainly in thermal power generation, Waste-to-Energy incineration facilities, and energy intensive industrial processes.

Extractable from the public European Pollutant Release and Transfer Register (E-PRTR) of the European Environment Agency [36], geo-references for all European activities with air and water emissions provided basic information for the positioning of European excess heat activities. Since the E-PRTR database contains activity information sorted under different emission type categories, processing of gathered data was needed to identify only those activities emitting carbon dioxide (perceived as an indicator of the presence of combustion facilities and thus excess heat), see Fig. 3 and Fig. 4.

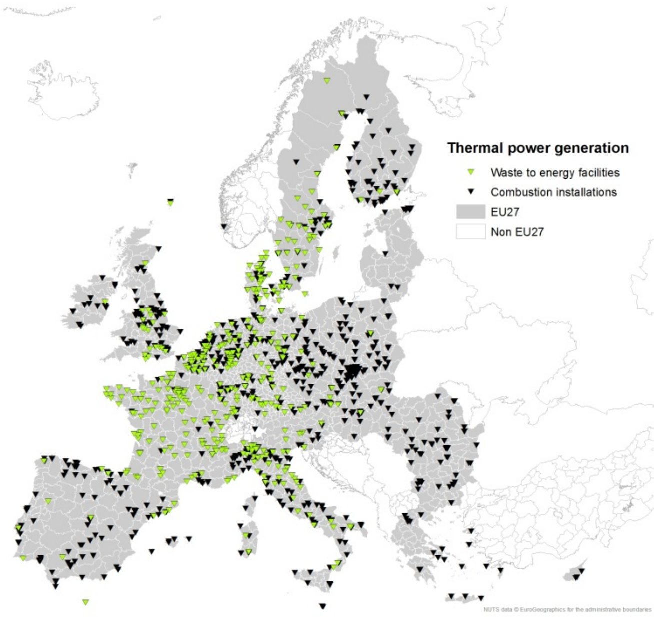

Fig. 3. Locations of major combustion installations above 50 MW, and waste incineration facilities, for power and heat generation in Europe. Main sources: [36], [37], [38].

As for information on annual volumes of rejected excess heat from the considered activities, real data is seldom readily available. Initially, it was attempted in the first pre-study project to perform a reversed calculation sequence, based on quantified carbon dioxide emissions given in E-PRTR database and anticipated specific emission factors (released carbon dioxide per input energy unit) for different fuels used in each activity sector, derivable from [31]. Due to several reasons, e.g. uncertainties in some reported annual carbon dioxide emission volumes in the E-PRTR database it was decided to postpone this approach until consolidation of input data could be performed.

Yet, as a consequence of this approach, all 2497 considered EU27 excess heat activities found in the E-PRTR database, were manually designated a main activity category, corresponding to those used in the IEA Energy balances [31]. In this process, a total of 190 activities were disregarded since no obvious activity association could be established. With regard to thermal power generation, the E-PRTR data thus comprised of 961 major combustion installations with an installed capacity exceeding 50 MW, and 161 Waste-to-Energy incineration facilities. Additional data on European Waste-to-Energy facilities was also gathered from the Confederation of European Waste-to-Energy Plants (CEWEP) [37] and from the International Solid Waste Association (ISWA) [38], to render a total count of 410 European waste incineration facilities, as illustrated in Fig. 3.

Industrial excess heat is normally recycled from five typical energy intensive industrial sub-sectors: chemical and petrochemical; iron and steel; non-ferrous metals; non-metallic minerals; pulp and paper production. A sixth excess heat contributing energy intensive sub-sector is also found in fuel supply and refineries. In terms of data, current recycling of industrial excess heat is difficult to discover since it is not reported in international energy statistics. The only bodies that report these heat streams are national district heating associations gathering own national statistics.

Still, an overview of European industrial excess heat recovery was presented in a recent study [30], where a total EU27 industrial excess heat recovery volume of 24.7 PJ was assessed for the year 2008. Although this estimation probably is an underestimation, since the situation in many countries not considered in the study is unknown, it is fair to say that current European industrial excess heat recovery is very limited. From the locations of major European industrial plants having excess heat, according to gathered information from the E-PRTR database and activity association to corresponding IEA main activities, it is clear that future European industrial excess heat recovery could be increased, see Fig. 4. Many of these industrial activities are located near to urban areas giving the possibility of transferring recovered excess heat to heat consumers by district heat distribution.

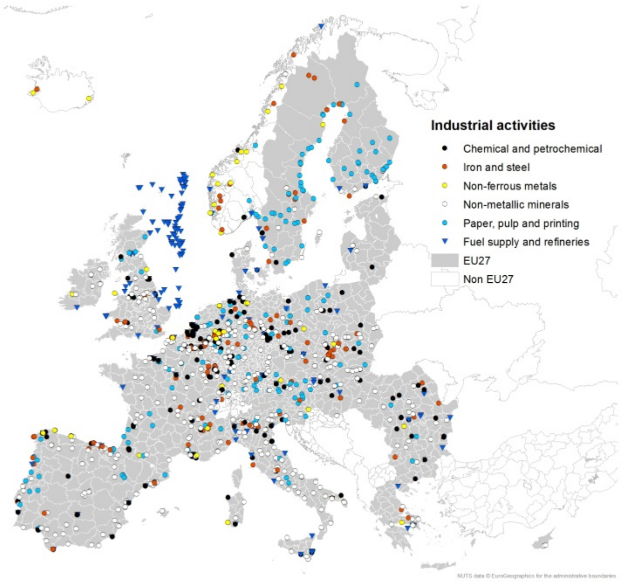

Fig. 4. Locations of major energy intensive industrial activities in Europe. Source: [36].

Regarding fuel supply and refineries, the gathered data within the first pre-study of the Heat Roadmap Europe 2050 project was compared to the findings of a recent study on the European petroleum refining industry [39]. This quality check proved satisfactory with reference to number of facilities. From the E-PRTR database a total of 191 EU27 refinery activities were extracted (including also some North Sea operating platforms), while 169 ground based oil refineries were anticipated in the related study. All the same, it should be noted that the above described procedure of extracting activity data from the E-PRTR database and the subsequent activity association to IEA main activity categories, involved manual operations and evaluations. For this reason, the data presented in this section should be perceived as indicatory only, since it may be incomplete in parts and thus deviate from the actual situation.

Local heat resources

Local heat resources are found mainly in the renewable heat streams from biomass incineration, annual solar irradiancies, and geothermal fields. The availability and magnitude of these local heat resources are heterogeneously spread over the European continent depending on e.g. forestry propagation, geographic location, and earth crust compositions. Of the three, biomass represents the most utilised heat supply resource to district heating systems today, and is currently used as original energy source in many European district heating systems. According to the Eurostat heat balance [40], 241 PJ of heat with biomass origin was supplied into EU27 district heating systems in 2009. Sweden had a lead position with an input of 88 PJ, while other significant supply appeared in Austria, Denmark, and Finland. Biomass originated fuel sources are mainly forestry and agricultural waste.

Regional conditions for solar district heating depends highly on the geographical location in Europe, since global solar irradiation is about twice as intense in Southern Europe compared to Northern Europe (ranging from approximately 4.7 GJ per square meter annually in northern and central regions to 7.2 GJ per square meter annually in central and southern regions, given south-oriented and optimally tilted surfaces). Some solar thermal installations in conjunction to district heating systems appear in Denmark, Germany, Austria, and Sweden, although currently at moderate levels. Denmark had a lead position with a solar heat supply of 0.108 PJ during 2009, according to [40]. Denmark has also seen continually increased interest in more solar thermal installations during the last couple of years, leading to lower installations cost for large solar collector fields, which has given possibilities for other European countries to benefit from this trend.

As for geothermal local heat resources in European regions, geographical location has a decisive influence regarding availability and practicability. Yet, geothermal heat suitable for direct use represents a vast energy reservoir, of which less than 0.001% currently is being utilised in district heating systems [41]. In the pre-study, data on estimated temperatures at 2000 metres depth per NUTS3 region was gathered from the Atlas of Geothermal Resources in Europe [42], as presented in Fig. 5.

By joining the information from [42] with population statistics, the pre-study project concluded that 4 % of the total EU27 population lives in NUTS3 regions with geothermal temperatures at or above 200 ºC, 8 % in NUTS3 regions with geothermal temperatures between 100 ºC and 200 ºC, and 19 % in NUTS3 regions with geothermal temperatures between 60 ºC and 100 ºC. From this, it was estimated that approximately one quarter of the total European population lives in urban areas that can be reached by geothermal heat through future distribution in district heating systems.

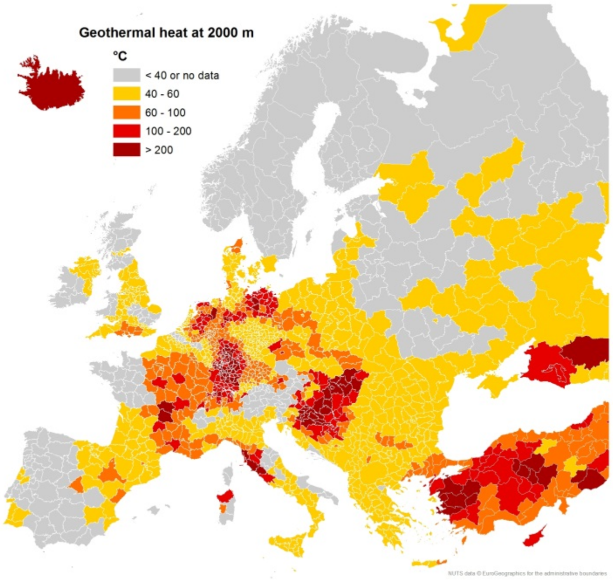

Fig. 5. Geothermal heat resources, by temperature level, at 2000 meters depth by NUTS3 regions. Source: [42].

In a recent study [43], the European Geothermal Energy Council (EGEC) reported that 212 district heating systems in Europe currently use partial input from geothermal heat, and expansions are foreseen in many countries until 2014. According to Eurostat energy statistics [40], systems in Belgium, Denmark, Germany, Lithuania, Hungary, Austria, and Slovakia utilised 2.5 PJ during 2009. French systems, of which about thirty are located in the Paris region, used 2.9 PJ in 2009, according to national SNCU statistics. New major geothermal projects are currently being implemented in Paris in France, Den Haag in Netherlands, and Vienna in Austria.

European district heating systems

An assessment of the spread and dissemination of European district heating is summoned in Table 2 and depicted in Fig. 6, where each red dot marks a city with at least one district heating system in operation. The map is based on the current content in the HUDHC database, which was created in 2010 and has been subject for two major updates and revisions (June-July 2011 and May-June 2012). The data has been gathered mainly from national European district heating organisations and administrative authorities, and is subject to continuous in-feed of new data. Since about 6000 district heating systems are anticipated to exist in Europe today (5400 located in EU27), the HUDHC database is yet not complete and deficits refer mainly to small systems in Germany, France and Poland.

As can be seen in Table 2, some 60 million EU27 residents are served by district heating systems in their daily life, corresponding to an average residential and service sector heat market share of 12%. But, existing district heat supply cover only part of the heat demands in the cities they serve. EU27 cities with at least one system host a total population of approximately 141 million residents, why more district heat could be delivered in the future by expanding existing systems. Additionally, about 57% of the total EU27 population lives in NUTS3 regions that have at least one district heating system.

Table 2. Overview of numbers of district heating systems in Europe according to the current content of the HUDHC database (June 2012)

	Europe	**EU27**	**EU27 population concerned**	
			[Mn]	**[%]**
Systems	4174	3549	60	12
- in cities over 5000 residents	2778	2430		
Cities concerned	3731	3233	141	28
- cities over 5000 residents	2432	2173		
NUTS3 regions - concerned	660	600	287	57
NUTS3 regions - all	1461	1303	500	100

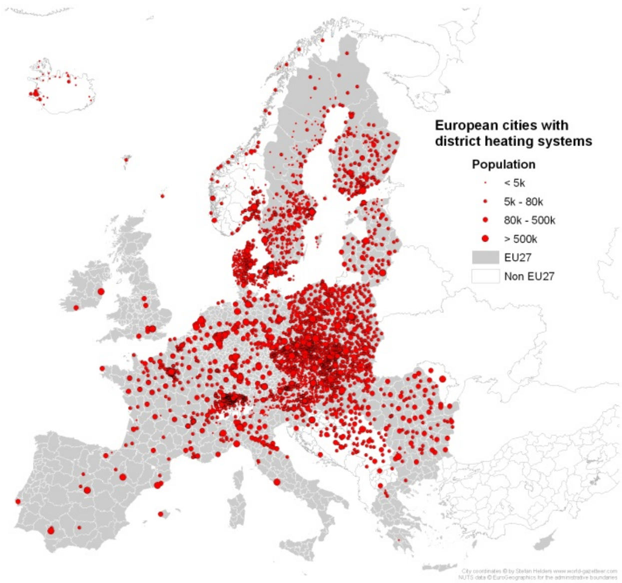

Fig. 6. European cities with district heating systems, by city size. The map shows 3731 cities with 4174 systems. Source: HUDHC database.

RESULTS

The results presented in this section will refer primarily to the performed analysis to identify European heat synergy opportunity zones unique for this study. As for the results from the first pre-study of the Heat Roadmap Europe 2050 project, which in essence included also an energy modelling sequence not addressed in this context, some major findings are mentioned in the Conclusions sub-section below.

The main results from the above described procedure of calculating viable transmission distances from all recorded district heating cities in the HUDHC database, to assess European heat synergy opportunity zones, are graphically presented in Fig. 7 and detailed in Table 3. Two significant observations can be drawn from the map presentation in Fig. 7: firstly, since district heating systems are present in most EU27 capitals and major cities today, although often at moderate levels of expansion, the heat synergy opportunities zones that they offer correspond generally to the locations of highly populated areas. In these instances, two central criteria for future expansions of European district heating are met: (i) close vicinity to high heat density concentrations, and (ii) current presence of district heating systems, acting in favour of future extensions since it is a greater leap to introduce a completely new technology than it is to extend and expand an existing one.

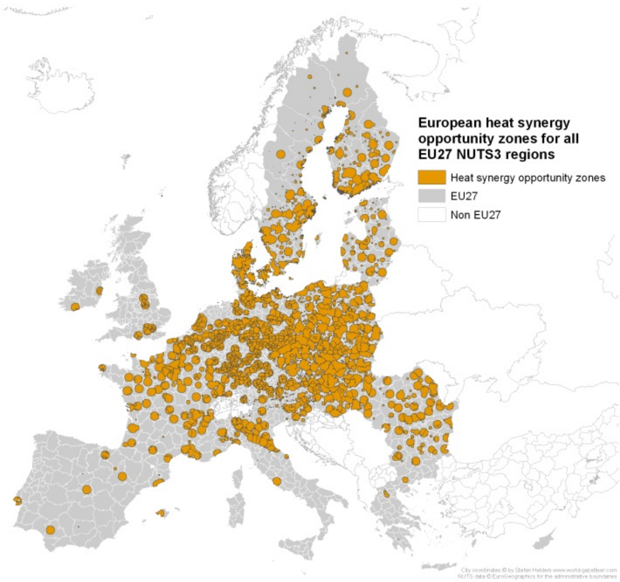

Fig. 7. EU27 heat synergy opportunity zones, by NUTS3 regions. Transmission distance determined by city heat demands (Max 30 kilometres). Source: HUDHC database.

Secondly, as also shown in Table 3, approximately 60% of all anticipated EU27 excess heat activities are located within the perimeters of these heat synergy opportunity zones, indicating substantial viability and rich possibilities for increased future excess heat recovery in Europe. Given applied assumptions, and an average EU27 specific heat demand of 23 GJ per capita and year (see Table 1), cities with approximately 50000 residents generate total residential and service sector low temperature heat demands to allow viable transmission distances of 30 kilometres. At even higher heat density concentrations, further extended viable transmission distances are conceivable.

Table 3. General properties of assessed EU27 heat synergy opportunity zones (HSOZ). Sources: [36], HUDHC database

	Total	HSOZ	[%]
European NUTS3 regions and land areas			
NUTS3 regions	1303	979[1]	75
Total land area (km^2)	4267644[2]	1283185	30
Energy intensive industrial activities			
Chem. & petrochemical	231	151	65
Iron & steel	140	101	72
Non-ferrous metals	30	17	57
Non-metallic minerals	421	204	48
Paper, pulp & printing	172	110	64
Fuel supply & refineries	191	63	33
Thermal power generation activities			
Combustion installations	961	595	62
Waste-to-Energy[3]	410	280	68
Grand Total	**2556**	**1521**	**60**

[1] Entire or part of NUTS3 region within heat synergy opportunity zone.
[2] EU27 total land area geographically calculated in ArcMap.
[3] Information on European Waste-to-Energy facilities were gathered also from [37] and [38].

CONCLUSIONS

To conclude, this study set out to describe the general background for the first pre-study of the Heat Roadmap Europe 2050 project, along with gathered data, approaches, and core findings, conceived within the mapping of local European conditions part of this project. To counteract two general tendencies regarding common comprehensions of district heating technology – depreciation of local conditions in generic energy modelling and static association to fossil fuels – data on European urban fabric, residential and service sector heat demands, excess heat activities, local heat resources, and European district heating systems, were assembled to provide a basis for alternative forecasts as regarding the energy future of Europe.

As a means for both analysis and dissemination, a Geographic Information System (GIS) software program proved to be a useful tool in the project. By its key properties, i.e. easy association of additional and complementary data to any spatially defined location, high capacity processing of spatial information, and highly communicative map outputs, GIS based analysis is thought to play an important role in the extension of the project, as disaggregated analyses of real life heat synergy collaborations in Europe will be performed.

Introduced in this study, the concept of heat synergy opportunity zones was established on the basis of calculated viable transmission distances from current European cities with district heating systems, as a complement to the related concept of excess heat ratios considered in the pre-study project. By their locations, as recorded in the Halmstad University District Heating and Cooling (HUDHC) database, European district heating systems are in general situated in close vicinity of highly populated urban areas and a significant share of European excess heat activities are within viable transmission distances from cities with district heating systems. These conditions provide notably beneficial spatial circumstances for increased excess heat recovery by district heat distribution in future Europe.

Given that circumstances in related dimensions of determining conditions (economical, behavioural, political, and organisational), are to form corresponding growth opportunities, district heating systems have the potential to contribute essentially to increased energy efficiency in the general energy balance of Europe. In the case of such a development, extended utilisation of recovered excess heat from energy and energy intensive industry sector activities, as well as renewable heat from local heat resources, could contribute to major fossil fuel substitutions, reduced carbon dioxide emissions, and reduced primary energy demands *per se*. As a consequence, reduced need for energy imports would increase future security of supply and render more positive balances of foreign exchange.

District heating, in itself a local technology solution, constitutes a key piece in the puzzle of organising efficient energy supply structures. Being the only recovery and distribution linkage between multiple local heat resources and local heat demands, district heating should be recognised as a highly versatile and flexible partner in the future European energy system.

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DHC13, the 13th International Symposium on District Heating and Cooling
September 3rd to September 4th, 2012, Copenhagen, Denmark

GREEN ENERGY SYSTEMS IN LOW CARBON ECONOMIES A GEOTHERMAL DISTRICT HEATING CASE STUDY

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Keywords: DHC in a low carbon society, Carbon Credits, Green Energy Systems, Geothermal Energy

ABSTRACT

In the fight on Climate Change one of the most ambitious activities undertaken by the international community have been the establishment of a set of marked based emission trading and financing schemes referred to as the flexible mechanism. As the (first) commitment period of the Kyoto Protocol is drawing to an end we can ask the question; "how does District Heating (DH) fared in these international trading schemes." Building on the experiences achieved from the Joint Implementation (JI) project Expansion and Development of Geothermal Energy in Zakopane Poland, we find that the expansion of a DH system in settlements with fossil fueled heating by individual source does have a substantial and verifiable Green House Gas (GHG) mitigation effect. We conclude that the financial contribution from sales of Carbon Credits can foster a noticeable support, but only under the right conditions and that DH systems and production facilities cannot be developed based on credit sale alone, but that the JI scheme can function as an incentive effect, to increase the expansion of DH networks and to "green" the energy production portfolio of the supply Company.

INTRODUCTION

The A key feature to mitigate climate change is the development of what is referred to as a *low carbon economy*; the drive towards a society that minimizes output of *Green House Gases* (GHG) to the biosphere, while still maintaining the opportunity to develop and prosper.

At the forefront of this challenge we find our *energy infrastructure*; that is the way we produce, distribute and consume energy. In this respect the extend and expansion of *District Heating* (DH) networks is of great importance, as DH is not only mandatory for the development of a high efficiency energy infrastructure, but also an excellent support system for CO_2-neutral production facilities.

In a European context the potential for DH is however much larger than the current extend of the system with numerous opportunities at Nordic and tempered latitudes. And in addition, where many of the new East European member states actually have substantial DH coverage, the state and efficiency of most of these systems are in dire need of renovation and renewal.

The question begs; how can we support the development and expansion of DH technology both at a European and a global level? The answer to this may be found in the wider perspective of the global strategic response towards climate change.

A global strategic response towards climate change has been the formation of the United Nations Framework Convention on Climate Change (UNFCCC) and in the auspices of this treaty, the formulation of the Kyoto Protocol (KP).

The relation to the development of DH systems comes in the operational part of the KP which is the development of *the flexible mechanisms*. The flexible mechanisms are a range of marked based emission trading schemes. Simply put the main goal of these mechanisms is to cap and reduce the global emission of GHG in the most cost effective way, either through trading of emission rights or through the co-financing of projects that mitigated the emission of GHG (*Climate Projects*).

There flexible mechanisms fall into three categories:

EU Emission Trading System (EU ETS) that enables GHG emitting companies to trade emission rights between them in the form of EU Allowances (EUA).

Clean Development Mechanism (CDM) that enables industrial countries/companies to invest in Climate Projects in developing countries outside the reach of the EU ETS in the form of Certified Emission Reductions (CER).

Joint Implementation (JI) that enables industrial countries /companies to invest in climate project in countries within the EU ETS in the form of Emission Reduction Units (ERU).

All these "currencies" (EUA, CER, ERU) that are utilized by the different mechanisms have a common value measured in ton CO_2-equivilants (tCO_2-e) commonly referred to as *Carbon Credits*.

As the development and expansion of District Heating systems can mitigate GHG emissions, DH systems can generate Carbon Credits and thus be developed as Climate Projects.

In this conference paper we will look at the case of the Joint Implementation (JI) project *"Expansion and Development of Geothermal Energy, Zakopane Poland"*[i] (EDGE) to investigate the interaction and effect of coupling a flexible mechanism with the development of a DH system.

Together with the company AAEN Consulting Engineers A/S I have been involved in the EDGE JI project since the beginning and am now managing the project. My role as a researcher on this project is therefore as a Participant Observer. And thou I am not independent of the case I can offer a large insight into its development.

The investigation will address the following questions:

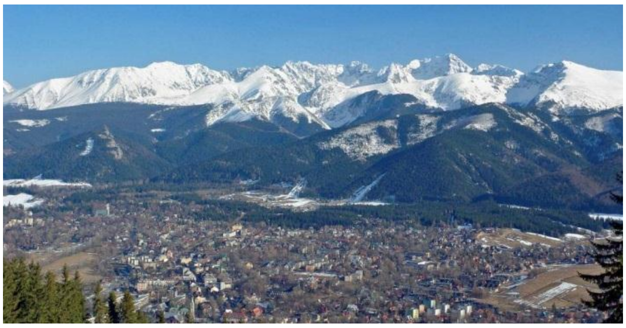
- Can DH systems benefit from the opportunities given by the flexible mechanisms?
- What amount of Carbon Credits can the development of a DH system generate?

THE CASE

The following is a short introduction to the case, the initial JI project design and how it changed over the course of the development of the DH system.

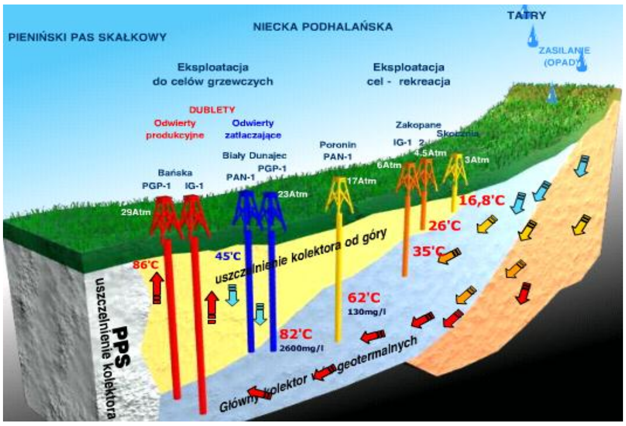
Background

Situated just above the Polish-Slovak border in the picturesque Tatra Mountain region of southern Poland, Zakopane is a well-known and popular tourist destination especially among domestic tourists. The town of Zakopane inhabits some 30.000 (2010) people but is visited by more than a million traveling tourist each year. And too little surprise as the region features some of Poland's most stunning landscape including the Polish Tatra National Park (Tatrzański Park Narodowy), which is part of UNESCO biosphere reserve list. Zakopane also features a small but vibrant skiing resort and is informally referred to as *"the winter capital of Poland"*.



Ill. 01 Image of Zakopane with the Tatra Mountain region in the background.

What is less well known however is that Zakopane can also be referred to as *"the geothermal capital of Poland"*. In the sub terrain below Zakopane you find The Podhale Trough (Niecka Podhalańska) a large reservoir of thermal water. The reservoir extends from the edge of the Tatra Mountains and up until the structure of the Pieniny Mountains' rock belt which constitutes a natural barrier trapping the water in a thermal reservoir. The Water that fuels the thermal waters reservoir is being supplied by the Tatra Mountain massif itself gathering precipitation and ground water from an area of approximately 350 km² in size. When percolating into the rock massif, the water is gradually heated. In depths of approx. 1000 meters the water is about 26°C and in depth greater than 2000 meters the water temperature reaches more than 80°C.



Ill. 02 The principle of geothermal energy reserves of Podhale region.

The availability of this resource has had an extensive impact on the economy and the environment of the region, both through direct utilization such as in thermal baths and water parks, but also through indirect use as the main energy resource for the district heating company of Zakopane; PEC Geotermia Podhalanska S.A. (Geotermia).

The utilization of geothermal energy for district heating in Zakopane has it's begin in the late eighties. IGSMiE of the Polish Academy of Sciences (PAN) built the Experimental Geothermal Plant Bańska Niżna–Biały Dunajec in the years 1989–1993. Several buildings from the nearby village Bańska Niżna were connected to the geothermal heat distribution network. By this it was proved that it was technically possible to heat houses utilizing geothermal waters. In December 1993 Geotermia was established by the National Fund of Environment Protection and Water Management.

However it was not until the mid-late nineties that the company became a more fully formed District Heating (DH) company with the establishment of a 3.5 km DH transmission line the town of Zakopane and the subsequent development of the DH network in the town. By the end of 2004 Geotermia's annual heat seal topped 280.000 GJ.

The transition from a state run research project to a commercial energy supply entity was however not without issues. The extensive investments needed both for the production facilities for utilization of the geothermal water and for the DH infrastructure, made it difficult for the company to compete with individual heating solutions. This issue was to form the basis for the EDGE JI project.

A good start

The case story for this project actually originates from another Climate Project, the JI project "*Utilization of methane gas from Landfill and Sludge, Zakopane, Poland*"[ii]. This project, developed by AAEN A/S in 2004, was the very first JI project to ever be developed and approved in Poland. It was during the development of this project that the idea originated of developing a JI project for the DH Company Geotermia as well, to assist the expansion of the DH network and of the geothermal capacity. The first commitment period for the JI mechanism wasn't set to be fully implemented until 2008. But the mechanism was open for early mover projects from 2005 to initiate a trail period for the mechanism.

In early 2005 AAEN A/S issued a *Project Identification Note* (PIN) for the JI project *"Expansion and Development of Geothermal Energy, Zakopane Poland"* (EDGE). The scope of the PIN was to displace fossil fuel heat production by individual source with CO_2-neutral geothermal energy on District Heating. The project also included the establishment of a new DH transmission line from the geothermal extraction installation to the neighbouring town of Nowy Tag and the establishment of a new geothermal extraction well possibly producing Combined Heat and Power. In the PIN the project was projected to generate some 61 $ktCO_2$-e in the trail period, 246 $ktCO_2$-e in the first JI commitment period (2008-2012) and 267 $ktCO_2$-e in the second JI commitment period (2013-2020).

The PIN was approved by the DH Company Geotermia via a *Letter of Intent* (LoI) in which Geotermia states there involvement in the project and that they will conduct the activities stated in the PIN based on the sale of Carbon Credits. Subsequently the Polish Ministry also approved the PIN through a *Letter of Endorsement* (LoE).

Based on the PIN, LoI and LoE the *Project Design Document* (PDD) could be created. The PDD is key document required for the validation and registration of the JI project. The PDD details the boundaries of the project and describes the baseline methodology, crediting period, project additionality, GHG mitigation calculation methodology, project environmental impact, required investments etc. The PDD must be validated by an independent accredited entity to insure that the project is within the scope of the UNFCCC and JI mechanism.

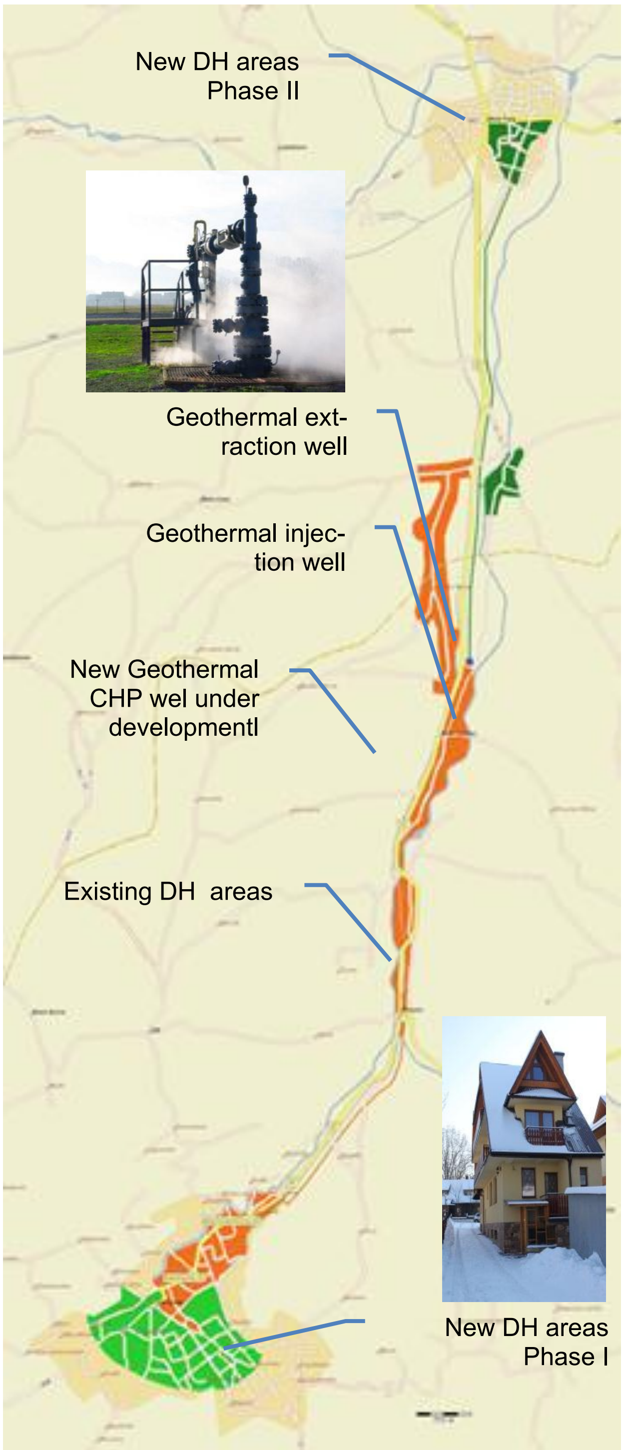


Figure 03 the JI project scope and phases

The PDD was finalized and determined (approved) in early 2006 and as such the project was ready to be initiated. All that was needed to commence was a *Letter of Approval* (LoA) from the Danish and Polish ministries. At this point the project hit a snag that would last for the better part of *4 years* and hold the generated Carbon Credits in suspension, not knowing if they could ever be verified or sold.

An issue of governance

The main issue was the interpretation of the allocation of emission allowances in the National Allocation Plans (NAP). In essence the NAP is an extensive allocation plan that all EU member states had to create in connection to the establishment of the EU ETS and the JI mechanism.

The NAP is simply put a publication on how a nation planes to reach its mitigation goals. There are different arguments behind the establishment of the NAP publication principle. One of the main reasons being the avoidance *leakage,* which is the situation where a GHG mitigation activity in one area, result in a GHG increase in another area. Another issue was the risk of *double counting*. In the early stages of the flexible mechanism, emission allowances were both auctioned (as EU Allowances) through the EU ETS and allocated directly through the NAP (as Assigned Amount Units). This created the risk of double counting where a mitigation activity in theory could be accredited multiple times. This issue also related to the JI mechanism as the ERUs in the JI, in essence is an offset of the EUAs in the EU ETS.

All in all this resulted in the DH Company Geotermia being unsure of whether they could afford selling there emission reductions as ERUs or if they would need them as AAUs or indeed if they would be better off selling them as EUAs. In addition the Polish Ministry could not issue the LoA until they had an operational NAP. This would prove to be a huge undertaking, mandating the creation of whole new public offices and extensive negotiations with the European Commission.

On lessons learned in reference to NAPs the European Commission have since stated; “Chief among these lessons is that the process is very time-consuming” and “…the NAPs for the first trading period were too complex and not sufficiently transparent. Complexity makes it hard for companies and other market actors to understand a NAP and thereby creates uncertainty.”[iii] As a result the European Commission has decided that NAPs will not be part of the third commitment period (2013-2020). Instead allocations will be determined directly at EU level.

By 19th of April 2010 the EC published a Commission Decision that the Polish NAP for the 2nd commitment period had been approved[iv] and by July 2010 the Polish Ministry issued a LoA in the EDGE JI project.

Thus by the end of 2010 the first Monitoring Report could be issued and the generation of verified emission reduction was underway.

Design, Additionality, Baseline & GHG mitigation

In the Project Design Document (PDD) [1] the project was been divided into two phases (see figure 03). The first phase included the expansion of the DH network in Zakopane and the full utilization of the existing geothermal well. The second project phase included the connection to the neighbouring town of Nowy Tag and the expansion of the geothermal capacity by establishment of a new geothermal extraction well.

The provisions for a Climate Project (JI/CDM) state that a Climate Project must be *additional* to be eligible. Simply put Additionality requires that the GHG emissions after implementation of the project activity are lower than those that would have occurred in the *most plausible alternative scenario* (baseline scenario) to the implementation of the project activity.

In many cases the most plausible alternative is either Business and Usual (BAU) or inaction. In the case of the EDGE project the Baseline scenario was defined as: "No new consumer connections in Zakopane, no new boreholes and no new distribution pipeline to Nowy Targ and thus the unimpeded release of CO_2 to the atmosphere until some future time when the expansion and development of geothermal energy becomes required by law or becomes an economically attractive course of action." Thus the Baseline scenario in the EDGE project would be inaction.

Closely linked to the Baseline scenario of the project is the Baseline calculation. In the case of the EDGE project the Baseline is represented by the continued individual heating of houses, offices, hotels, etc. by fuels such as coal, oil, electricity, coke and natural gas.

The results of the baseline calculation that was use for the Project Design Document (PDD) can be view in figure 04, where the top curve represents the baseline emission and the sloping curve the emission reduction that the project would entail.

Based on the Baseline calculation the GHG mitigation potential of the project can be calculated based on a replacement of individual fossil fuel with CO_2-neutral DH.

Monitoring, Verification & Transfer

The monitoring is executed in a Measure, Record and Verify cycle starting with the creation of a Monitoring Report (MR) [2]. The MRs are done in continues instalments usually 1 year or 6 month apart. Each instalment is called a monitoring period and the ERU calculation is made based on the conditions specific for that period (e.g. number of DH clients, load distribution, etc.).

For JI projects (under track 1) there is some manoeuvrability between the theoretical assumptions in the PDD and the actual project methodologies presented in the (first) MR. The very long delay on the LoA described in the paragraphs above, actually had some positive outcome. Because the project had been (more or less) on-going since 2006 there was a lot of available data designed to comply with a JI project. Thus baseline emission and GHG mitigation calculations could be conducted in much greater detail and with much less inaccuracy than what would have been the case in the beginning of the project.

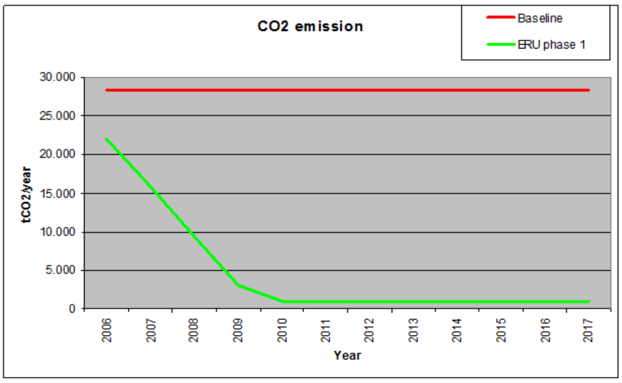


Figure 04 the baseline calculation for the EDGE project

When the MR is finalized it forms the basis for a Verification Report (VR) in which the *Verifier* control and approve the calculations and measurements made in the MR. The VR is in turn used to form the basis for the application for transfer of Carbon Credits from the JI project, which can then be invoiced to the credit buyer.

ERU production calculation

The data foundation for the ERU calculation in the MRs became the supply contracts written between the DH Company Geotermia and the new DH consumers that was part of the JI project. In these contracts the new DH consumers listed the utility type, fuel type and annual fuel consumption of their previous individual installation. Not all new consumers would list their previous utilities (approx. ½ did), but this still gave a much more exact representation of the actual fuel mix of the area, then what you would get from the theoretical assumptions used in the PDD.

With the representative fuel mix data from the new consumers, it was possible to establish a weighted mean for the fuel mix for the whole area. Different fuels have different emission intensities, given by a CO_2 Emission Factor (EF) measured in t CO_2-equivilant / GJ. Oil for example has as an EF of 0.075 t CO_2-e/GJ[v] whereas Coal (lignite) has an EF of 0.109 t CO_2-e/GJ[vi]. In addition each fuel type has an adjoining energy installation, this energy installation as an Energy Efficiency dependant on the installations age. By finding the weighted mean of the fuel mix and coupling this with the average Energy Efficiency of energy production installation it is possible to calculation a weighted mean CO_2 Emission Factor (EF) for the whole area. This can be calculated as:

$$EF_{\bar{x},z} = \frac{\sum_j (EF_j + EE_{\bar{x},j}) + \sum_k (EF_k + EE_{\bar{x},k}) + \cdots}{j + k + \cdots} \quad (1)$$

Where;

$EF_{x,z}$ = The weighted mean CO_2 Efficiency Factor (EF) for the Zakopane area [tCO_2-e/GJ]

EE_j = The EF for the fuel type j [tCO_2-e/GJ]

$EF_{x,j}$ = The Energy Efficiency for the average technical installation

j,k,… = The different fuel types

Thus using the representative fuel mix and utility types in Zakopane a common EF for the whole area could be determined and valued at 0.126 t CO_2-e/GJ.

In addition to the common CO_2 Efficiency Factor found via the supply contract, the ERU calculation would be based on actual heat sales for each consumer for each

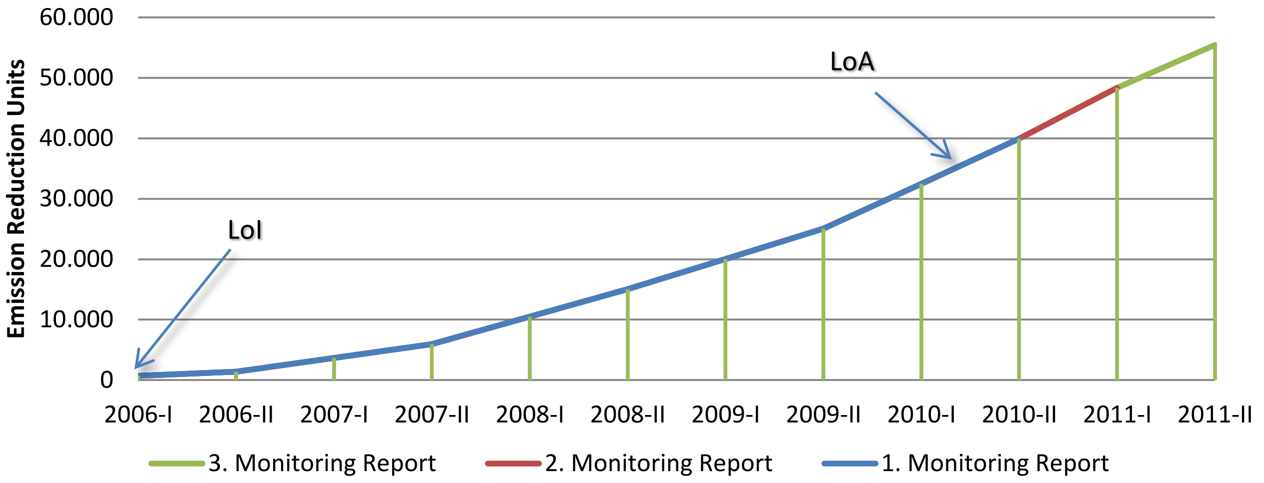


Figure 05 actual verified ERU production of the EDGE JI project

monitoring period. Thus the ERU production from Energy Replacement could be calculated as;

$$\sum_{w} H_w \times EF_{\bar{x},z} \qquad (2)$$

Where;

H_w = Heat Sale to consumer [GJ]
w = Heat consumers in monitoring period
$EF_{x,z}$ = The weighted mean CO_2 Efficiency Factor for the Zakopane area [tCO_2-e/GJ]

The common EF is however only representative for the Energy Replacement made on geothermal energy. The ERU calculation must also be adjusted in reference to the *load distribution* of the energy production, as peak and reserve loads are supplied by natural gas. This is done by extracting the accumulated heat production for each production facility for the prevailing monitoring period and from this calculated the percentile load distribution of the different fuels sources. The ERU production is then adjusted in reference to the load distribution and the CO_2EF for the different fuel sources.

$$\sum_{w} H_w \times (L_{base} \times EF_{\bar{x},z} + L_{peak}(EF_{\bar{x},z} - EF_{peak})) \qquad (3)$$

Where;

H_w = Heat Sale to consumer [GJ]
w = Heat consumers in monitoring period
L_{base} = Load distribution for *base load* [%]
$EF_{x,z}$ = The weighted mean CO_2 Efficiency Factor for the Zakopane area [tCO_2-e/GJ]
L_{peak} = Load distribution for *peak load* [%]
EF_{peak} = The EF for the peak load fuel [tCO_2-e/GJ]

The load distribution of Geotermia can be seen in figure 04 (in the calculations the oil contribution was deemed negligible).

In addition to the ERUs produced from the direct source of Energy Replacement, a secondary contribution was found in the form of an Energy Efficiency improvement at end user. By comparing the previous fuel consumption and utility type with the energy consumption after connection to the DH network, it was found that an argument could be made that switching from old individual fossil based installations to new modern DH installations resulted in a decrease in total energy consumption.

$$EE_a = H_a - \sum_{j} FC_{j,y} \times CV_j \times EE_{\bar{x},j} \qquad (4)$$

Where;

EE_a = The Energy Efficiency (EE) improvement at consumer a
H_a = Heat Sale to consumer a [GJ]
FC_j = Fuel Consumption of fuel type j in period y (one year)
CV_j = Calorific Value of fuel type j
$EE_{x,j}$ = The EE for the average technical installation using fuel type j

Thus and Energy Efficiency (EE) improvement factor as an average of all consumers could be calculated based on previous and current energy consumption. In the final verification of the first monitoring report an EE improvement factor of 20% was approved.

Finally renewal and maintenance costs of the existing geothermal installation were also included in the ERU calculation. As the yield of the geothermal extraction well and the reinjection well will deteriorate over time if not maintained, a *renewal and abrasion maintenance* constant was introduced. The deterioration was set at a level of 2 % a year equivalent to a 50 % yield reduction over 50 years, after which the well would be unfeasible to operate. Compared with the baseline geothermal energy production a positive maintenance contribution could be found at 744.2 tCO_2-e/year.

The ERU calculation is however not complete yet as the operation of the DH system also entails some activities that produces GHG emissions; namely *own consumption* of electricity. The calculation of GHG emission through *own consumption* of electricity was done by listing the electricity consumption for the prevailing monitoring period of the DH system that is included in the JI project (all new consumers after 2006) and multiply this amount [kWh electricity] with the CO_2EF for the national Polish electricity grit [0.85 t CO2/MWh].

All in all the ERU calculation can be resembled as follows:

$$ERU_y = \sum_{w} (H_{w,y} \times EF_y) \times EE + M - OC_y \qquad (5)$$

$$EF_y = \sum_{w} H_w \times (L_{base} \times EF_{\bar{x},z} + L_{peak}(EF_{\bar{x},z} - EF_{peak}))$$

Where;

ERU_y	=	Emission Reduction Units produced in monitoring period y [tCO_2-e]
$H_{w,y}$	=	Heat Sale to w consumers in period y
w	=	[GJ]
y	=	Heat consumers in monitoring period
EF_y	=	Monitoring period
		The CO_2 Emission Factor found in peri-
EE	=	od y
M	=	See cal. No. 3 [tCO_2-e/GJ]
		Overall Energy Efficiency improvement
OC	=	[%]
		Renewal and abrasion maintenance constant [tCO_2-e]
		Own Consumption of electricity for the period y [tCO_2-e]

The result of the ERU production calculations can be seen in figure 05. The graph plots the current verified ERU production of the EDGE project in Zakopane.

The EDGE project results so fare

Since the project commencement in 2006 430 new consumers have been added to the DH network. This may not sound as much, but because of the commercial nature of the Zakopane area, the consumers are a collection of residences, apartment buildings, hotels, offices, public facilities etc. that has large heat consumption. In 2011 the heat sale to these new consumers amounted to some 93.000 GJ. Compared to a standard 130 m^2 residential heat consumption of 18.1 MWh/year the DH network expansion thus fare equals more than 1.400 standard households.

In addition to this DH network expansion, work has also commenced on the renovation of on a 2nd reinjection well, which has been out of operation for the last 10 years due to abrasion damage. This is done in effort to ready the geothermal system for the establishment of the new geothermal extraction well. The renovation of the old reinjection well is planned finalized in 2012.

Since the commencement of the JI project in 2006 and up until the last Monitoring period ending 31/12 2011, the project has generated 55,455 tCO_2-e in verified emission reductions and is projected to have generated some 71 $ktCO_2$-e by the end of the first commitment period in 2012. The initial project potential stated in the PDD (version no. 3) was of approx.144 $ktCO_2$-e. Thus if this projection hold the project will only have generated half the emission reductions of if initial theoretical potential. There are several reasons for this difference between the project potential and the actual production, which I will list in the following.

CONCLUSION

In the introduction we asked a range of questions, we will try and answer these in the following.

Can DH systems benefit from the opportunities given by the flexible mechanisms?

The short answer is yes, but only under the right conditions. First off the EDGE JI project has up until 2011 generated 55,455 tCO_2-e and is projected to generate some 71,000 tCO_2-e by the end of the commitment period.

The exact carbon price of this project is subject to a non-disclosure agreement and cannot be listed here, but the ERU price in general have fluctuated between 6-12 € tCO_2-e over the duration of the commitment period. The costs of developing, monitoring and verifying JI project also fluctuate significantly from project to project, but in general cost for small scales projects can be set between 2-4 € tCO_2-e. Using these values on the Geotermia case we can evaluate the potential added income from the JI mechanism.

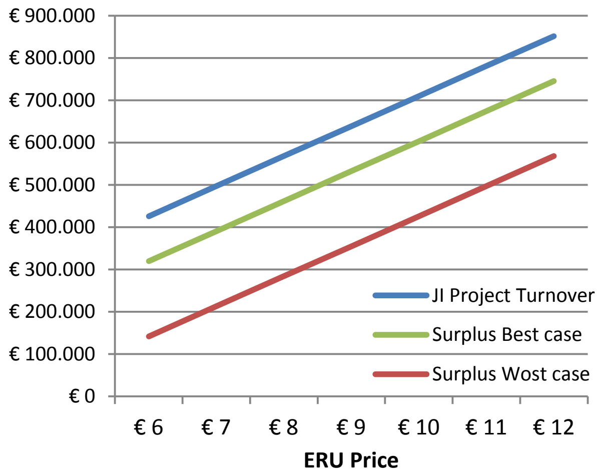


Figure 06 potential added income from a District Heating JI project utilizing data from the EDGE JI project for a full commitment period (2006-2012) at a fluctuating ERU price and fluctuating project cost price

As it can be seen from figure 06 the potential added income from the JI project is very sensitive to ERU price fluctuations and JI project cost fluctuations. The ERU price can however be stabilized through an Emission Reduction Purchas Agreement (ERPA) that locks the price at an agreed level for the duration of the commitment period.

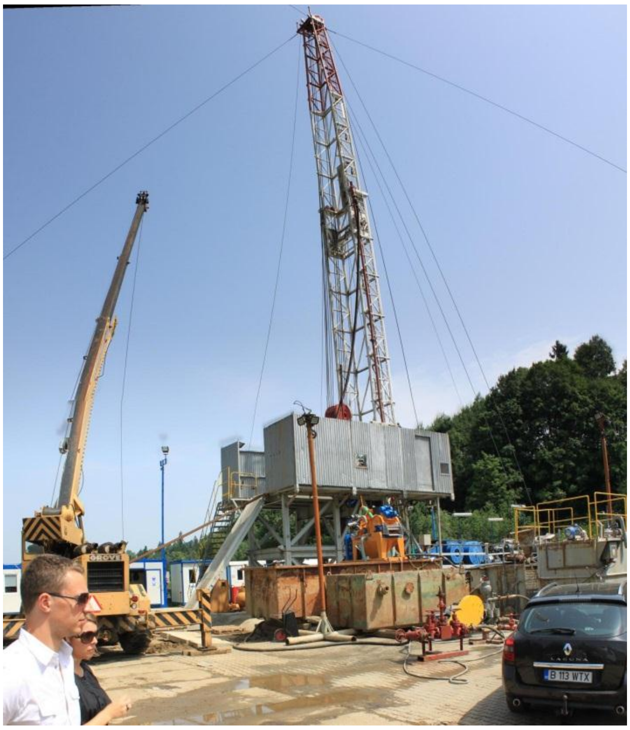


Image 01 one of the old derelict reinjection wells is being renovated in 2011, to ready the system for a new geothermal extraction well

The ERU price agreed upon in an ERPA is in general always lower than the prevailing market price for Carbon Credits calculated from the EU ETS market, at the time that the ERPA was entered into effect. If the EDGE JI project was to be plotted on the graph in figure 06, the project would be situated somewhat in the centre of the graph area.

At the market conditions throughout 2012 the carbon price has been at an all times low of 3-4 € tCO_2-e. This is mainly a result of the uncertainties related to the next commitment period. At this price level there is no room for the establishment of a DH based JI project.

What amount of Carbon Credits can the development of a DH system generate?

To gauge this we can plot the generation of ERU in relation to sales of heat in the EDGE JI project.

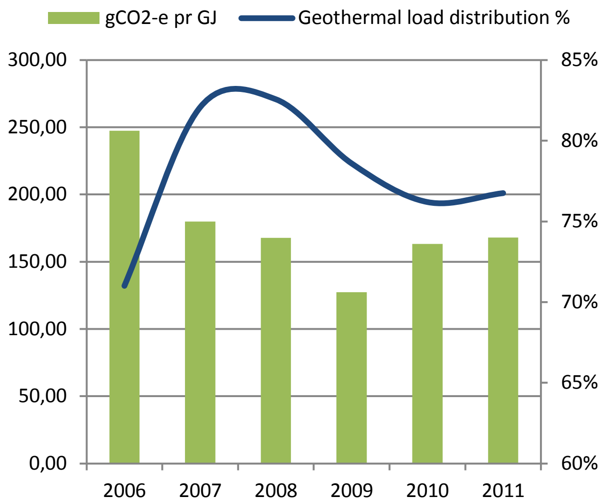


Figure 07 shows the relation between geothermal energy in the load distribution and the generation of ERUs pr. GJ DH. 2006 is off because it entails the start up of the project

If we exclude the year 2006, where the data of off because it was the start-up year for the project, we get and average ERU generation per produced GJ District Heating of 161 gCO_2-e pr. GJ District Heating sold on the Zakopane DH network. If we couple this with the heat consumption of a standard (Danish) household of 65 GJ/year, we get that the GHG emission reduction pr. House hold corresponds to 10.5 tCO_2-e a year.

Image 02 the old derelict coal boiler sits beside the new modern DH installation in a monastery in Zakopane

According to "Københavns Energi A/S" the main energy supply company in Copenhagen a standard household in Copenhagen fuel by an oil boiler emits some 5.33 tCO_2-e a year[vii], so in this respect a 10.5 tCO_2-e a year reduction seems worth the effort from a climate perspective.

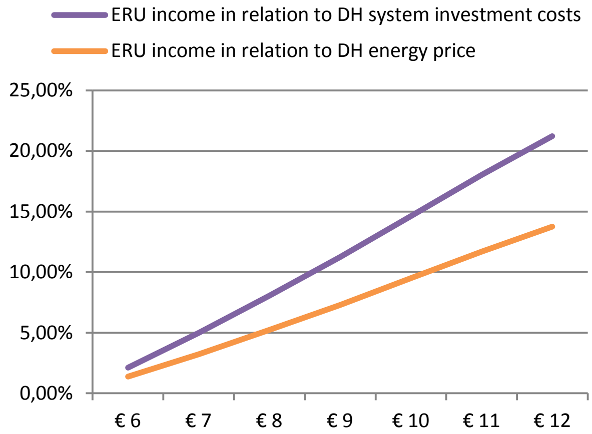


Figure 08 the graph shows a the impact of the JI contribution from sale of ERUs (worst-best case scenario) in relation to DH installation cost and DH energy price for a consumer in Zakopane.

In figure 08 the potential contribution from sale of ERUs in the worst worst-case scenario and the best best-case scenario, is compared to first to an approx. installation cost for the DH system for a consumer in Zakopane (a 6174 € investment amortized over 20 years at 5% interest) and second a DH price of 16.74 € GJ.

As it can be seen in figure 08 the impact of the potential contribution from JI emission reduction sales can be between 2.1-21.2% in investment costs, between 1.4-13.8% on energy purchases and between 0.8-8.3% on the total annual costs.

Of course combining the worst-worst and best-best case give you some large differences, but this also shows the importance of addressing the issue of ERU pricing and JI project costs if a Climate Project is to have any real effect. In the case of the EDGE JI project the theoretical impact is repentantly 10.8% on investments, 7.0% on energy costs and 4.3% on the total annual costs.

This of course should be viewed in reference to the investment costs associated with DH systems as a whole including the investment in new energy production facilities. E.g. in relation to the construction of a new geothermal extraction and reinjection system we are looking at investment cost around 5 m €.

Looking at the income componential from ERUs it is clear that Carbon Credits cannot support the expansion of a DH network and establishment of new production facilities on its own. For this the DH system and energy production facilities are to investment intensive. But the JI mechanism does functions well as support system for a DH network development.

The most important thing in reference to the accumulated generation of Emission Reduction Units is the expansion speed of the District Heating network. In the PDD it was expected that the geothermal DH energy could be expanded to the neighbouring town of Nowy Tag (see figure 03). This could have increased the thermal output of DH network with some 300.000 GJ.

However to achieve this expansion potential the CO_2-neutral energy production potential of Geotermia should increase, because at the current thermal capacity of the existing geothermal well of approx. 12 MW, any new the DH expansion would mainly be fuel by natural gas (see figure 09).

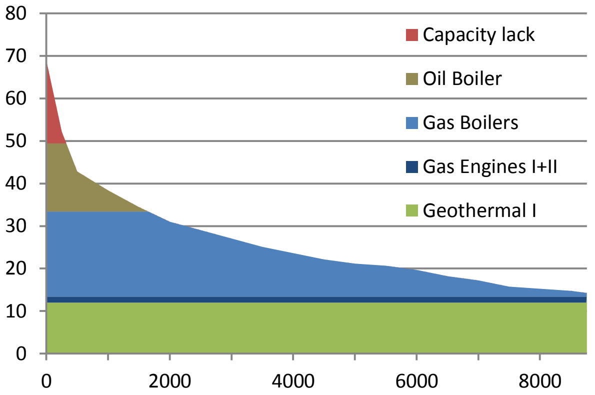


Figure 09 duration curve of 2020 DH expansion incl. Nowy Tag on existing plant portfolio

Under the condition sketched in figure 06 the load distribution will change substantially, where geothermal energy will decrease from 76.3 % to 46.7 % of the total production and natural gas would increase from 18.4 % to 40.8 % (gas engines excluded). As it can be seen in figure 07 the ERU generation pr. produced GJ is decreasing, as the load distribution becomes increasingly CO_2 intensive. Thus the tipping point for the continued development of the DH network in the Zakopane area becomes the continued "greening" of the DH supplier Geotermia's energy production facility portfolio.

The establishment of a new geothermal well have been part of the plan from the project initiation. However acquiring finance for the approx. 5 m € geothermal installation did prove more lengthy than anticipated. Coupled with the extensive delayed first payment of the JI project, the start-up activities, such as the renovation of a reinjection well, have not commenced before the middle of 2010.

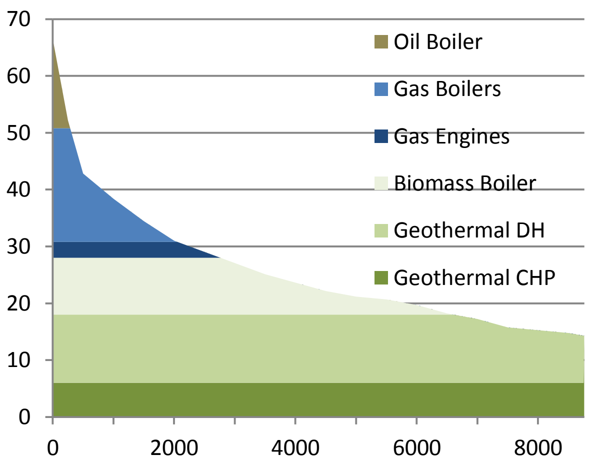


Figure 10 duration curve of 2020 DH expansion incl. Nowy Tag on a fully developed green plant portfolio

The planes for increasing the CO_2-neutral capacity of the production facilities in Zakopane are however under way. Figure 10 illustrated the initial development potential for CO_2-neutral energy supply in Zakopane including the neighbouring town of Nowy Tag.

The illustrated capacity increase would result in an 88% CO_2-neutral energy production, including the production of green electricity on geothermal energy.

Reflexion

The flexible mechanisms are definitely not perfectly in there design; the EU ETS is crippled by the massive surplus of emission allowances in the inventory, the CDM is hampered by high project development costs and rigid calculation methodologies and the JI has been hold back by the extensive legislative development the implementation of the mechanism calls for.

Putting these issues aside, it is still the opinion of this researcher that the positive development contributed by these mechanisms outweighs the negative in reference to institutional development in countries with no prior history for planning green energy systems, technology transfer and market development for green tech and green energy planning and financial support for the development of green energy systems.

In the battle against Climate Change the most additional way of developing our green energy systems is to develop them now and on as many locations as possible.

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ANALYSIS OF DIVERSIFICATION OF FUEL IN DH SOURCES. POTENTIAL OF REDUCTION OF GHG

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Keywords: District heating system, Fuel diversification, GHG reduction

ABSTRACT

For a variety of reasons, possibilities for reducing the use of expensive fossil fuel in central heat supply systems (CHSS) are currently being sought. One of the most effective solutions to this problem is the replacement of fossil fuels with cheaper renewable energy resources from local sources, in other words, diversifying energy resources in heat supply sources.

The paper describes a mathematical model developed by the authors that can be used to compare and evaluate (from the economic and ecological perspectives) various alternatives for the diversification of fuels, thereby facilitating a quick and justified decision for the most advantageous solution. Approbation of the method developed by the authors has been carried out on the boiler house in the village of Ādaži, Latvia.

INTRODUCTION

Energy efficiency measures are now being introduced more and more often in buildings. The goal of these improvements in energy efficiency is to reduce thermal energy consumption as much as possible. This means that in the future the demand for centrally produced thermal energy will decrease significantly, which will in turn lead to an increase in heat supply tariffs, because as the variable costs decrease, the impact of fixed costs on the tariffs will increase. One of the most effective solutions to this problem is to replace ever more expensive fossil fuel with cheaper local renewable energy resources, in other words, to diversify energy resources. Diversification of energy resources with renewable resources is a longterm solution that requires a serious approach to developing and implementing a longterm development strategy. Experience shows that the time and financial means invested in such measures is justified. By diversifying fossil fuels with renewable energy resources it is possible to at least partly solve serious problems of the 21st century, namely, how to decrease carbon dioxide emissions, how to ensure a more stable heat supply, and how to promote the use of local biomass, which lessens dependence on imported fossil fuels.

Such diversification of fuels in central heat supply sources is one of the most effective and least expensive instruments available to reach the climate change goals set by the European Union and Latvia.

The paper examines options for the diversification of fossil fuels by partly replacing them with various types of biomass fuel. The goal of the paper is to develop a method for the analysis of energy resources and the approbation of the method on the boiler house in the village of Ādaži, Latvia.

METHOD OF ANALYSIS OF FUEL DIVERSIFICATION

In analysing the diversification of fuel in boiler houses of central heat supply systems, it is important to find not only the optimal economic solutions, but also to pay close attention to their impact on the environment and climate. This method was therefore developed in such a way that it may help assess and compare various types of fuel diversification from both the economic and ecological perspectives.

To this end, an algorithm was developed with which it is possible to analyse various alternatives of fuel diversification in specific boiler houses. The diversification analysis algorithm can be seen in Fig. 1.

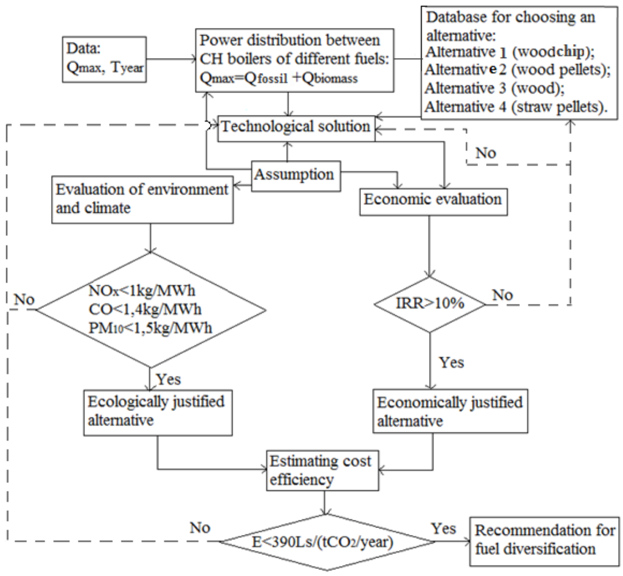

Fig. 1 Diversification of fuel analysis algorithm

The algorithm consists of the following eleven blocks, or modules:

- raw data;
- distribution of capacity between boilers burning different fuels;
- database for choosing an alternative;
- technological solution;
- assumptions;
- evaluation of environment and climate;
- economic evaluation;
- ecologically justified alternative;
- economically justified alternative;
- estimating cost efficiency;
- recommendation for fuel diversification.

Module 1. Raw data

An analysis of fuel diversification begins with an evaluation of the consumer heat load. Based on the amount of heat energy needed by consumers, an optimal capacity for the biomass technology is chosen. A heat load duration curve of the boiler house is entered into the model as raw data; this shows the maximum heat load capacity requirement (Q_{max}) and the number of hours of heat energy demand over a year's time ($T_{h/year}$).

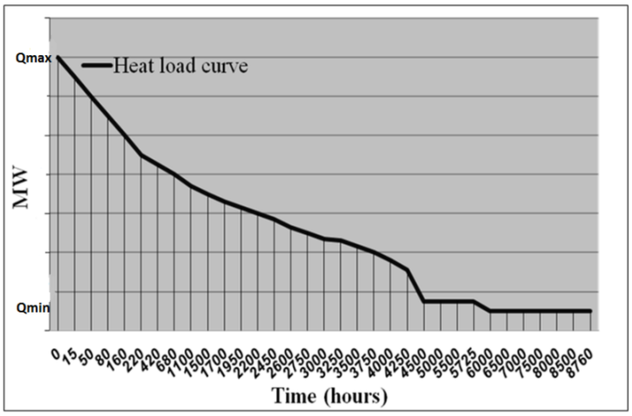

Fig. 2 Heat load duration curve

Figure 2 shows a heat load duration curve that depicts the heat load and demand for it in the heat supply system by the hour over a year's time. This curve shows that the maximum heat load (Q_{max}) is only 15 hours per year and the hot water load during the summer (Q_{min}) is approximately 3840 hours per year.

Module 2. Distribution of capacity between boilers burning different fuels

An evaluation of the heat load curve will determine the required capacity for the biomass boiler needed for the diversification of the boiler house presently burning fossil fuel. This is described by the formula:

$$Q_{max} = Q_{fossil} + Q_{biomass} \quad (1)$$

where

Q_{max} – total thermal energy capacity for the boiler house (MW);

Q_{fossil} – capacity of fossil fuel facility (MW);

$Q_{biomass}$ – planned capacity of biomass boiler (MW).

The summer heat load must be taken into consideration when analysing Figure 2, because this is essential in choosing the necessary boiler capacity. If the boiler house also provides for the summer heat load and if it does not have a cogeneration station installed, then an evaluation of the installation of two biomass boilers is suggested, because the efficiency of a boiler working with a relatively small heat load decreases. Therefore, this module must determine the optimal diversification alternative for both the distribution of capacity in regard to fossil fuel and also the distribution of capacity between the biomass boilers.

The method developed in this paper proposes the use of the specific load indicator MW/MW. The specific biomass boiler load is determined by applying the actual biomass boiler capacity to the installed biomass boiler capacity. The calculation for the specific load of the biomass facility is [1]:

$$q = \frac{Q_{act}}{Q_{inst}}, \frac{MW}{MW} \quad (2)$$

where

q – specific load of biomass boiler, MW/MW;

Q_{act} – actual capacity of biomass boiler, MW;

Q_{inst} – installed capacity of biomass boiler, MW.

The indicator defines how burdened the biomass boiler is during the heating season. The nearer the value of q is to 1, the more burdened is the biomass boiler.

Module 3. Database for choosing an alternative

Usually three to five alternatives are chosen in order to achieve a valid comparison. The model provides four renewable fuel alternatives for diversifying fossil fuel with renewable fuels:

- Alternative 1 – woodchips;
- Alternative 2 – wood pellets;
- Alternative 3 – wood logs (firewood);
- Alternative 4 – straw pellets.

Several factors must be taken into account when choosing an alternative:

- the availability and price of the fuel;
- the moisture content of the fuel (%);
- the lowest heat of combustion of the biomass (MWh/t);
- opportunities for the automation of the process.

Module 4. Technological solution

In choosing a technological solution between several engineering alternatives, the economic and ecological criteria must be taken into account. When evaluating and calculating this module, attention must be paid to the location of the boiler house, the surrounding area, the total area of the boiler house, the efficiency of the facility at various heat loads, and the quantity of fuel needed. The technological solution for each boiler house must be calculated individually.

Module 5. Assumptions

To simplify the calculations, the following assumptions are put forth:

- NO_x, CO, PM_{10}, and CO_2 emissions factors (g/kg);
- consumption of electricity (kWh_{el}/MWh);
- employee compensation calculated according to technological solution (LVL/month);
- fuel costs at current market prices (LVL/t);
- moisture content of biomass (%);
- highest heat of combustion of the fuel (MWh/t);
- ash content of biomass (%).

Module 6. Evaluation of environment and climate

Climate and environment indicators, which are determined by emissions in the air, are considered when evaluating energy resource diversification projects.

One of the goals of diversification is to reduce carbon dioxide emissions. As fossil fuels are diversified, carbon dioxide emissions are reduced because local biofuels are considered CO2 neutral due to the carbon dioxide emitted when burning biomass taking part in natural processes.

Therefore, the energy resource diversification process can be characterised by the following climate indicators [3]:

- amount of carbon dioxide over one heating season – t_{CO2}/year;
- amount of carbon dioxide compared to the amount of thermal energy produced – t_{CO2}/MWh_s.

The absolute climate indicator t_{CO2}/year is one of the essential indicators that characterises the results of the energy resource diversification project. This indicator describes the carbon dioxide savings achieved from replacing fossil fuel.

The indicator value t_{CO2}/year is determined in two ways: according to thermal energy produced or according to the consumed amount of fuel.

The calculation according to produced thermal energy can be performed using the following formula [4]:

$$CO_2 = \frac{(E_{CO_2} \cdot Q_{sar.})}{\eta} \tag{3}$$

where

CO_2 – amount of carbon dioxide savings over one heating season, t_{CO2}/year;

E_{CO2} – CO_2 emissions factor for fuel, t_{CO2}/MWh;

$Q_{sar.}$ – amount of thermal energy produced, MWh/year;

η – technology efficiency.

The value of this indicator can also be determined according to the amount of fuel consumed in one year [4]:

$$CO_2 = B \cdot Q_z^d \cdot E_{CO_2} \tag{4}$$

where

CO_2 – carbon dioxide emissions, t_{CO2}/year;

B – amount of consumed fuel, t/year;

Q_z^d – lowest heat of combustion for fuel, MWh/t;

E_{CO2} – CO_2 emission factor (fuel emission factor), t_{CO2}/MWh.

Depending on what fossil energy resource is diversified with what biofuel, the actual amount of harmful emissions can both decrease as well as increase. Therefore, the use of environmental indicators can firstly compare the various biofuels with each other according to amounts of harmful emissions the produce. When comparing biofuels, SO_x emissions are not taken into account because sulphur content in biofuels is negligible. Sulphur emission content is determined in order to judge the possible impact of the emissions on the metal parts of biomass boilers, because such emissions can promote corrosion of biomass boilers [2].

The actual indicator values t_{NOx}/year, t_{SOx}/year, t_{CO}/year, $PM_{2.5}$/year, and tPM_{10}/year are determined by the formulas [4]:

$$CO = B \cdot E_{CO} \tag{5}$$

$$NO_x = B \cdot E_{NO_x} \tag{6}$$

$$SO_x = B \cdot E_{SO_x} \tag{7}$$

$$PM_{10} = B \cdot E_{PM_{10}} \tag{8}$$

$$PM_{2.5} = B \cdot E_{PM_{2.5}} \tag{9}$$

where

CO – amount of carbon dioxide produced over one heating season, tCO/year;

NO_x – amount of nitric oxide produced over one heating season, tNO_x/year;

SO_x – amount of sulphur oxide produced over one heating season, tSO_x/year;

$PM_{2.5}$, PM_{10} – amount of particulate matter produced over one heating season, $tPM_{2.5}$/year and tPM_{10}/year;

B – amount of consumed fuel, kg/year;

E_{CO}, E_{NOx}, E_{SOx}, E_{PM10}, $E_{PM2.5}$ – emission factors, g/kg.

The required amount of fuel (B) is determined according to Formula 10 [3]:

$$B = \frac{Q_{sar.}}{(\eta \cdot Q_z^d)} \tag{10}$$

where

B – amount of biofuel, kg;

$Q_{sar.}$ – amount of thermal energy required, kWh;

η – boiler efficiency;

Q_z^d – lowest heat of combustion for fuel, kWh/kg.

Module 7. Economic evaluation

In order to implement the diversification of fossil fuel with renewable energy resources, certain financial resources must be invested in the project. The size of the investment depends on the diversification alternative chosen.

When investments are applied to the annual carbon dioxide savings, the result is the indicator LVL/(tCO_2/year), which is called investment efficiency. This indicator determines how much money must be invested in the project in order to decrease carbon dioxide emissions by one ton per year. The investment efficiency indicator is used to decide which alternatives are cheaper and which ones are more expensive means of decreasing climate change [3], [5].

Internal rate of return (IRR) values for seven and fifteen years with the goal of defining the percentage of profit from investments can be determined from the definition of investments, savings, and specific cost.

Modules 8 and 9. Ecologically justified alternative and economically justified alternative

Economic and ecological evaluations are equally important in the fuel diversification algorithm. If one of these modules does not correspond to the criteria put forth, other alternatives must be chosen.

Criteria for an ecologically justified alternative:

- NO_x<1 kg/MWh
- CO<1.4 kg/MWh
- PM_{10}<1.5 kg/MWh

A system generating a 10% profit in its seventh year indicates an economically justified alternative.

Module 10. Estimating cost efficiency

Alternatives are compared according to investment efficiency, that is, invested financial resources to the annual quantity of carbon dioxide savings. The criteria put forth is E<390 LVL/(tCO_2/year).

Module 11. Recommendation for fuel diversification

The best alternative for the boiler house from both the economic and ecological perspective is chosen.

APPROBATION OF FUEL DIVERSIFICATION EVALUATION METHODS

An approbation of the fuel diversification evaluation method is performed on the boiler house in Ādaži, Latvia. Ādaži is located in Ādaži District, 25 km northeast of Riga. The population of Ādaži District is 9900. Thermal energy in Ādaži District is produced in both a centralised system and local heat sources as well as in individual heating systems.

The graph of the heat load of the central heat supply system (CHSS) in Ādaži village is entered into the raw data, and this results in a maximum capacity of 4 MW for the required heat load. The entire maximum heat load requirement is provided by fossil energy resource technologies: a cogeneration station with a thermal energy capacity of 0.5 MW and two water heater boilers with a combined capacity of 3.5 MW. The heat load curve shows that the cogeneration station thermal energy load is the primary load (0.5 MW). This factor must be taken into account when choosing capacities for biomass systems. If the CHSS has a cogeneration station, then priority will always be given to the cogeneration heat load.

The optimal biomass boiler capacity is chosen according to the heat load curve. Three capacity variants are chosen:

- biomass boiler with 1 MW capacity;
- biomass boiler with 1.5 MW capacity;
- biomass boiler with 2 MW capacity.

The capacities put forth are tested with the specific load indicator MW/MW offered by the method. According to the calculations, a biomass boiler with 1 MW capacity will receive enough of a burden, because the specific load indicator is 0.92 MW/MW.

The following load distribution is further put forth for the diversification of fuel in the Ādaži boiler house:

$$4MW = 0.5MW(cog.) + 2.5MW(gas\ fuel) + 1MW(biomass\ fuel) \quad (11)$$

At this load distribution, the biomass boiler will produce 4724 MWh of thermal energy annually (calculated according to the heat load duration curve for the Ādaži village boiler house).

In studying and analysing the factors put forth by the method, four alternatives have been suggested:

1. woodchips with a moisture content of 40% – 2.79 MWh/t;
2. wood pellets with a moisture content of 10% – 4.6 MWh/t;
3. wood logs with a moisture content of 40% – 2.84 MWh/t;
4. straw pellets with a moisture content of 15% – 4.0 MWh/t.

The fact that the biomass boilers must be partially automated, so that the constant presence of an employee in the boiler house is not needed, has been taken into account when choosing an alternative. After analysing this fact, it was concluded that the wood logs alternative is not suitable for the fuel diversification project at the Ādaži boiler house.

In choosing a technological solution for the Ādaži boiler house, several factors have been taken into account:

- the space available in the boiler house for the new project is quite limited;
- the boiler house is located 300 metres from the residential houses;
- the area around the boiler house is quite small.

After considering the moisture content of the biofuels, their lowest heats of combustion, and the biomass boiler efficiency, the amount of biofuel required to produce 4724 MWh/year of thermal energy was calculated (see Table 1).

Table 1. Required quantity of biomass, per year

Alternatives	Quantity of biomass, tons/year
Wood pellets	1141
Woodchips	1924
Wood	2079
Straw pellets	1312

Table 1 shows that the least amount of wood pellets is required – 1141 tons per year – because wood pellets have a low moisture content, a high boiler efficiency, and the highest lowest heat of combustion.

Several assumptions were put forth in evaluating the diversification of the Ādaži boiler house in order to simplify the calculation process. As seen in Table 2, assumptions have been made based on information available in books and the experience of experts.

Table 2. Assumptions

Alternatives	Fuel purchase costs, LVL/t and LVL/m^3	Electric energy consumption, kWh_{el}/MWh_h	Moisture content %	Heat of combustion MWh/t	Ash content %	PM_{10} g/kg	NO_x g/kg	CO g/kg
Wood pellets	100 LVL/t	7.47	10	4.6	0.3	1.55	3.93	4.8
Woodchips	7.20 LVL/m^3	25	40	2.79	5	2.15	0.99	2.7
Straw pellets	85 LVL/t	8.7	15	4	7	9	3.39	30

For example, the 7.20 LVL/m³ cost of woodchips is assumed based on surveys of CHSS experts who are directly associated with the management of woodchip boiler houses.

RESULTS

Four different fuel diversification alternatives for the Ādaži boiler house have been evaluated with the help of the developed method.

Figure 3 shows the heat load duration curve in Ādaži village. The heat load curve shows that the cogeneration station thermal energy load is the primary load (0.5 MW). This factor must be taken into account when choosing capacities for biomass systems.

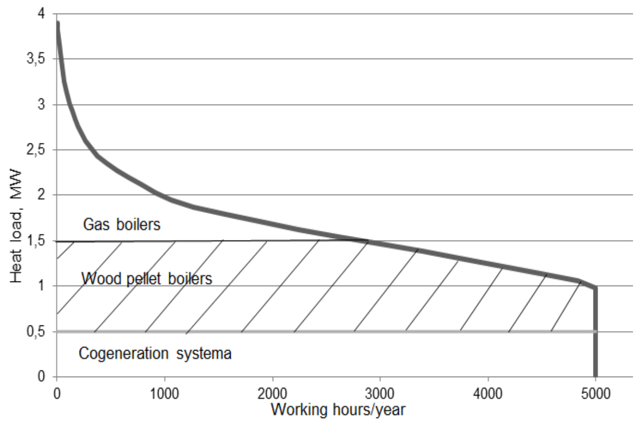

Fig. 3 Distribution of Ādaži boiler house capacity in the heat load duration curve

A maximum heat load capacity requirement of 4 MW is determined according to Figure 3. According to calculations, a biomass boiler with 1 MW capacity will be burdened enough, because the specific load indicator is 0.92 MW/MW.

Figure 4 shows the calculated emission amounts generated from the production of 4724 MWh of thermal energy from the fuels examined.

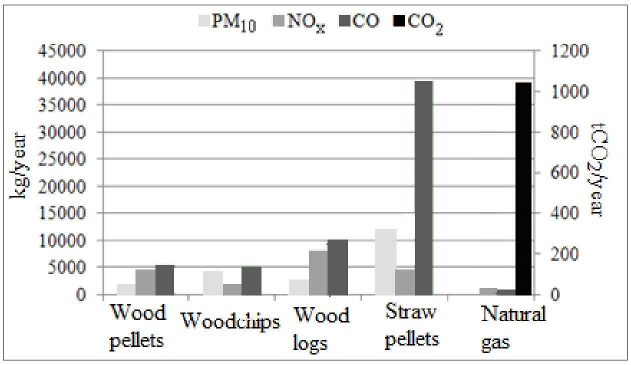

Fig. 4 Emission amounts from natural gas and alternative fuels

Straw pellets produce the most harmful emissions, especially carbon monoxide (39360 kg/year) and particulate matter (11808 kg/year). The large amount of CO is explained by the high ash content typical of straw. The straw pellet becomes covered with ash during the combustion process, which in turn decreases oxygen flow to the pellet, thereby creating a CO emission, which is the result of incomplete combustion. The high particulate matter content can be explained by the same ash content mentioned above as well as by the addition of mineral substances that are created during the harvesting of the straw from the field [6].

In the case of wood pellets, woodchips, and wood logs, the amount of particulate matter and carbon monoxide emissions is considerably lower than for straw pellets, although more nitric oxide is created from wood pellets and wood logs than from straw. For example, the burning of wood pellets creates 6.7 times less particulate matter, 7.2 times less carbon monoxide, and 2 times more nitric oxide. It can thus be declared that these three types of wood fuels are cleaner from an environmental perspective than straw pellets. However, when these three wood fuels are compared to each other, wood pellets and woodchips are at an advantage over wood logs because the burning of wood logs produces the most CO and NO_x.

When natural gas and biofuels are compared, it can be concluded that the burning of natural gas creates practically no particulate matter (see Figure 4), and therefore carbon monoxide, carbon dioxide, and particulate matter emissions are increased as the result of diversification. The increase in harmful emissions in the case of wood fuels is lower than for straw pellets. For example, when wood pellets are compared to natural gas, the increase in CO is 4.7 t/year, the increase in NO_x is 3.6 t/year, and the increase in PM10 is 1.8 t/year. When straw pellets are compared to natural gas, the increase in CO is 37 t/year, the increase in NO_x is 3.6 t/year, and the increase in particulate matter is 11 t/year. But the total increase in harmful emissions from each alternative is insignificant compared to the decrease in carbon dioxide achieved (1044.14 tCO_2/year), which can be obtained by implementing the diversification of natural gas with wood pellets, woodchips, or straw pellets.

In order to perform an economic analysis of each alternative and to compare them to each other, it is first necessary to determine the capital investment needed for each alternative. Capital investments include the financial resources needed to install the systems and adapt the boiler house.

Table 3 shows the initial investments needed for each alternative:

Table 3. Capital investments

Capital investments	**Alternative 1**		**Alternative 2**		**Alternative 3**	
	Number	**Ls**	**Number**	**Ls**	**Number**	**Ls**
Biomass boiler	2	72287	1	61000	2	109367
Fuel storage bunker	20000		-		20000	
Fuel storehouse	-		35 000		-	
Engineering communication	96 610		275 388		96 610	
Tractor	-		28 000		-	
Ash storage containers	2	612	2	612	4	1224
Capital investments, Ls	189 509		400 000		227 201	

The costs in Table 3 for biomass boilers, fuel/pellet storehouse, tractor-excavator, and ash storage containers are determined according to actual prices.

The size of savings from each alternative can be seen in Table 4. The greatest savings from the diversification project are obtained from a transition to biomass.

Table 4. Savings

Alternatives	Savings from reduced emissions, LVL/year	Savings from transition to biomass, LVL/year	Total, LVL/year
Alternative 1	931	39 213	40 144
Alternative 2	871	107 137	108 008
Alternative 3	694	41 793	42 487

The savings are greatest (107 137 LVL/year) in the case of woodchips because, when compared to wood logs and straw pellets, woodchips are the cheapest biofuel.

Savings from decreased emissions do not differ much between the wood fuel alternatives, although their difference when compared to straw pellets is significant, because straw pellets create the greatest amount of harmful emissions (see Fig. 4).

Table 5 shows a comparison of diversification alternatives according to cost per MWh of thermal energy produced. Capital investments have not been taken into account in the cost analysis calculations.

Table 5. Cost analysis

Costs LVL/MWh	Alternative 1	Alternative 2	Alternative 3
Biomass purchase costs Ls/MWh	24.15	9.77	23.61
Natural resources consumption tax LVL/MWh	0.07	0.08	0.12
Biomass boiler maintenance LVL/MWh	0.30	0.53	0.61
Land lease LVL/MWh	-	0.15	-
Electric energy consumption LVL/MWh	0.75	2.53	0.88
Total costs, LVL/MWh	25.27	13.06	25.22

The woodchip alternative stands out in Table 5 with its cost of only 13.06 LVL/MWh. The production of thermal energy from woodchips is almost two times cheaper than from straw or wood pellets. Capital investments, however, must also be calculated into this thermal energy cost.

The internal rate of return (IRR) values for seven and fifteen years with the goal of defining the percentage of profit from investments is calculated after the definition of capital investments, savings, and specific costs (see Fig. 5).

Fig. 5 Internal rate of return

In evaluating the alternatives for diversification for the Ādaži boiler house, the same amount of attention has been paid to evaluating the situation from an ecological as well as an economic perspective.

In calculating the amounts of harmful emissions attributable to the amount of thermal energy produced, it was concluded that carbon monoxide (CO) from straw pellets exceeds the amount defined by the method (CO<8.33 kg/MWh). Straw pellets as an alternative are therefore rejected.

In calculating the criteria of an economically justified alternative, it was concluded that woodchips and wood pellets are the most economically advantageous alternatives.

Considering that the Ādaži boiler house diversification project has limited financial resources, criteria E was set at <250 LVL/(tCO_2/year).

Figure 6 shows the effectiveness of investment costs compared to the decrease in carbon dioxide achieved. Considering the limited finances of the project, the woodchip alternative cannot be realistically implemented because E<383 LVL/(tCO_2/year). See Figure 6.

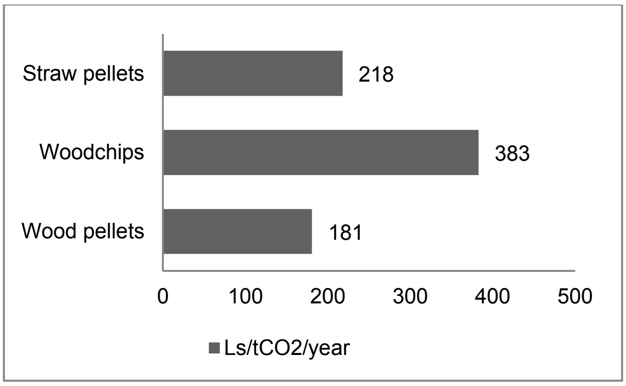

Fig. 6 Effectiveness of investment costs

The calculations in Figure 6 show that, considering the effectiveness of investment costs compared to the decrease in carbon dioxide achieved, the most advantageous alternative for the Ādaži boiler house project is to implement a wood pellet heating system.

In evaluating the technological solution for the Ādaži boiler house and the efficiency of a wood pellet boiler compared to the heat load, a decision has been made to install two pellet boilers, each with a capacity of 0.5 MW.

The following capacity distribution is put forth for fuel diversification in the Ādaži boiler house:

$$4MW = 0.5MW(cog.) + 2.5MW(gas\ fuel) + 0.5MW(1\ biomass\ boiler) + 0.5MW(2\ biomass\ boiler) \quad (12)$$

The results of an evaluation of four different fuel diversification alternatives for the Ādaži boiler house performed with the help of the method described in this paper confidently show that the most effective solution is to use wood pellets.

CONCLUSION

1. The paper demonstrates that the developed evaluation algorithm for energy resource diversification alternatives works well and can be applied to the evaluation of energy resource diversification. With this algorithm is it possible to choose the most ecologically and economically advantageous alternative that is best suited to a specific energy source.

2. In applying the developed method for the evaluation for fuel diversification, each energy source must be evaluated separately, because each boiler house is unique, for example, in its geographic location, its size, its heat load duration curve, etc.

3. Diversifying natural gas with biofuel results in a significant decrease in carbon dioxide, although the amount of harmful emissions (NO_x, PM_{10}, CO) increases slightly. The decrease in carbon dioxide of 1044 t CO_2/year is considerably more significant than the increase in the other harmful emissions. In the case of wood pellets (10% moisture content), harmful emissions increase by 10 t/year; in the case of woodchips (40% moisture content), they increase by 9.6 t/year; in the case of wood logs (40% moisture content), they increase by 19 t/year; and in the case of straw pellets (15% moisture content), they increase by 54 t/year.

4. The use of wood fuel is more ecologically and economically effective than the use of straw pellets, because the burning of straw pellets results in four to seven times more carbon monoxide and particulate matter, and straw pellets are less cost-effective (the longest repayment period and the lowest internal rate of return).

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VARIATION IN CO_2 EMISSION CAUSED BY APPLICATION OF DIFFERENT BIOMASS IN COMBINED HEAT AND POWER PLANTS WITH DISTRICT HEATING

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Keywords: CO_2, CHP, Biomass, Biogenic

ABSTRACT

Case studies carried out for Combined Heat and Power (CHP) plants and CHP's connected to district heating grid show a significant variation of CO_2 emissions associated to production and delivery of 1 kW/h heat caused by variations in biomass quality.

Differences in biomass moisture content, energy density and transporting distance contribute to differences in CO_2 and Primary Energy (PE) values and should be taken into account when calculating the environmental impact of different biofuels.

Lately, another issue have risen; shall biogenic CO_2 emissions also be included in the assessment? The contribution from delayed CO_2 removal from the atmosphere depends on the crop rotation period for biomass. Together with high moisture content a long rotation period might increase the CO_2 emissions from biomass CHP to 75 g CO_2/kWh.

Today, the lack of unambiguous standardization prevents a reliable comparison of energy solutions and opens up for creative calculations of PEF-values as well as CO_2-equivalents, due to the use of different systems boundaries and quality of the biomass.

In this case study different types of biomass are utilized as the energy source for heat delivered from a CHP plant to a predefined district heating grid with seasonal adjusted flow, supply and return temperatures.

INTRODUCTION

During the last decades increasing focus has been put on reduced use of fossil fuels, increased use of renewables and increased energy efficiency. Recent data from IEA [1] indicates that in order to prevent a more than 2K increase in the average global temperature, use of biomass might contribute substantially to the needed 17% increase in energy production from renewables. Another important issue for EU is the need for reliable delivery, which might not be met by fluctuating import.

Concurrent, the energy needed for extraction of oil is increasing [2]. From 1996 to 2010 the energy return on (energy) investment (EROI) has decreased from 59:1 to 40:1, excluding energy for transportation and refining.

This demonstrates the need for utilization of other renewables. As Table 1 shows, the shares of biomass vary between different regions. A large potential for an increased use in Europe exists, even though several studies indicate large variations in potential biomass. Estimates for year 2100 vary from 100 EJ/year to 4500 EJ/year, depending on calculation methodology and possible growth in energy crop production [3]-[9]. Future production estimates for 2050 vary between 50 to 450 EJ. In a review study [3] the potential share of biomass in different regions is estimated to be between 2 to 44%.

Table 1 Share of biomass in different regions based on studies [1], [3]-[9], carried out in the period 2005-2010

Region	**Use of biomass** [TWh/year]	**Biomass use of total [%]**	**Unused potential** [TWh/year]
North America	861	2.7	5528
Europe	556	3,5	2427
Latin America	722	18,2	5972
China	n.a.	23.5	
East Asia	n.a.	25.1	
South Asia	n.a.	56.3	
Asia	6444	n.a.	6000
Middle East	0.0	n.a.	194
Former USSR	139	n.a.	2778
Africa	2306	60	5944
Sum world	39.7-45	8.7	28833

Even though the potential seems large, energy efficiency measures should be implemented, to reduce primary energy consumption and CO_2 emissions.

Biomass as fuel can be produced by different means. In this study only the most relevant biomass types for the Nordic marked are examined. The intention with this study is not to carry out a Life Cycle Assessment (LCA) for a specific fuel, but to show how variations in basic characteristics will influence on the PE, Primary Energy Factor (PEF) and CO_2 emission values for a CHP connected to a district heating grid.

STANDARDS AND METHODS FOR CALCULATION OF CO_2 EMISSION AND PRIMARY ENERGY

In order to increase the utilization of biomass for both heating and power production in Europe, different EU strategies, directives and legislations have been enforced.

The most important are; The “Energy Performance of Buildings Directive” (EPBD) [12], The “Renewable Directive” [13] , The “Cogeneration directive” [14] and the new proposed “Energy Efficiency Directive” [15] with their appurtenant standards as the EN-15603 [16] and the EN 15316-series [17].

Today, several committees, especially the CEN TC 371 are working with harmonization of the existing standards and thereby to implement the legislation. A total of 42 standards (31 EN and 11 EN/ISO) related to EPBD were published in 2007-2008 [18].

The “Energy Performance of Building Directive” (EPBD) [12] states that the energy performance of a building shall be expressed by a numeric indicator of primary energy use. Primary energy factor for a specific fuel is defined to include all energy that is needed to extract, transport, process, transform and store the energy carrier until it is delivered as 1 kWh power or heat to the end user. Whilst the previous version of EPBD [19] and EN 15603 [16] also included a similar calculation for CO_2-equivalents [12]. Today, there exists no standardized database that enables a direct comparison of PEF and CO_2 emission between different biofuels like biomass, wood logs, wood chips, pellets and waste delivered from different producers. A selection of energy carriers are described in EN 15603 [16], but the lack of detailing level might prevent utilization of the most environmental friendly energy carriers locally since all values in the standard are based on average European values.

A systems approach of describing bioenergy systems is developed in [20] with the intention of making a standardized method that enables comparison of greenhouse gas emissions (GHG) from bio and other non-renewable energy system. This method indicates a need for detailed calculation, where Life Cycle Assessment (LCA) in later studies has been the preferred tool.

EN 15603 also states that transport could be included in the inventory, but this is to be decided by each nation. Several studies have shown the impact of transport which might contribute up to 20% of the CO_2 emissions [21]-[22].

The EN 15316-series [17] further introduces the power bonus method. In order to promote CHP, the environmental impact of produced heat will be reduced by the assumed impact of exported power. This means that the PEF and CO_2 values for heat will include energy for exploitation, transporting, processing, utilization and storage subtracted the PEF and CO_2 from replacement of the exported power. Different countries might apply different values for the substituted power, since the exported electrical power is multiplied with a PEF that might vary between 1.5 to 4.05 per kWh depending on the production method of the substituted power. A detailed description of this calculation method is shown in [25] and [26]. Notice, that the power bonus could only be utilized for CHP when heat is the base load.

In the renewable directive [13] the calculation methodology includes even more parameters like, reduced emission from possible soil carbon capture, and annualized emissions from carbon stock changes caused by land-use change.

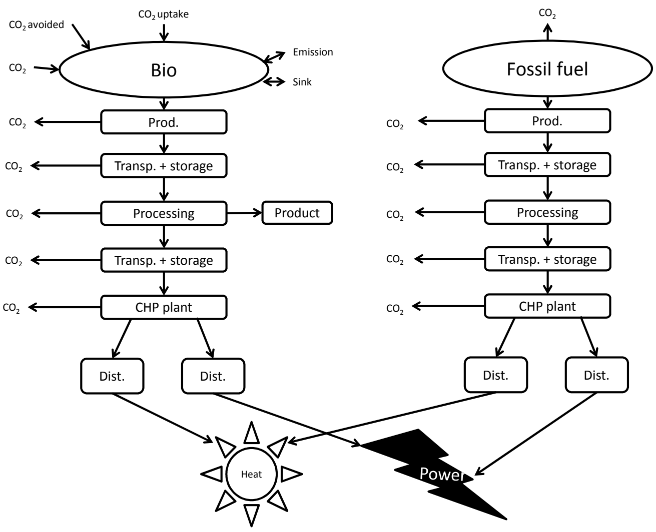


Figure 1 Comparison of CO_2 emissions from bio and fossil fuel chains based on [14] and [20].

Main differences between bio chains and fuel chains are illustrated in Figure 1, including the possible absorb CO_2 during growth, avoided emissions from soil carbon accumulation, carbon capture, geological storage and savings from excess electricity from cogeneration.

Recent studies of biogenic CO_2 [27]-[30] demonstrate that the actual emission from biomass is dependent on rotation length of the crop, see Figure 2. Short term biomass production might depending on, crop, localization, fertilization needs, transporting distance, processing level and storage, be considered almost CO_2 neutral. Slow growing crops like forest might never reach CO_2 neutrality. Other studies [29] have in addition shown that the albedo effect might influence on those emissions. Crops grown at high latitudes might reduce the CO_2 emissions due to a larger period of snow covered cutting areas and thereby increased albedo effect. One study [28] describes three different methods for CO_2 accounting, a) biogenic CO_2 as zero, b) partly included depending on production method or c) as a system where all Carbon flows are accounted.

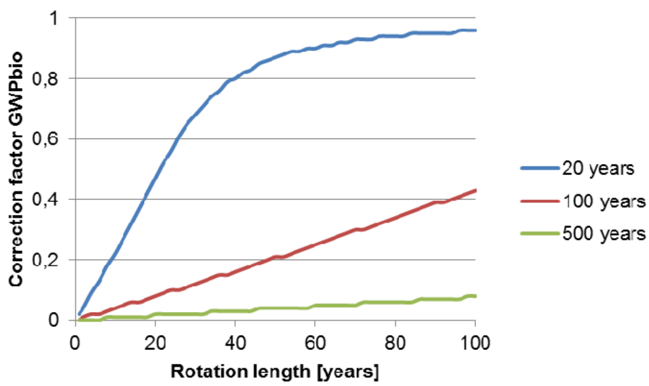


Figure 2 Example of GWP for biomass with different rotation length based on [30]

The different studies mentioned above are not totally in accordance with the pre-accepted fact, that use of biomass will not emit CO_2. Therefore, studies based on that assumption will not be coherent [32]. Figure 1 shows possible steps to be included in the balance.

COMPARING THE ENVIRONMENTAL IMPACT

At present, the variety of methods developed to describe the environmental impact of different products, processes and systems might distort the comparison. Ecological footprint, embodied carbon footprint, carbon calculation, low carbon, 100% renewable and different phrases with the prefix green, for instance green labelling, are used to describe the environment-friendliness of a product or a process. This diversity of methods and parameters cause confusion both among scientists, politicians, decision-makers and the public since they are all used at the same time and no formal link or conversion factor exist between the different methods. As a result, different approaches will provide different values for both CO_2 and PEF.

Today, well-documented studies are based on Life Cycle Assessments (LCA) with a cradle to grave perspective. A set of superior standards are developed for example the EN-ISO 14040 [33] and EN-ISO 14044 [34].

Another method to conduct the LCA of a system is The Environmental Product Declaration method (EPD) where so-called PCR's (Product Declaration Rules) describe in more detail how a LCA for a specified system should be carried out. This include; system boundaries, what processes to be included, cut-off rules and how to divide the environmental burden between different inputs and products see, CPC 171; Electrical Energy [35], CPC 173; Steam and hot Water [36].

At present several methods for performing the LCA of a product or process exist. Some of the most applied are CML 2001, Cumulative energy demand, Cumulative exergy demand, Eco-indicator 99, Ecological footprint, Ecological scarcity 1997 and 2006, Ecosystem damage potential, IMPACT 2002+, ReCiPe (Midpoint and Endpoint approach), TRACI and USEtox.

In addition the IPCC 2001 (Intergovernmental Panel on Climate Change) and IPCC 2007 provide numbers/ weighting factors for some of the most relevant parameters which enable a comparison of GHG with CO_2, based on the global warming potential (GWP) of the different gases. Thus, a CO_2 equivalent is developed which consists of emissions from CO_2, NO_2 and CH_4. Other gasses may also have an impact, but those are presently not included in the CO_2 equivalent.

Weighting factors for green house gas (GHG) will depend on the chosen methodology [38][39]. Application of different impact categories such as; climate change, ozone depletion, acidification, human toxicity, eco-toxicity, toxicity might have different weighting.

For all LCA it is imperative to describe which method is utilized, since different weighting factors are applied; Usually IPCC values are applied where, CO_2 equals 1, methane (CH_4) = 25 and NO_2 has a GWP of 298.

Production of biomass and biofuel

Contradictory to an ordinary LCA, this study do not focus on all possible impact categories, but evaluate GWP by described CO_2 equivalents (IPCC method) and the primary energy recourses that is used to deliver 1 kWh of heat to the end user.

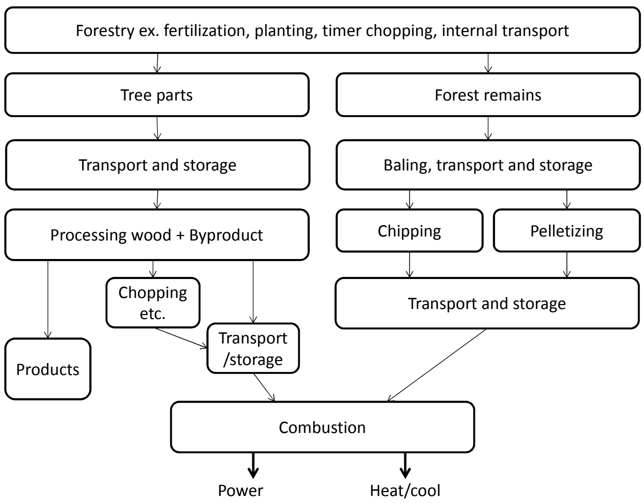


Figure 3 Simplified bio chain

Figure 3 shows some of the parameters influencing the CO_2 emission from biomass like; crop, forestry, fertilization, transporting distance, processing level and storage, and later on the final processing in a plant.

Allocating challenges

Allocation is a method for sharing of the environmental impact and burden. Several allocation methods I burden exist; the Power Bonus, Energy, Exergy, Price/Economical, 200%- and Alternative Production method. Some of the different allocation methods are described in [26].

When different products are produced at the same time by use of the same resources like thermal and electric power from a CHP the environmental impact has to be divided between the different products.

Another example when different fuels are used, such as heat and waste that originally is a byproduct from another process. The allocation is also an issue when different fuels are applied, which the following example illustrates. Heat can be produced by biomass. Biomass can be exclusively grown for heating purposes; hence the total environmental burden shall be placed upon the heating. On the other hand biomass might be a by-product from the production of timber, where only the residue is used for heating. Consequently, it is presumptive logical to place most of the burden to the production of timber except for the energy/CO_2 needed for transportation to the power plant. The residue may also have other applications like sawdust or chipboards, and at present there exist no standard describing and defining the correct allocation method to be applied. Therefore, the PEF and CO_2 emissions of fuel can be calculated based on an alternative production of the materials.

Waste is excluded from this study, since the composition of municipal waste is strongly dependent on local recycling schemes, where the non-renewable part can constitute up to 45 % [39] [41]. When biomass from waste is burnt in an incinerator, at least two opposite approaches are applied; a) to measure and count all CO_2 emissions regardless of origin, or b) to consider CO_2 from biomass as neutral usually based on an average distribution.

Waste is perhaps the most difficult fuel to decide correct allocation principle for; when correctly sorted a major part of the waste is recyclable, thus having a value as a raw material. On the other hand, incineration of waste might reduce the methane emissions from anaerobe decomposition of organic matter. In the EU the legalization has changed and deposit of organic matter is no longer legal, so the use of CH_4 reduction principle might therefore no longer be applicable in EU, but might be applied in other regions where landfill still is allowed.

Waste needs to be treated separately in each case since the composition of the waste depends on the suppliers/customers. Variations might also occur due to source; even municipal waste will vary according to location and over time.

Comparison of different fuels

In this chapter some of the parameters affecting the PEF and CO_2 values for biomass are evaluated.

Wood logs, wood chips, bark, shavings, pellets, briquettes and grinded wood, wood powder are possible biomass products for utilization in a CHP. Other biofuels like bio oil and biogas are kept outside this study due to large variety of production methods and raw materials.

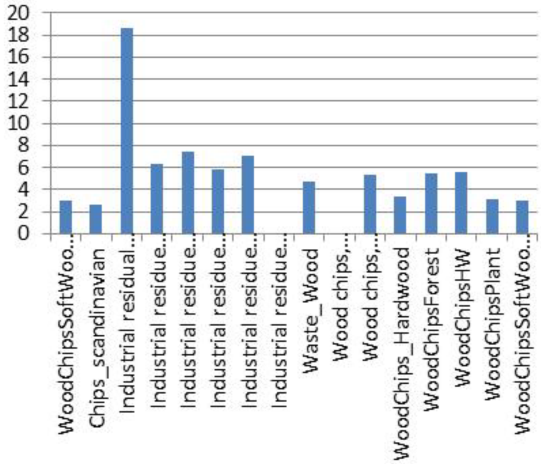
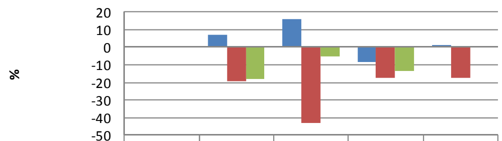


Figure 4 CO_2 equivalents [gCO_2 /kWh] for different biomass based on [42]

Figure 4 shows CO2 equivalents for different biomass as fuel. Biomass can be extracted and produced by several methods, see Figure 3. Wood logs might be the least energy intensive method, which hardly requires any treatment besides transport, whilst wood chips and pellets might need more comprehensive processing.

Even though wood logs and chips might seem to be the most preferable biomass, the transporting phase should be kept in mind. If a fuel is transported over a longer distance the impact of the energy density increases. Energy density for wood chips might vary between 400-1200 kWh/m^3 [48]. Therefore a correct value of the energy density is of major importance, when the transport of the biomass is assessed.



	Stemwood	Whole tree	Bark	Top with needles/ foliage	Tops without needles/foliage
Spruce tree/fir	0,0	7,0	16,3	-8,1	1,2
Pine	0,0	-19,4	-42,9	-17,3	-17,3
Birch	0,0	-18,1	-5,2	-13,8	

Figure 5 Deviation between average density and actual density for different three parts and types of wood, Reference value spruce 430, pine 430 and birch 580 [kg/m^3],

Figure 5, based on [49], show the differences in density for some common untreated raw materials (Nordic types of wood) and the different part of the wood. Stemwood is usually considered to be reference value, but there is a significant difference between bark and stemwood especially for pine.

Inclusion of biogenic CO_2

Assuming complete combustion, the carbon in fuel will react and form CO_2 ($C + O_2 \rightarrow CO_2$ + heat). Based on the molar weight will 1 kg of C form 3.67 kg CO_2 Depending on the rotation period of the crop, the emitted CO_2 from the combustion in this study be multiplied with a correction factor as shown in Figure 2.

Table 2 Physical properties for different biomass products based on results from [42], [44], [48]-[51]

Part	**Spruce tree/fir** [kWh/kg]	**Pine** [kWh/kg]	**Birch** [kWh/kg]	**Gray alder** [kWh/kg]
Stemwood 0% water	5,32	5,43	5,18	5,21
Stemwood 15% water	4,49	4,32	4,01	4,06
Stemwood 30% water	3,58	3,44	3,18	3,23
Bark (inner)	5,17	5,27	5,24	5,71
Bark (outer)	5,76	5,71	8,85	7,13
Stump	5,33	6,21	5,17	5,35
Wood from branches	5,36	5,55	5,18	5,24
Bark all	5,44	5,64	5,84	6,03
Needles/ foliage	5,33	5,84	5,38	5,48

Table 3 Physical properties for different biomass products based on results from [42], [44], [48]-[51]

	Spruce tree/fir	**Pine**	**Birch**	**Gray alder [**
Average density [kg/m^3]	430	490	580	350
Carbon content [wt% dry basis]	52,3-53,6[1]	51,9[2]-52,4	47,4-57,0[1]	n.a.

5)Bark 6)Pruning

Table 4 CO_2 biogenic emission correction factor for species with different rotation length based on GWP_{100}

Rotation period [years]	**Spruce tree/fir**	**Pine**	**Birch**	**Gray alder [**
1	0	0	0	n.a.
10	0,02	0,02	0,02	n.a.
20	0,16	0,15	0,17	n.a.
50	0,41	0,40	0,44	n.a.
100	0,85	0,82	0,90	n.a.

There is a substantial difference in net heating value both between different sorts of biomass as well as the different part of the material. The most important factors describing the possible energy potential is a combination of energy density (e.g. net calorific value) and moisture content. This is confirmed in a recent thesis [53] that emphasizes the importance of other factors such as net calorific value, water content and ash forming properties. Main factors influencing the water content are temperature, precipitation and covering during intermediate, temporary and final storage, in addition to processing and drying.

In our previous studies a model for CHP utilizing biomass as energy source producing power and delivering heat to a predefined district heating grid with seasonal adjusted flow, supply and return temperatures are carried out [25],[26],[54]. Efficiencies for part load are used to demonstrate the overall rise in CO_2 emission.

Table 4 and Figure 6 show the impact rotation period will have on the CO_2 emissions, provided that the rotation periods are achievable. In reality, rotation length depends on crop, r<20 years is not relevant for spruce, pine and birch. Usually, when rotation length decreases, other emissions related to fertilizing, transport etc. increase due to reduced energy density.

Figure 6 below further illustrates the impact of moisture level. If biogenic CO_2 should be included in the calculation of CO2 emissions from a CHP, the moisture content will influence on the overall emissions.

Pure untreated wood often have moisture content around 50%. Processing and treating reduce water content, thereby increasing the net calorific value for the fuel. Usually, CHP plants are designed according a specific fuel. If the moisture content is too high, the CO_2 emissions will rise.

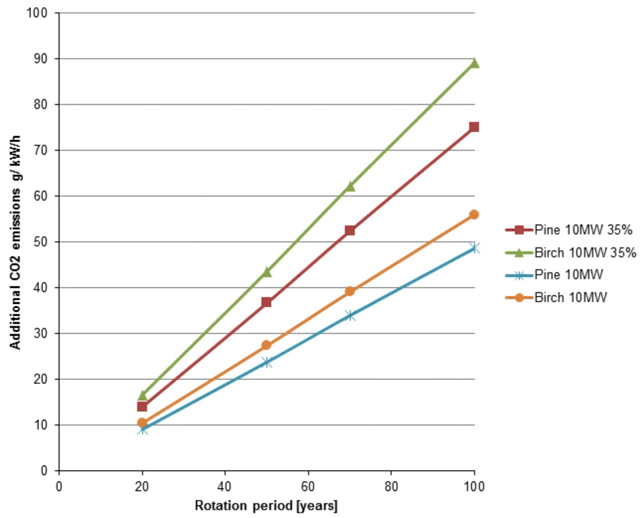


Figure 6 Additional CO_2 emissions per produced kWh when biogenic CO_2 is included, with 0% and 35% moisture based on 100% load of the CHP.

CO_2 emission caused by processing and transport

Emissions caused by processing depend on pre-treatment of the biomass and the quality of the final product. Unfortunately, few producers are able and/or willing to provide exact data on energy consumption for drying and processing.

The most energy efficient producers often produce multiple products, where the processes are integrated. A detailed calculation is complex, and there exist at present no standard for division and allocation of the burden. For example wood chips might be produced as byproduct from wood board production, where heat are produced by wood chips and heat at different temperature levels are utilized for drying.

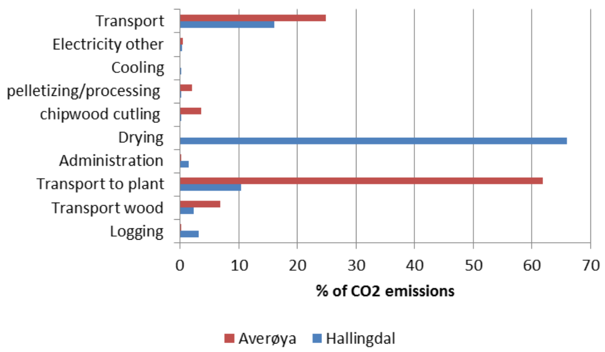


Figure 7 Contribution to CO_2 emissions from two different biomass chains based on

Figure 7 shows the difference between two Norwegian biomass producers from different locations. Averøya utilizes Canadian biomass and exports to Germany, whilst Hallingdal utilizes local produced biomass.

In the Hallingdal case, drying is included in the CO_2 emissions, even though waste heat is claimed to be the source. Other countries like Sweden consider waste heat without any environmental impact. A detailed knowledge of systems boundaries is important when comparing products.

DISCUSSION

As shown, the power and overall efficiency of the CHP will be reduced when the moisture content in the biomass increases. Concurrent, the CO_2 emissions and the PEF values will rise. Usually, dependent on fuel this will increase the ash amount, which must be transported from the plant further increasing the CO_2 emissions and PEF values.

According High moisture level will not only influence direct emissions caused by reduced heating value. Auxiliary electrical energy can, in a typical case, be reduced with 17% [45]

Our preliminary calculations, utilizing the Power Bonus Method indicate increase of PEF values and CO_2 emissions for heat and power production. More detailed calculations of moisture levels influence on efficiency at part load are needed to evaluate the annual impact.

Even though standards and requirements for biomass exist, fuels of variable quality are delivered to the CHP plants. The quality of the fuels should be further evaluated; several Norwegian plants do not achieve design performance [56]

Waste heat needs to be discussed; different allocation methods might distort the competition between companies.

CONCLUSION

CO_2 emission related to production and operation of district heating grid has been carried out in a previous study [25]. Later work focusing on part load efficiencies and behaviour has shown the importance of part load behaviour [26].

This work further demonstrates the importance of a strict methodology, where different biomass qualities are utilized; Firstly, a decision whether biogenic CO_2 should be included in the accounting. Secondly, allocation rules to be used in calculation both for CO_2 emission and PEF need to be defined. Thirdly, strict control of the delivered fuels moisture content should be kept in order to avoid unnecessary emission.

Today, the on-going debate between LCA practitioners might cause confusion, since results depend on system boundaries, allocation methods and quality of the fuel. This might also prevent future investments in CHP caused by overestimation of CO_2 emissions and eventually CO_2 taxes.

If biogenic CO_2 should be a part of the CO_2 emission evaluation, there will be a need for development of standardized CO_2 emissions and rotation periods for different biomass. In addition there is a need for a review of existing standards and development of new concise regulations.

FURTHER INFORMATION

Results from yearly calculation of PE and CO_2 equivalents based on part load behaviour for district heating of different sizes will be presented in later work.

Questions regarding this paper may be addressed to: Monica.Berner@sintef.no

ACKNOWLEDGEMENT

This work is made possible by the PhD project; Primary Energy Efficiency (PEE) where Nordic Energy Research is the main financial contributor with additional support from the district heating/energy industry in the respective participating countries.

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ECOHEAT4CITIES: RISING AWARENESS FOR EFFICIENT AND RENEWABLE HEAT

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Keywords: heat performance, ecoheat4cities, district heating, renewable energy, labelling, energy assessment

ABSTRACT

Providing efficient and renewable heat for a future society is one major solution of nowadays energy dilemmas in Europe. 50% of the primary energy consumption in EU27 is heat. The need of changes in heat supply is obvious, if today's ambitious targets of a high renewable energy share shall be reached in the near future. This paper presents several results gathered the Ecoheat4cities project, which aims at the reduction of non-technical barriers for an efficient, renewable heat, and it increases the awareness for this type of heat. Work package 3, guided by AGFW, was the main focus of the authors. Nevertheless the project consists of five more work packages, therefore further research results are available.

INTRODUCTION

The work presented here is one of the results of the Ecoheat4cities project, which is run by Euroheat&Power as a coordinator until the end of 2012. The main aim of the whole project is to support district heating and cooling and the use of renewable energy sources, coupled to an overall decrease of primary energy consumption. Ecoheat4cities addresses non-technological barriers through promoting municipal and public acceptance of district heating and cooling systems, by establishing a voluntary green energy (heating and cooling) labelling scheme to encourage local politicians, citizens and potential investors with the information needed to make choices based on renewable energy and energy efficiency .

The focus of this paper is work package 3 "DHC Green-labelling implementations" (WP3), where the main calculation rules were decided on and adapted to European and national needs. Guidelines for the labelling process were developed and statutes for good governance were worked out.

THE PROJECT STRUCTURE

The project is driven by a project team of seven project partners, that are namely in alphabetic order: AGFW, German Heat and Power Association, BRE United Kingdom, Danish Technological Institute, Delft University of Technology Netherlands, Euroheat& Power Belgium, Lithuanian Energy Institute and SDHA Swedish District Heating Association. The project team takes care of six Work packages dealing with Management (WP1), Green-Labelling criteria (WP2), DHC Green labelling implementation (WP3), Guidance to DHC companies (WP4), Guidance to cities on "Smart heating and cooling" (WP5), Communication and Dissemination (WP6).

FIRST RESULTS

The major output of the first 10 months was the definition of the relevant criteria for the performance assessment of a heating systems. These criteria must encourage the use of district heating for European municipalities, utilities and consumers and make the combined effects visible that come from the use of renewable and resource efficient energy sources in district heating. In the long run, the criteria must contribute to the goals of the Renewable Energy Directive.

The first step was to collect a long list of environmental criteria addressing district heating. As a first step, this was done by examining existing standards, regulations, policy documents, directives and other relevant sources where information regarding suitable criteria may be found. As a second step in the project, this list of relevant existing criteria was reviewed in order to select the most important ones, best fulfilling the purpose of the study. When compiling the short list, it was important that the criteria must allow for comparability with individual technologies, avoid incoherencies and conflicts with legislation in practice and allow for some comparability between the countries.

The three criteria that were found to best meet the objectives of the labelling scheme are

- Primary energy $f_{\mathrm{P,dh}}$,
- Carbon dioxide emissions K_{dh} and
- Share of renewable and recycled energy R_{dh}.

The reason for using these criteria is that they correspond well with the EU targets for renewable energy and allow for comparison between different heating technologies and their competitors. The E4C project has a strong European dimension in contributing to the 20-20-20 targets. Figure 1 illustrates the three criteria linked to the three R's Reduce, Recycle, Replace for a decarbonised future.

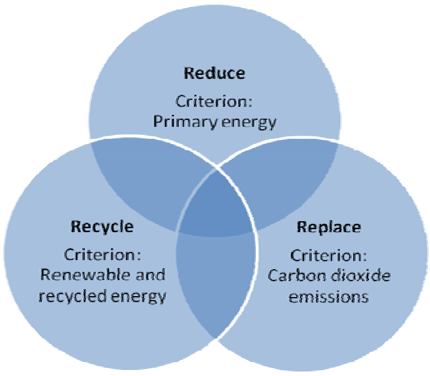

Figure 1, Three labelling criteria.

Dependent on the system boundaries, several methodologies exist to assess the different criteria. The methodologies based on existing standards were collected to ensure the best possible harmonization with the policy framework in Europe.

WORKPACKAGE 3

Based on the work under WP 2, the modalities for a practical application of the methodology to the labelling process are elaborated in WP 3. The labelling procedure as such was conceived on the basis of experiences from similar existing schemes (i.e. primary energy assessment in Germany) and was kept as light as possible. The scheme was overviewed by the project partners and the reference groups. The labelling process was reviewed after test-labelling of the first 30 systems and amendments to the underlying documents and methodologies were applied. Finally, labelling guidelines and statutes for a good governance of the label were elaborated.

LABELLING GUIDELINES

The Guidelines for expressing the energy performance drawn up during the project provide methods for the calculation of the three criteria. Different tiers pay attention to different needs on EU level and national level. On tier 1 level the Green-labelling scheme has a pan-European scope and can, similarly, be applied in each country. It is the European default framework that is described in the main part of the guidelines. When binding national regulations are to be used in a country, the energy assessment is done on tier 2 level with national adjustments. This is respected in national annexes. Tier 1 and tier 2 level calculations are based on default values, which may be replaced by measured data from a plant on tier 3 level. Tier 3 level is the most exact and accurate level and will lead to the best label.

All energy indicators used for labelling are to be determined with the same energy data, system boundaries and time period. Due to the many factors that can affect district heating systems, the indicators can fluctuate over time. This variation can be limited by basing the calculation on a broad range of data. Existing schemes should be calculated using the energy data from the last three years. The indicators on the basis of measured energy rating reflect the energy performance of the past. In order to certify the most accurate performance, the time period between the energy data and the date of certification shall not exceed two years. The energy data shall be validated by a plausibility check.

The calculation method for the three criteria is based on a thermodynamic system. Usually the area supplied by a single heating network is bordered by the primary side of building substations. Within this area, all energy inputs and all energy outputs are considered as shown in figure 2. Energy as input to the system is weighted by its specific conversion factor. Thus, the heat losses of the heating network are taken into account as well as all other energy used for extraction, preparation, refining, processing and transportation of the fuels to produce heat.

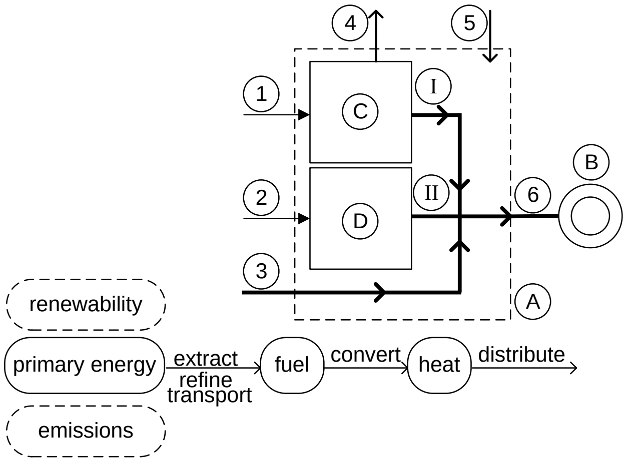

Figure 2. System boundaries for DH energy rating

A	system boundary
B	heat consumers
C	cogeneration unit
D	heat producer
1	fuel input to cogeneration unit $E_{F,chp}$
2	fuel input to heat producer $E_{F,hp}$
3	heat from external source Q_{ext}
4	chp electricity $E_{el,chp}$
5	auxiliary electricity $E_{el,aux}$
6	delivered heat Q_{del}
I	heat from cogeneration unit Q_{chp}
II	heat from heat producer Q_{hp}

In the labelling guidelines, the non-renewable primary energy factor as defined in EN 15603 is used and calculated according to EN 15316-4-5 (2007) if no national calculation rules are given [1,2]. National variations are to be defined in a national annex. The non-renewable primary CO_2-emission coefficient represents the emissions of a district heating system if no national calculation rules are given. The renewable and recycled fraction R is the ratio of heat from renewable and/or recycled energy carriers to total heat in %. If electricity is used as fuel (e.g. for heat pumps or electric boilers) 20% of this electricity is regarded as renewable/recycled. The achieved results are ranked in a seven class system. The reference values for the determination of the energy classes is calculated with a fixed set of data and a system set-up according to figure 3.

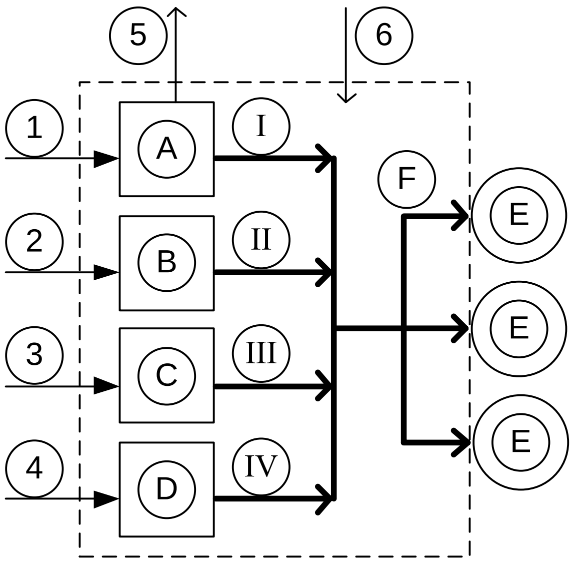

Figure 3, Setup of the reference system

A extraction-condensation chp-unit with η_{chp}
B heat producer for natural gas with $\eta_{hp,ng}$
C heat producer for biogas with $\eta_{hp,biogas}$
D heat producer for wood chips with $\eta_{hp,wood}$
E heat consumers
F district heating network with η_{hn}
1 hard coal with $f_{P,coal}$ and $K_{P,coal}$
2 natural gas with $f_{P,ng}$ and $K_{P,ng}$
3 biogas with $f_{P,biogas}$ and $K_{P,biogas}$
4 wood chips with $f_{P,wood}$ and $K_{P,wood}$
5 chp-electricity with $f_{P,el}$ and $\sigma \cdot \beta_{chp}$
6 auxiliary electricity with $f_{P,el}$, K_{el}, β_{aux}
I heat from coal chp-unit with β_{chp}
II heat from natural gas with $\beta_{hp,ng}$
III heat from biogas with $\beta_{hp,biogas}$
IV heat from wood chips with $\beta_{hp,wood}$

The reference system provides the flexibility for tier 2 and tier 3 to calculate the energy performance with different methodologies adjusted to national needs constraining the comparability between the classes. In the ecoheat4cites project calculation tools for the criteria are provided.

For comparison, any other energy system may also be evaluated with the ecoheat4cities methodology elaborated in WP3.

GOOD GOVERNANCE

For good governance of the label, statutes are elaborated, providing rules of procedure with regard to the institutions, governing the ecoheat4cities labelling, concerning the ecoheat4cities labelling process and the certification bodies for ecoheat4cities labelling. The ecoheat4cities label is governed by an European Steering Board and is supported by an European Technical Committee, which consists of independent third parties such as universities, research institutes or similar organisations with sufficient technical background. Regional Advisory Groups will be established in each country where the national needs are reflected and a related national annex is elaborated and taken care of. National certification bodies are authorised to apply the label according to the ecoheat4cities labelling guidelines. The development of the legal frame of the ecoheat4cities label is currently ongoing and shall be finished latest at end 2012.

CONCLUSIONS

The scheme is being designed to encourage district heating and cooling companies to market the performance of their products from a primary resource perspective (combined effects of the use of renewable energy sources, and energy efficiency) and for European consumers - including public and private purchasers - to easily identify them as eco-heating and cooling options.

By providing a defined procedure for the energy assessment of district heating systems in work package 3 of the project, it is now possible to calculate three criteria: primary energy consumption, the renewable share, and CO_2 emissions. The results are classified with a system of seven categories, where ranking is adjusted to national needs by using a fixed reference system. The reference system is fictive but technically defined in the same way for all countries

This trick enables the ecoheat4cities label to respect e.g. different energy assessment methods and different primary energy factors, because they are linked on a national level to the same reference system. However, a national annex is necessary if deviation from project definitions on EU-level is wanted.

Once the label is installed in the DH branch, it will be a helpful tool to achieve strategic long-term objectives such as enabling and directing the expansion of DHC towards increasingly sustainable and future-proof systems, a contribution of DHC to reduce the EU's import dependency, and de-carbonize the heating and cooling sector. Test label actions within the project gave a promising outlook showing the advantages of DHC.

AKNOWLEDGEMENTS

The research project ecoheat4cities Contract N°: IEE/09/798/SI2.558275 was co-financed by the European Commission in the Intelligent Energy Europe program. The authors would like to thank the EC and the EACI for their support.

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