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TO ANALYSE MEASUREMENTS IS TO KNOW!

Analysis of hourly meter readings in district heating systems

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ABSTRACT

Renewable energy sources dominated the world energy supply until the beginning of the 20th century, when fossil energy became the dominant energy source worldwide. Today, fossil fuels contribute to over 80% of world energy supply. But there are two major reasons why fossil energy use has to stop. First, fossil energy is limited and will not last forever. Second, emissions of carbon dioxide change the climate with a risk for huge changes in the conditions of life for a large part of the world. A conversion back to renewables is necessary, but must be done at a major increased efficiency compared to the pre-fossil era. This change in energy supply is occurring, and district heating can play a major role in a renewable energy supply system. However, in order to stay compatible, district heating technology has to develop to increase system efficiency. Traditionally, district heating systems are divided in three parts: heat generation, distribution, and substations, but from a system point of view the system border has to be put in the climate shell of the connected buildings. Heat supply and distribution have been contentiously supervised and controlled by the district heating operators. The secondary heating systems in the heated building have building control systems in various extents and managed by the building operators. But, to increase system efficiency, all parts of the system have to be included in the optimisation. Automatic meter reading systems that up through 2015 will be installed in all district heating substations in Sweden can be used to overcome the lack of information to optimise the entire district heating system. This work is an initial analysis of substations and secondary systems using hourly meter readings. District heating systems are rather homogenous from a heat load point of view while the attached buildings are heterogeneous. The heterogeneity is what makes fault detection for district heating customers so difficult. The most difficult is not to detect what is wrong but to know what is right. To know what is right, knowledge of each individual customer is necessary. In this study, it is estimated that 75% of all connected customers

have fault in substations and secondary systems. In today’s district heating systems, this is compensated for by increased supply temperature. In future district heating systems with essential lower distribution temperatures, this will not be an available option. Continuous commissioning of substations will be necessary to detect faults quickly.

ACKNOWLEDGEMENTS

There are two people who made it possible for me to spend five years digging in the wonderful world of district heating to whom I want to extend my gratitude. First, I would thank my supervisor Sven Werner. I cannot think in what way a supervisor could be better! Always interested in my work, always willing to share from his limited time and infinite knowledge in energy matters in general and district heating matters in particular. Thank you Sven! My manager Lars-Inge Persson, has been genuinely supportive and positive about my work from the beginning. I would like to thank the colleges in SET in Halmstad University for pleasant companionship around the coffee table. In particular, I would like to thank my PhD-student brother Urban Persson. We have had great discussions in a large variety of subjects, high and low, often far away from district heating matters. I would also like to thank the staff in my host department, Department of Energy Sciences at LTH, my co-supervisor Svend Frederiksen for being a safe backup, and Bengt Sundén and Elna Andersson for solving all administrative matters in the best way. The research was financially supported from Fjärrsyn, the Swedish district heating research programme founded by the Swedish Energy Agency and Swedish District Heating Association, and Öresundskraft.

My greatest and most important supporters, however, are those I have at home. My beloved wife Johanna and the three best kids in Universe: Oscar, Mauritz, and Otto.

LIST OF PUBLICATIONS

This thesis is based on the following papers, referred to in the text by their Roman numerals. The papers are appended at the end of the thesis.

Paper I	Gadd H, Werner S. *Daily heat load variation in Swedish district heating systems*. Article in press. Applied Energy 106 (2013) 47–55
Paper II	Gadd H, Werner S. *Heat load patterns in district heating substations*. Article in press. Applied Energy 108 (2013) 176–183
Paper III	Gadd H, Werner S. *Achieving low return temperature from district heating substations.* Article in press. Applied Energy 136 (2014) 59-67
Paper IV	Gadd H, Werner S. *Fault detection in district heating substations.* Submitted for publication.

Other related publications by the author

Gadd H, Werner S. *Daily heat load variation in Swedish district heating systems.* Earlier version of Paper I presented at the 12th International Symposium on District Heating and Cooling, 2010, Tallinn.

Gadd H, Werner S. *Thermal Energy Storage for District Heating and Cooling.* Chapter 18 in Cabeza (ed), Advances in thermal energy storage systems. Woodhead Publishing 2015.

The author’s contributions to the publications

Paper I Developed the method together with Sven Werner. Performed the calculations and wrote the paper with guidance from Sven Werner.

Paper II Developed the method together with Sven Werner. Performed the calculations and wrote the paper with guidance from Sven Werner.

Paper III Developed the method and performed the calculations. Wrote the paper with guidance from Sven Werner.

Paper IV Developed the method and performed the calculations. Wrote the paper with guidance from Sven Werner.

POPULÄRVETENSKAPLIG SAMMANFATTNING

Fjärrvärme är ett centraliserat uppvärmningssystem där varmt vatten distribueras i ett rörnätverk och används främst till byggnadsuppvärmning och för att värma varmvatten. Fjärrvärme finns i alla länder på norra halvklotet men har störst marknadsandel i Norden och Baltikum. I Sverige används fjärrvärme för att värma c:a 60% av all byggnadsyta. Två stora fördelar med fjärrvärmesystem, ur ett energisystemperspektiv, är att man kan generera både el och värme med en verkningsgrad på över 90%, och att man har en stor flexibilitet vad gäller vilka energikällor man kan använda. Främst är det energikällor som annars är svåra att använda i enskilda byggnader, så som t ex avfall och träflis men även att man kan ta tillvara överskottsvärme från industrier eller geotermisk värme.

Fjärrvärmesystem brukar traditionellt delas upp i tre delar: produktion, fjärrvärmenät och fjärrvärmecentral. Produktion är där värme genereras och kan komma från en mängd olika källor. Fjärrvärmenätet består av två parallella isolerade rör som levererar hett vatten till byggnader och transporterar tillbaka det avkylda vattnet till produktionen.

Fjärrvärmecental är där värmen överförs från fjärrvärmenätet till byggnadens värmesystem och är normalt placerade inne i de anslutna byggnaderna. Eftersom de anslutna byggnaderna värmesystem påverkar fjärrvärmesystemet måste man även inkludera byggnadernas värmesystem vid en optimering av fjärrvärmesystemen. Den svagaste punkten i dagens system är just fjärrvärmecentralerna och byggnadernas värmesystem. En viktig del i detta arbete har varit att identifiera fel i dessa och resultaten visar att i c:a 75% av de analyserade byggnaderna kan fel identifieras.

I varje fjärrvärmecentral finns en värmemätare som används för att mäta hur mycket värme varje kund använder. Från och med 2015 kommer alla värmemätare att läsas av automatiskt på grund av att det kommer att vara lag på att debitering av värme skall baseras på verklig förbrukning och inte som tidigare, baserat på uppskattad användning. Detta innebär i sin tur att alla svenska fjärrvärmebolag kommer att ha tillgång till stora mängder

mätdata från de anslutna byggnaderna. I detta arbete har mätvärden för värmeleveranser till 146 fjärrvärmecentraler analyserats. Dessutom har totala värmeleveransen till hela fjärrvärmenätet i 20 olika fjärrvärmenät analyserats.

I denna avhandling har dessa mätvärden använts i två syften. Dels att analysera värmelastvariationer, på dygns- och årsbasis, i fjärrvärmecentraler och i hela fjärrvärmesystem. Dels att identifiera fel i byggnadernas värmesystem och fjärrvärmecentraler.

Vad gäller dygns- och årsvariationer visar resultaten att skillnaderna mellan olika fjärrvärmenät mycket små, medan skillnaden mellan olika byggnader är stora. Det beror på fjärrvärmenätets utjämnande effekt som brukar benämnas *sammanlagring* och beror på att effekttoppar i olika byggnader är spridda både i tiden och geografiskt i fjärrvärmenätet.

Resultaten från den andra delen av arbetet visar att mätvärden från värmemätare kan användas för att identifiera fel. Detta skulle t ex kunna leda till att servicebesök kan utföras efter behov istället för som idag planeras efter almanackan. Fel som uppträder både i fjärrvärmecentraler och byggnadsuppvärmningssystemen kan ha flera olika ursprung t ex:

i. Komponenter som har slutat fungera helt eller delvis.
ii. Komponenter som är felaktigt dimensionerade eller felaktigt installerade.
iii. Felaktiga inställningar i styrsystem.

Det kan med andra ord både vara fel på den fysisk utrustning och komponenter och fel som beror på den mänskliga faktorn.

I detta arbete har alla analyser utförts manuellt. Om man skall använda det praktiskt på fjärrvärmeföretagen måste de automatiseras annars kommer kostnaderna för mantid bli större än nyttan.

LIST OF CONTENT

INTRODUCTION

Background

Historically, renewable energy has completely dominated the world's energy supply. Wind and water supplied mechanical energy for pumps, mills, and other industrial needs. Wood was used to supply thermal energy for metal work, space heating, and cooking. Wind was used to power transportation, such as sail ships, and draft animals like horses and oxen pulled carts for transportation as well as ploughs for agriculture. [1].

The fossil energy supply era began in the 18th century, both a result and a prerequisite of the industrial revolution. Traditional biomass continued to be the dominant energy supply until the beginning of the 20th century when coal became the world's dominant energy source; today, coal continues to make a considerable contribution. Oil became a substantial source of energy in the 1920s. Around 1970, oil surpassed coal as the most prevalent energy supply in the world. From 1950 on, natural gas also increased in proportion in the energy supply [2]. As of 2007, fossil fuels contributed more than 80% of the world's total primary energy supply, with oil constituting 34%, coal and peat at 27%, and natural gas at 21% [3].

The fossil era, however, has come to the end of its road. There are two major reasons why existing fossil energy systems must change. The first is to decrease climate change. Changes in the climate are already apparent, with increased average global temperature, lower heat demands, melting polar ices and glaciers, rising sea levels, and acidification of the oceans [4]. The second is to attain a sustainable energy supply. Fossil fuels are a limited source of energy and they will not last forever. According to [5], we are actually facing peak oil at this very moment. Peak oil is a situation where the extraction of oil has reached its peak and from that point will decline. It was foreseen in 1956 by M. King Hubbart, a geologist employed by Shell oil company [6].

The next energy supply system must be based on renewable energy sources. Compared to previous use of renewable energy sources, they have to be used at a much higher efficiency than historically to be sustainable.

Efficient energy use

Fossil fuels have been, and still are, cheap and energy dense, which is why the fossil-based energy supply has become inefficient. Power plants, for example, convert fuels such as gas, coal, oil or uranium, but lose 40–70% of the energy in the fuels due to heat loss from the energy conversion. High-exergy sources like gas, oil and electricity is used to supply low-temperature heat demands, such as space heating and domestic hot water in buildings. I.e. inefficiencies are present both in the energy supply systems as well as in the energy end use. In future sustainable energy supply systems based on renewable energy sources, the efficiency in both supply and energy end use has to increase significantly.

Techniques to increase efficiency for renewables are nothing new. In a description from around 1770, on behalf of His Royal Highness, the king of Sweden[1] tile ovens and fireplaces were to be improved to decrease the use of wood [7]. The wood was needed in the iron industry and the king was worried that there would be a lack of it. The improvement not only increased energy efficiency, it also increased comfort. Tile ovens store heat due to their large mass and people could go from feeding wood for space heating purposes more or less continuously to only a few times a day. What we can learn from this historical view is that a decrease in energy use does not have to result in a decrease in comfort. On the contrary, it is possible to both decrease use and increase comfort by introducing more intelligent energy supplies. Another more recent example of renewable energy source that is still used, but at a major increased efficiency, is wind energy. The efficiency of modern wind power plants is about 2.5 times higher than for the old wind mills and wind pumps [8]. In combination with the transition from the direct use of mechanical energy to generation of electricity, it is possible to utilise the wind energy not only when there is a need for seed grinding or water pumping, but for large numbers of applications year round, not only has mechanical efficiency increased, but the utilisation time has increased to another magnitude.

In future energy supply systems, we cannot afford the to perpetuate the inefficiencies embedded in the present energy system. The energy supply

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[1] Adolf Fredrik. Born 1710, King of Sweden 1743-1771

and energy use must be more integrated with one another to use energy more intelligently. One of the major advantages of district heating from an energy system point of view is that recovered heat from other processes or from low-value assets that can be used. District hearing is a centralised system mainly used for building heating described in more detail further down. Since many energy-using processes have low-temperature losses, one way to increase system efficiency is to have sequential supply where possible; as such, district heating can play an important role in the future [9]. By using combined heat and power (CHP) plants not only heat, but also renewable electricity can be generated from low-value energy assets like waste and demolition wood. Another advantage of district heating is fuel flexibility. What is an available and competitive heat supply today may not be competitive tomorrow, but it is possible to change the heat supply over a few years in district heating systems. In Sweden, all district heating systems have turned from nearly 100% fossil energy supply to almost 100% recycled and renewable energy supply in a period of 30 years, illustrated in Figure 1, without decreased comfort! Most people in Sweden have not even noticed that they have been part of an energy system transition from a fossil-based energy supply to a renewable-based one.

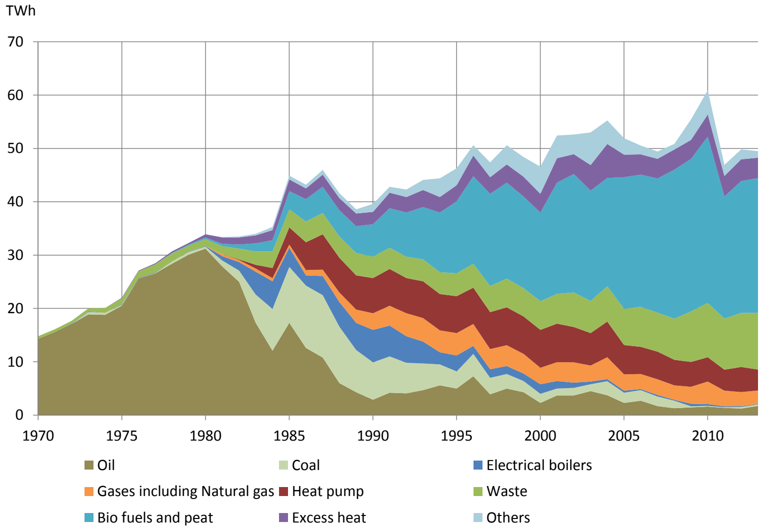

Figure 1. Annual fuel supply to Swedish district heating systems 1970–2013. (Data from [10] and [11])

District heating can play a key role in future sustainable energy systems. Denmark is largely dependent on fossil energy, but Lund et al. [12], have shown that the country could have a 100% energy supply that would last until 2060 through the use of renewables with district heating as an increased part of the energy supply. Hence, district heating, a technology more than 100 years old, is in many ways more modern than ever in terms of future renewable energy supply systems.

System efficiency has to improve for district heating systems to remain competitive for the future. It has been known for decades that decreasing distribution temperatures is the most efficient way to improve system efficiency. Today, the average supply temperature is about 86 °C in Sweden and 81 °C in Denmark. Corresponding return temperatures are 47 °C and 45 °C, respectively [13]. With today's technology, a supply temperature of about 70 °C and return temperature of less than 35 °C is possible [14]. Relatively high system temperatures compensate for faults in substations and customer secondary systems. Traditionally, heat supply and distribution have been continuously supervised, but substations and customer secondary systems have not. There are no cost-effective ways to identify faults continuously in customer systems because the quantity ranges in the thousands or tens of thousands in each district heating system. In recent years, automatic meter reading systems have been installed in most district heating systems in Sweden, which are able to deliver hourly meter readings for energy, flow, and supply and return temperatures, totaling approximately 35,000 meter readings for each substation in the district heating system. The main part of this work is to sort through this gold mine of information in order to identify faults in substations and customer secondary systems. This knowledge can be used to develop tools to automatically identify and prioritize faults in substations and secondary systems without using expensive man-hours.

The driving political force to introduce high frequency meter readings has been for customers to be more aware of their energy use, and thereby encourage energy savings. Still, this only affects the end use of energy. For a society to become energy efficient, the energy supply itself has to be efficient. High frequent meter readings can both decrease end use and increase system efficiency for future sustainable energy supply systems.

Purpose and scope

The purpose of this work is to increase system efficiency in district heating systems. Since 2009, most district heating companies have introduced hourly meter reading in all substations in district heating networks. Apart from billing, the meter readings could be used to analyse heat usage in the connected heat demands. The purpose of this work in the short-term is to perform an introductory analysis of the meter readings to identify how they can be used and what can be identified in the data. Over the long-term, the results could be used as a base from which to develop automatic fault detection in district heating substations and secondary building heating systems.

Limitations

All analysis in the attached papers is based on annual data sets of hourly meter readings for energy, flow, and supply and return temperatures. Analyses have been performed for 20 district heating networks (Paper I) and 146 district heating substations situated in two different district heating networks (Papers II–IV).

All analyses are theoretical, but are performed with real meter readings from substations and networks used in the day-to-day work in district heating companies. One annual data set has been analysed for each district heating system and district heating substation. No evaluation of energy savings potential or economical profitability analysis has been performed.

Outline of thesis

The short introduction above is followed by a brief description of district heating technology. This is followed by a section describing how data collection have developed, a prerequisite for this work. After that comes a description of demands for future district heating systems including pros and cons of the new opportunities. Presentation of major results from the appended papers, conclusions, and suggestions for further work finish off the thesis.

DISTRICT HEATING TECHNOLOGY

District heating is a centralised system for heat supply in urban areas and is utilised in most countries in the northern hemisphere. The Nordic countries and the Baltic states have the largest market penetration [15]. District heating is primarily used for space heating and domestic hot water in buildings. There are several advantages to a centralised heat supply, such as lower specific boiler cost, higher boiler efficiency due to larger units, lower local air pollution due to air pollution control, and lower global environmental impact due to heat supply from low worthy energy sources. It is common to divide a district heating system into three parts: heat supply, distribution (i.e. district heating network), and district heating substations. However, from a system point of view, the system border should be put in the climate shell of the connected buildings. The building heating system must be included because faults in the building heating systems will affect the efficiency of the other three system parts. This chapter will briefly describe the four parts of district heating systems. Since most of this work is based on meter readings from heat meters, there is also a section that describes heat meters and automatic meter reading systems. For detailed information on district heating technology, in addition to what is described below, refers to [16].

Heat supply

The basic idea for district heating is the possibility to utilise energy sources that would be difficult to use otherwise. Five strategic resources for heat supply in district heating systems are heat from combined heat and power plants, heat recovery from waste incineration, industrial excess heat, geothermal heat, and heat from fuels difficult to use in local boilers, such as wood waste, straw, or olive stones [17]. The most suitable heat source is determined based on local conditions. The heat source must have a major lower cost than the alternative heat supply for local heating for two reasons: first, apart from the heat cost, a distribution cost will be added to the end user cost, illustrated in Figure 2; second, nearly all of the buildings close to the district heating network must choose district heating for their heat supplies in order to decrease the distribution cost. That is, district heating must be considered the most attractive heating alternative for all or almost all presumable customers along the district heating network if it is to be competitive.

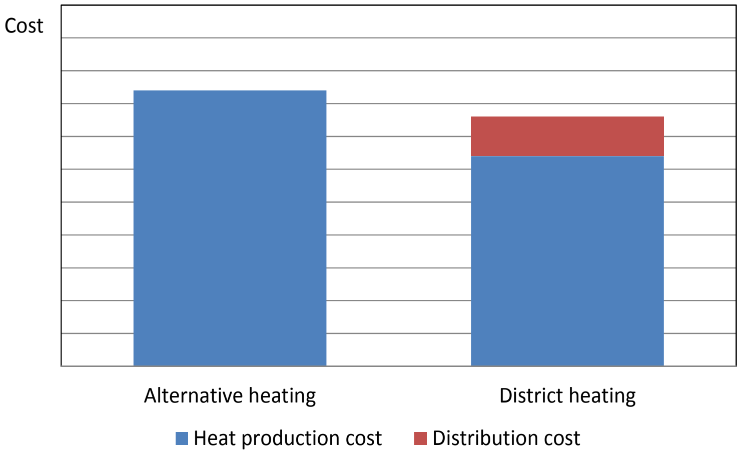

Figure 2. Market condition for district heating illustrating that the heat generation must have essential lower cost than local generated heat.

A mix of several different heat supplies are typically used in a district heating system to handle the fluctuations in heat demand over the year due to changing outdoor temperatures. For base load, plants with high investment cost and low operational cost are used; for peak load, plants with low investment cost and high operational cost are used. It is also common to have heat storages in district heating systems that can be used for peak load reduction and to optimise electricity generation and can be used as a reserve for unplanned boiler stops.

District heating networks

The district heating network connects a large number of small heat demands to one large heat demand. Because only a few heat supplies exists in each network, it is easy to change if market prices or availability of a heat source or fuel changes compared to individual heat supply. This is the reason why the district heating network is the most important part of the district heating system from a strategic point of view. While a heat supply plant has a lifetime of about 30 years, a district heating pipe has a lifetime of 50–100 years. The most important limiting factor for a heat supply, apart from price, is that the supply temperature must be high enough for all customers. Distributing temperatures are from an energy system point of view is an issue of great importance and will be further discussed in chapter ‘*Future district heating systems*.’ below.

There is a contradiction between the cost for a district heating network and the distribution temperatures. Low distribution temperatures increase the efficiency in the district heating system. If the supply temperatures are decreased, the pipes have to be wider for the same amount of delivered energy, but the larger dimensions will increase the cost [18]. Consequently, new network technology has to focus on decreased cost for pipes and trenching.

District heating substations

Heat from the network is transferred to building heating systems via district heating substations. There are two major connection types: direct connection and indirect connection. In direct connected buildings, there are no heat exchanges between the primary system (district heating network) and the building heating system, whereas in indirect connections, the district heating network and the customer building heating systems are hydraulically separated by a heat exchanger. Direct connection is more efficient from a temperature level point of view because indirect systems result in a temperature loss in the heat exchangers. The advantage of indirect systems is that you can have different pressure levels in the primary system, which is necessary in cities with large differences in altitude. Another advantage is that water hammers in the primary system are not transferred to the secondary systems. Indirect coupled systems dominate Sweden’s heating systems totally; all data in this work come from indirect coupled district heating systems and substations.

A substation is rather simple from a technical point of view. For the primary functions it contains, in addition to piping, heat exchangers, control valves, temperature sensors, pumps, and a control unit (Figure 3). Then there are secondary components, such as safety and shut-off valves, filters, expansion vessel, brackets, insulation, and covers. This simplicity makes the substation robust and result in low demand for maintenance.

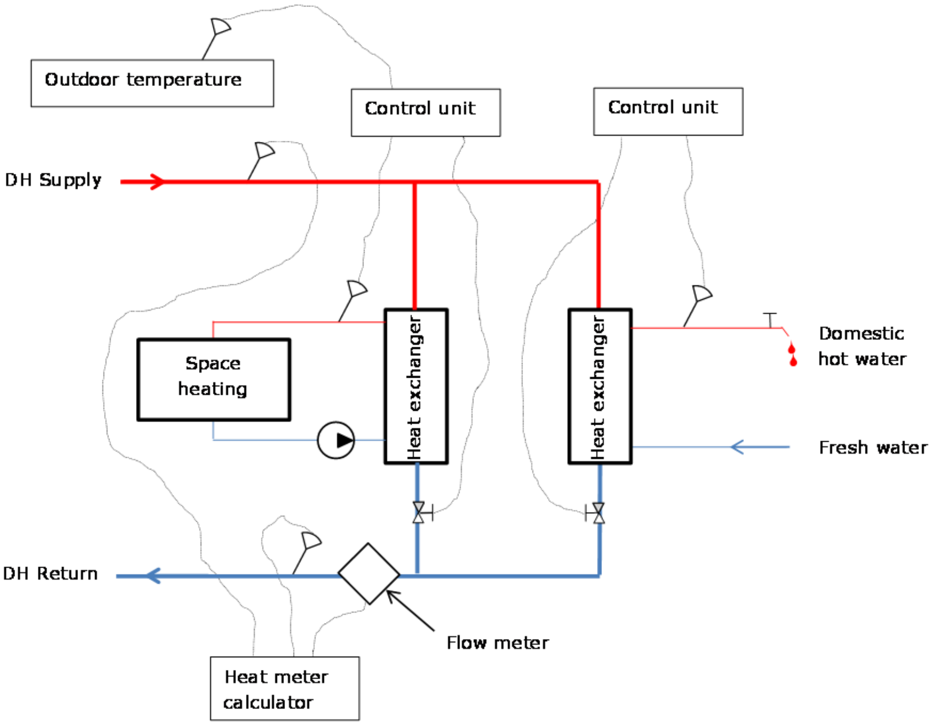

Figure 3. Schematic overview of indirect coupled district heating substation with heat meter.

Customer secondary systems

District heating is mainly used for space heating and domestic hot water. Space heating is delivered by radiator and through ventilation. The two different parts can at first sight be doing the same thing: Heating the building, but they are actually used for two different heat demands. Radiator heating compensates for heat transfer trough the climate shell and is normally supplied by radiators or floor heating. Heated ventilation air increases the temperature of outdoor air to a comfortable indoor temperature; air coils in air handling units normally supply the heat. Space heating is in operation 24 hours a day as long as the outdoor temperature is so low that the building has a heating demand. Ventilation air systems are only in operation if the building is in need of it. In some buildings, such as hospitals and multi-dwelling buildings, ventilation is needed 24 hours a day, 365 days a year, but an office only need ventilation when people are at work, such as during daytime on workdays. Use of domestic hot water differs significantly among different buildings. In multi-dwelling buildings, the use of domestic hot water is rather high while industrial or office buildings can have zero or close to zero use of domestic hot water heated by district heating. This implies that the heat demand for different types of buildings differs a lot. One building’s correct heat demand pattern may be a fault heat demand pattern in another building.

Heat meters and automatic meter reading

Heat meters

Heat meters have traditionally and continue to be used primarily for billing purpose. A heat meter typically consists of three parts: a flow meter, a pair of temperature sensors, and a calculator (See Figure 3). The flow meter is normally mounted in the primary return pipe. The two temperature sensors are also mounted in the primary side, one in the supply pipe and one in the return pipe. The flow meter and temperature sensors are connected to the calculator. The calculator computes the energy by flow meter readings, temperature difference readings, and inbuilt values for density and heat capacity factor.

Automatic meter reading systems

Automatic meter reading systems gather meter readings from thousands of customers and collect them in a central database. They have been in operation in Sweden for more than 20 years. The meter readings can be transmitted in a range of techniques, both by wire and wirelessly or by a combination of wire and wireless. Previously, before 2009, only larger electricity customers were connected due to the demand to report hourly electricity use to the Swedish national grid operator [19]. On 1 July 2009, a law was enacted [20] requiring electricity providers to charge every customer connected to the electrical grid for actual monthly use rather than by estimations based on previous use. Most district heating systems in Sweden are operated by companies that also operate local electrical grids, so automatic meter reading systems have been installed in many district heating systems. From 1 January 2015 it will be mandatory by law [21] to charge district heating monthly by actual use, implying that hourly meter readings for all district heating customers can be available in 2015.

Smart grids, smart homes, big data, and Internet of things

Four terms often used conceptions are ‘smart grids,’ ‘smart homes,’ ‘big data,’ and ‘Internet of things.’ Smart grids are mainly used in the energy sector referring to the next generation of electrical grids. Traditionally, electricity has been generated in large centralised plants and distributed to users via a national grid. ‘Smart grids’ normally refer to the future electrical grid where generation and use of electricity are more decentralised. This will create a demand for transition for network operators to become more like network optimisers [22]. ‘Smart homes’ relates to supervised dwellings with possibility to have supervision of energy use, locks on doors, alarms, sensors to avoid damages due to moisture, among others. A prerequisite is that information, data, is to be easily accessible between building system and users/owners.

‘Big data’ and ‘Internet of things’ are more general terms that refer to the fact that a lot of things can be connected to the Internet, or other networks, at low price and thereby be supervised and reachable from anywhere momentarily, such as smart homes. One interpretation of Internet of things is ‘A worldwide network of interconnected entities’ [23]. Applications of Internet of things can be found more or less daily in newspapers and magazines. For example, offshore wind turbines have high costs for service visits, but remote diagnostics can help identify problems before any harm is done, thus avoiding down time as well as the possibility to extend service intervals [24]. Another example closer to the topic is an ongoing project at Luleå University of Technology, where information from the local district heating system, information from the national building records, and geographical data are combined in a tool to identify single buildings with high relative energy demands to be used for municipality energy-saving strategies [25].

The basis of smart grids, smart homes, big data, and Internet of things is cheap access to large amounts of data and data communication, a development that has been made possible thanks to the development of information and communication technology (ICT).

Four generations of data collection

Increasing measurements is nothing new. It has been on-going for a long time and four generations of data collection have been identified.

The first generation of data were collected by taking manual readings for temperature, pressure, or fuel levels etc, throughout a plant or factory. A change in a process or machine could be performed by manually turning a valve or increasing fuel supply. The second generation is when sensors that could generate electrical signals became common and the collection could be centralised to a central control. The data were still registered on paper, but was done by printers and not by hand. The third generation of data collection is when computers became affordable and increased the possibility to not only collect but also analyse large amounts of data at low cost. Common for the first three generations is that the data is mainly accessible locally. In the fourth generation, the development of ICT has opened up opportunities to connect almost everything to anything and can be accessed from anywhere.

The cost for data collection was a limitation for generations one through three. Investigations were conducted to determine the necessary data that to collect, and which meters and communication devices should be installed. Today, in generation four, data collection has become cheap resulting in a tendency to collect data because it can be of some use rather than for a specific purpose.

This implies that data from several different sources can be collected easily in one database or can be accessible in one spot at low cost. The limiting factor is not data and measurements, but the ability to sort and analyse the data to transform the data to useful information.

The district heating industry has collected data for supervision of the heat supply and distribution for decades, but the boundary conditions are set by the heating demands of the district customers by their substation and secondary systems, and customers’ faults have been treated as a local problem even though it affects the efficiency of the entire system. Most of meter reading at customers in district heating systems has, until recently, been performed manually by personnel walking from building to building reading heat meters. The meter readings were then transferred to the customer records for billing. This methodology is a combination of the first and third generation of data collection. The introduction of automatic meter reading systems opens for meter readings from heat meters to step into the fourth generation of data collection. Automated meter reading allows for 35,000 hourly meter readings for each subscription annually. It is not done for a specific purpose, but because it is possible and many people realise that the data can be useful. A demand to collect meter readings monthly resulted in systems that were built to be read hourly, even though no one knew what to do with meter readings with such high resolution.

Meter readings ownership

The ownership of the meter readings are not expressed in any Swedish act or decree. There is demand for energy companies to report and serve customers with meter reading [26] and the Swedish Energy Markets Inspectorate recommends that energy companies should be obliged to serve as a third party, identified by the customer, with meter readings for electricity [27]. The ownership of the meter readings is a non-issue at present. However, from an energy efficiency point of view it could be useful to make energy meter readings public. If energy meter readings were public, lack of energy efficiency competence at the building operators could be identified, and compensated for by energy efficiency experts who could analyse the energy use in buildings on a large scale to identify inefficiencies in order to sell energy efficiency services.

But, fault detection in substations and secondary systems with high frequency meter readings not only reveals knowledge about customers' heat demand. It also reveals knowledge of behaviour. Analysis of companies' energy use patterns might reveal changes in production methods, a competitive advantage. Public meter readings could also risk trespasses on personal integrity. It might not be a problem in a multi-dwelling building with dozens of flats, but for a single dwelling building it would with a one-hour resolution metering be possible to identify working times. With increased resolution, it would be possible to see showers or even single hot water taps. This would certainly be a risk for trespass of personal integrity. High-resolution measurements could be of interest not only to take energy efficiency measures but for other purposes as well. Information about customers' use of domestic hot water could perhaps be of interest for companies selling shampoo, while information about hours people are away from their homes could be of interest to companies that sell security systems, or for burglars!

FUTURE DISTRICT HEATING SYSTEMS

District heating has survived more than one-hundred years of development and competition from other heating alternatives. The most important reason is the flexibility of heat supply. District heating technology has, and must continue, to develop henceforth in order to stay competitive for the future.

Four generations of district heating systems.

District heating development can be split in four generations, and characteristic is that the distribution temperatures have decreased with each generation. The first generation, from the end of the 19th century use steam with a supply temperature of 2–300 °C as energy carrier. The second generation is high-temperature water systems with a supply temperature of about 150 °C; these are still common in Eastern European countries. The third generation are the heating systems that have been developed over the latest decades, and are used today, with a supply temperature of 80–110 °C. So, what will be the fourth generation of district heating? Lund and Werner have describe what the next generation of district heating, (4GDH) could look like [28]. The most characteristic for 4GDH is the low distribution temperatures with a supply temperature of 50 °C and return temperature of 20 °C. Lower temperatures will improve system efficiency. By decreasing distribution temperatures, utilisation of low temperature heat sources and electrical output from CHPs increases and heat losses decrease. Lower distribution temperatures also imply that other materials in distribution pipes, such as PEX, could be used, resulting in lower building cost for networks. That low distribution temperatures are advantageous from a thermodynamic point of view has been well known for several decades and has been investigated continuously in the literature and seem to be the never ending story in district heating research. In 1977, Brumm described the importance of low supply temperature in order to increase electricity output from CHP plants [29]. In 1980, Amberg described how decreased return temperature using the heat from the return pipe for low temperature demands in order to decrease return temperature; it is interesting from both a technical and economical point of view [30]. In 1997, Rüetschi described the importance of district heating operators to improve customer devices to decrease return temperatures in order to remain competitive. Çomaklı et al investigated the gain from decreased system temperatures from both an energy point of view and an exergy point of view in 2004 [31], followed by Rosen et al in 2005 [32], and by Gong et al in 2012 [33].

Fourth generation district heating – New demands

District heating is used to heat buildings to 20 °C and domestic hot water to 50 °C. Why is the supply temperature over 80 °C? There are two main reasons: First, buildings' secondary systems have traditionally been designed for high supply temperatures from individual boilers fired with coal, coke, fuel oil, gas, or wood. It was rational to have high supply temperature since it reduced radiator areas and volumes of domestic hot water storages. However, according to Hasan, Kurnitski, and Jokiranta [34, 35], radiators in many countries seem to be oversized by a factor of at least two, often more. Essentially, the level of supply temperature to space heating could be lower, also in older buildings. Second, district heating substations and buildings' secondary systems suffer from large amount of faults. Paper IV states that only one quarter of the analysed buildings have substations and secondary systems working by the book. To compensate for these faults, district heating system operators increase the supply temperature.

Increased distribution temperature is not an option in the fourth generation of district heating systems. All substations and building secondary systems have to work at optimum levels, and faults have to be detected quickly, otherwise the district heating operators will not be able to supply all customers with heat, and customers will suffer from diminished comfort regarding indoor temperature and/or domestic hot water temperatures. In district heating systems, heat generation and distribution traditionally have had continuous commissioning, but substations have not. The secondary systems have building control systems at varying extents, but optimisations adapt to high supply temperatures from district heating systems.

More intelligence has to be introduced in order to run the fourth generation district heating systems. An intelligent system is characterised by three parts: measurement, analysis, and action based on the analysis [36]. Today's district heating systems could be regarded as intelligent based according to this definition when it comes to heat generation and distribution, but for substations only the first part is taking action, measuring. This work introduces the second part: analyses. Next, taking action based on analyses can have two meanings: either something is broken and needs to be repaired or settings need to be changed. The latter could be performed by some kind of demand side management, as described in Johansson and Wernstedt [36, 37], where the entire district heating system can be optimised.

Fault detection in district heating substations

There are several reasons why fault detection in district heating substations is difficult to perform. Heat demands are different for each individual building. Social heat demands are unpredictable and typical patterns can be difficult to identify. The standard instrumentation is designed for control and metering locally, and additional instrumentation has not been defendable for cost reasons. This was stated in a 1996 report from VTT Building Technology [38] and remains true. Analyses of heat load patterns with high resolution meter readings in district heating customers in the literature are scarce and the reason is lack of meter readings. In 1996, Aronsson analysed the heat load and heat power demand for 50 buildings in Gothenburg, with a meter reading resolution of 15 minutes. In this case additional meter equipment was added and the effort that was necessary to collect the data is striking [39]. In a master thesis by Nilsson and Tengqvist from 2013, 48 different customer categories were identified by analysis of heat demand pattern using meter readings from conventional heat meters [40]. Analyses in order to develop methods for fault detection from meter readings have been of more interest. An early work by Delsing and Svensson [41] used the unexpected differential temperature to identify faults. Work has also been performed with focus on identifying faults in sensors. Chen and Lan [42] developed a method for fault detection of sensors. Yliniemi [43] describes a method to detect temperature sensor faults by noise amplitude detection to recover faulty meter readings and presents methods to be able to separate hot water use from space heating. This is very interesting from a heat load pattern point of view. Statistical methods where a predicted heat load is compared with the actual used hourly meter readings and a method to detect drifting flow meters are presented in Sandin, Gustafsson, and Delsing [44]. Drifting flow meters are a well-known problem that, apart from reduced revenues, present a trustworthiness problem. A related work where statistical methods on hourly meter readings for detection of faulty flow meters is developed in Kiluk [45].

METHOD

In this work, analysis of hourly meter readings from 20 district heating systems and 146 substations from two different district heating networks have been performed. The district heating systems is located in Sweden varying in size and geographical location and the district heating substations originate in the district heating systems in Helsingborg and Ängelholm, both situated in the south of Sweden. All analyses are theoretical, but the meter readings originate from real heat meters in real substations used in the day-to-day work.

In Paper I, energy meter readings for supplied heat from 20 district heating systems have been analysed. A new method for quantification of daily variation was developed and applied to 20 Swedish district heating systems of varying size and location.

In Paper II, energy meter readings for 141 district heating substations, are analysed by identifying four heat load patterns and two descriptive parameters. The four heat load patterns defined are continuous, night set back, time clock operation five days a week, and time clock operation seven days a week. The two descriptive parameters are annual relative daily variation, defined in Paper I, and annual relative seasonal variation, defined in Paper II. The method is used to characterise heat loads, but the method in general could be applied to all types of networks, such as roads, railroads, telephone networks, and other forms of energy networks like electricity, district cooling, and gas. Figure 4 presents data from one district cooling system, two district heating systems, and three national electricity supplies. The district cooling system, located in Helsingborg in the south of Sweden, is used mainly in the daytime in the summer, while electricity in all three countries analysed is used continuously from both annual and daily perspectives.

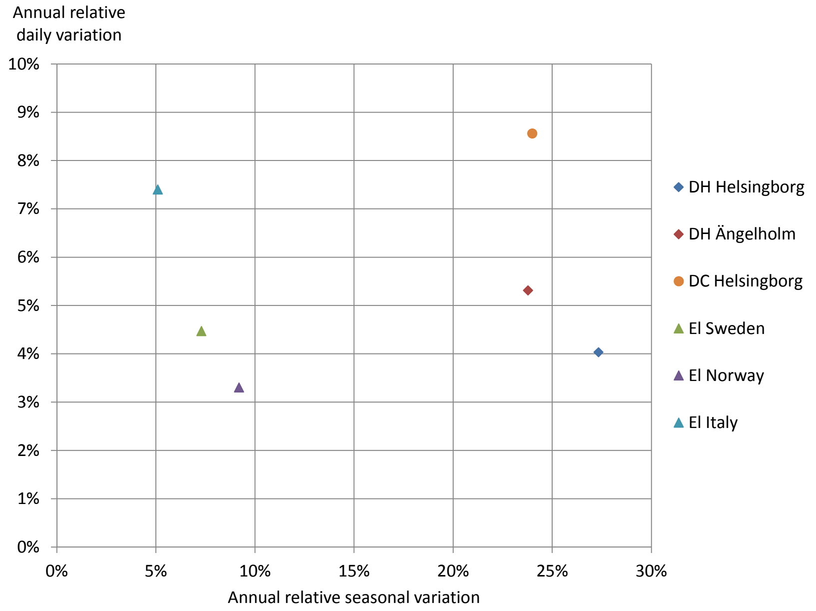

Figure 4. Annual relative daily variation and annual relative seasonal variation for one district cooling system (DC Helsingborg, two district heating systems (DH Helsingborg and DH Ängelholm), and three national electrical grids (El Sweden, El Norway, and El Italy [46]).

In Paper III, delivered energy and flow to 140 substations have been used to analyse differential temperatures in substations. A new method using differential temperature signature where temperature difference is plotted against outdoor temperature is defined. The method can be used both for fault detection and as a quality assurance of fault elimination.

In Paper IV, delivered energy and flow from 135 substations have been analysed manually. For five different customer categories, multi-dwelling buildings, industrial demands, health care and social services, trade buildings, and public administration buildings, three types of faults or symptoms of fault have been identified: unsuitable heat load pattern, low temperature difference, and poor substations control. The heat load patterns are the same as those defined in Paper II. Low temperature difference, a symptom of fault, is defined as all temperature differences below or equal to 45 °C. Poor substations control is typically a result of irregular oscillations and/or bad correlation between heat demand and outdoor temperature.

RESULTS

This section summarises the major results from the appended papers. In Paper II-IV, the evaluated number of substations differs. The reason is that the data sets from the substations are of shifting quality and depending of the method used, different number of data sets had to be excluded due to lack of relevance depending on what type of data were missing.

Paper I

In Paper I, 20 Swedish district heating systems of different size and geographical location were analysed for daily heat load variations. Daily heat load variations in Swedish district heating systems are small. In this study, daily heat load variations are estimated to be between 3% and 6% with an average of 4.5%. Seasonal variations are at the analysed district heating systems 17% to 28% with an average of 24%. That is, seasonal heat load variations are approximately five times larger than the daily variations in the analysed district heating systems.

The size of heat storage to eliminate daily heat load variations is determined to be approximately 17% of the daily average heat supply, which corresponds to 2.5 m^3/TJ of annually supplied heat if the storage medium is water with a temperature difference of 40 °C. Loading and unloading capacity for heat storage should be about half of the annual average heat load to eliminate daily variations.

Paper II

In Paper II, 141 substations, split in five customer categories, were analysed based on heat load pattern, and two descriptive parameters, annual relative daily variations and annual relative seasonal variations. In customer substations, seasonal heat load varied from 20% to 40%, while daily heat load varied from 5% to 25%.

Daily heat load variation is the most dependent on customer category, including type of activity in the building where industrial, commercial, and public administration buildings have the highest daily heat load variations; health and social services buildings are at an intermediate level, while multi-dwelling buildings have the lowest daily heat load variation.
The most important cause for high daily variations is time clock operation control of ventilation. This is, or should be, implemented in buildings where activities take place only parts of the day, such as in schools and offices. To enhance the method, redefining customer categories based on indoor activities in necessary, but this information is not available at present.

Paper III

Paper III presents a novel method through which to identify temperature difference faults. It is based in temperature signature were differential temperature is plotted as a function of outdoor temperature. The advantage for this method is that temperature difference fault can be identified in single or a few days, but also, due to the method's swiftness, it can also be used for quality assurance for measures of work to increase differential temperature. An analysis of 140 substations also identified that temperature difference faults frequency of over 6% in a period of one year. On average the fault duration was at least 57 days, most probably longer since half of the substations had faults when the data sets started or ended.

Paper IV

Paper IV presents manual analyses of 135 substations. The result indicates that only 26% of the substations work correctly. Three different fault types were identified: low annual average differential temperature, unsuitable heat load pattern, and poor substation control. Low annual average temperature difference was identified in 68% of the substations. Though it has been known for decades that large differential distribution temperature is advantageous, its utilisation is still of vital importance. The hourly meter readings in combination with the method presented in Paper III offer an opportunity to work with distribution temperatures more efficiently. Unsuitable heat load patterns occur in the magnitude of 30% of the analysed substations and depend on incorrect settings in building control systems. It is a very common fault, but on the other hand it is a fault that is easy and non-costly to attend to. Poor substation control is just as low annual average differential temperature a symptom of fault, and was identified in 12% of the substations.

CONCLUSIONS AND FURTHER WORK

Future district heating networks are presumed to have essential lower distribution temperatures than those in operation today. Present temperature demands in district heating systems are the result of a combination of tradition and many faults in substations and secondary systems. In future district heating systems these faults will not be acceptable because they will result in decreased customer comfort. This work has shown that analysis of substations and secondary systems based on hourly meter readings can be of great importance for the development of future district heating systems. Previously, heat generation and distribution have been continuously commissioned, and the time has come to introduce continuous commissioning of substation.

Conclusions

While district heating systems are rather homogeneous from a heat supply pattern point of view, the attached buildings' heat demand patterns are heterogeneous. A major difficulty in fault detection in district heating customers is not to detect deviations, but rather to identify what is normal. One very important fact is that every building is unique when it comes to heat demand. A correct heat demand for one building can be a fault for others. This is also why many methods that identify deviations from previous heat demands presented in the literature may be difficult to apply successfully. When setting up thresholds for fault detection, one has to be careful when using methods with relative thresholds; it is better to try to identify absolute thresholds. At present, when three quarters of heat deliveries have some kind of fault, it is possible to identify customer categories in which general thresholds can be applied. However, over the long-term, thresholds and limits for fault detection must be set more or less on an individual basis. This implies that extended knowledge of customer activity in each building is necessary in order to conclude whether a heat load pattern is correct or not.

Another problem is that faults are coincidental and seem to have no occurrence pattern. In the analysed substations, all types of faults were identified in every customer category. This fact in combination with individual heat demands is the reason fault prediction is very difficult, if not impossible. The only way to identify faults quickly is to learn more about individual customer heat demands in combination with introduction of continuous commissioning. Implementation would result in service and maintenance visits governed by needs and not, as is common at present, by the calendar.

Further work

This work has shown that hourly heat meter readings contain large amounts of information. This is an initial work, as very few studies in this area have has been performed before, so there is more or less an open field for further research. Three main directions of further research, without order of precedence, have been identified. One is to continue to use the same data sources as in this work, i.e. those from automatic meter reading systems and customer records. This could include developing entirely new parameters, combining two or more existing or new parameters or methods, or improving accuracy in developed methods. The second is to use data other than meter readings and customer records, such as information from the national building record and data from building control systems, as well as introducing other sensors in the connected buildings, such as separate heat meters for domestic hot water or sensors for temperatures in secondary systems and differential pressure. The third direction is to apply the fault detection methods in district heating systems and inventory buildings to confirm whether the methods work or not in order to develop and improve the methods.

One issue that has been raised during this work is how a higher resolution in the meter readings would affect the results. At the moment, with a large amount of faults, it is probable that major faults are hiding minor faults that could be identified with increased meter reading resolution; hence, the low-hanging fruits have to be picked before increased resolution is useful. However, for future generations of district heating systems with essential lower distribution temperatures, it is probable that increased resolution can be useful or even necessary to identify faults in district heating substations and customer secondary systems rapidly.

Lord Kelvin once stated, “To measure is to know!” This has been, and still is, true. But since there is an overflow of data in today’s society, it would not be out of place with a slight modification to say,

> “To analyse measurements is to know!”

REFERENCES

[1] Vanek F, Albright L. Energy Systems Engineering: Evaluation and Implementation: McGraw-Hill Higher Education; 2008.

[2] Everett B, Boyle G, Peak S, Ramage J. Energy Systems and Sustainability. Second ed. Oxford: Oxford University Press; 2012.

[3] IEA. Key world energy statistics. Paris 2009.

[4] IPCC. Fifth Assessment Report. 2014.

[5] Aleklett K, Höök M, Jakobsson K, Lardelli M, Snowden S, Söderbergh B. The Peak of the Oil Age – Analyzing the world oil production Reference Scenario in World Energy Outlook 2008. Energy Policy. 2010;38:1398-414.

[6] Cambell CJ, Laherrère JH. The end of cheap oil. Sientific American, March 1998.

[7] Cronstedt CJ. Beskrifning på Ny Inrättning af Kakelugnar Till Weds Besparing Jämte Bifogade Kopparstycken (Description of Instalation of tiled oven for wood saving). Kongl. Tryckeriet, Stockholm, around 1770.

[8] Sidén G. Förnybar energi (Renewable energy). Studentlitteratur, Lund 2009.

[9] Persson U, Werner S. District heating in sequential energy supply. Applied Energy. 2012;95:123-31.

[10] Annual statistics http://www.svenskfjarrvarme.se/Statistik--Pris/Fjarrvarme/Energitillforsel/ accessed 2014-06-30: Swedish District Heating Association; 2003-2013.

[11] Annual statistics. Swedish District Heating Association; 1970-2002.

[12] Lund H, Möller B, Mathiesen BV, Dyrelund A. The role of district heating in future renewable energy systems. Energy. 2010;35:1381-90.

[13] Gadd H, Werner S. Achieving low return temperatures from district heating substations. Applied Energy. 2014;136:59-67.

[14] Gummérus P. Analys av konventionella abonnentcentraler I fjärrvärmesystem (Analysis of conventional substations in district heating

systems) [Doctoral thesis]. Gothenburg: Chalmers University of Technology; 1989.

[15] Euroheat & Power, DHC_2009_Statistics_Table.pdf, District Heating and Cooling-2009 Statistics. http://www.euroheat.org/Statistics-69.aspx accessed 2012-06-04.

[16] Frederiksen S, Werner S. District Heating and Cooling. Lund: Studentlitteratur; 2013.

[17] Werner S. District Heating and Cooling. Encyclopedia of Energy 1; 2004. p. 841-8.

[18] Frederiksen S. A Thermodynamic Analysis of District Heating [Doctoral Thesis]. Lund: Lund Institute of Technology; 1982.

[19] Riksdagen. SFS 1997:857. Ellag (Electricity distibution act). Stockholm.

[20] Riksdagen. SFS 1999:716. Förordning om mätning, beräkning och rapportering av överförd el (Decree on metering, calculation and reporting of transporter of electricity). Swedish Ministry of Enterprise.

[21] Riksdagen. SFS 2008:263. Fjärrvärmelag (District heating act). Stockholm.

[22] From operators to optimisers. Modern Power Systems, 33; 6: p26-7 2013.

[23] Roman R, Zhou J, Lopez J. On the features and challenges of security and privacy in distributed internet of things. Computer Networks. 2013;57:2266-79.

[24] How big data can lead to lower cost. Modern Power Systems, 34;5, 2014.

[25] Kirunas energiförbrukning på Google Earth (The city of Kiruna energy demand in Google Earth). http://www.ltu.se/ltu/media/Kirunas-energiforbrukning-pa-Google-Earth-1.116846 accessed 2014-04-07: Luleå University of Technology; 2014.

[26] Swedish Energy Market Inspectorate. EIFS 2014:2 Energimarknadsinspektionens föreskrifter och allmänna råd om mätning, rapporteringoch debitering av levererad värmeenergi (fjärrvärme) (The Swedish Energy Markets Inspectorate decree and general advises regarding metering, reporting and delivery of thermal energy (District heating)).

[27] Swedish Enery Markets Inspectorate. Vägval för en utvecklad marknad för mätning och rapportering av el. (Crossroads for a developed market of metering and reporting of electricity). Eskilstuna 2012.

[28] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. Energy. 2014;68:1-14.
[29] Brumm W. Fragen der Temperaturspreizung. Fernwärme International. 1977;6:129-33.
[30] Amberg HF. Verbesserte Ausnutzung von Fernheiznezen durch Senken der Rücklauftemperatur. Fernwärme international. 1980;9:151-5.
[31] Çomaklı K, Yüksel B, Çomaklı Ö. Evaluation of energy and exergy losses in district heating network. Applied Thermal Engineering. 2004;24:1009-17.
[32] Rosen, A M, Le MN, Dincer I. Efficiency analysis of a cogeneration and district energy system. Applied Thermal Engineering. 2005;25:147-59.
[33] Gong M, Wall G, Werner S. Energy and exergy analysis of district heating systems. The 13th International Symposium On District Heating and Cooling. Copenhagen 2012.
[34] Hasan A, Kurnitski J, Jokiranta K. A combined low temperature water heating system consisting of radiators and floor heating. Energy and Buildings. 2009;41:470-9.
[35] Peterson S. Analys av konventionella radiatorsystem (Analysis of conventional radiator systems) [Licentiate thesis]. Gothenburg: Chalmers University of Technology; 1998.
[36] Johansson C. On Intelligent District Heating [Doctoral Dissertation]. Karlskrona: Blekinge Institute of Technology; 2014.
[37] Wernstedt F. Multi-agent systems for distributed control of district heating systems [Doctoral thesis]. Karlskrona: Blekinge institute of Technology; 2005.
[38] Ahonen M, Hyvärinen J, Kuismin J, Pakanen J. Fault detection methods for district heating substations. Research notes 1780. Oulu: VTT Building technology; 1996.
[39] Aronsson S. Heat Load of Buildings Supplied by District Heating: An analysis based on measurements in 50 buildings [Doctoral thesis]. Gothenburg: Chalmers University of Technology; 1996.
[40] Nilsson C, Tengqvist H. Kategorisering av fjärrvärmekunder utifrån användarmönster (Categorisation of district heating customers based on heat demand pattern) [Master Thesis]. Lund: Lund University; 2013.
[41] Delsing J, Svensson B. En ny metod för funktionsdiagnos och felsökning av fjärrvärmecentraler utifrån värmemängdsdata (A new method for operation diagnosis and fault detection in substations by using heat meter readings). Luleå: EISLAB, Luleå university of technology; 2001.

[42] Chen Y, Lan L. Fault detection, diagnosis and data recovery for a real building heating/cooling billing system. Energy Conversion and Management. 2010;51:1015-24.
[43] Yliniemi K. Fault detection in district heating substations [Licentiate Thesis]. Luleå Luleå University of Technology; 2005.
[44] Sandin F, Gustafsson J, Delsing J. Fault detection with hourly district energy data. Stockholm: Swedish district heating association; 2013.
[45] Kiluk S. Algorithmic acquisition of diagnostic patterns in district heating billing system. Applied Energy. 2012;91:146-55.
[46] ENTSO-E. Consumption Data. https://www.entsoe.eu/data/data-portal/consumption/Pages/default.aspx accessed 2014-07-10.