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Gadd, Henrik

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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

TO ANALYSE MEASUREMENTS IS TO KNOW!

Analysis of hourly meter readings in district heating systems

Henrik Gadd

LUND UNIVERSITY

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Fakultetsopponent: Professor Erik Dahlquist, Avdelningen för energi, bygg och miljö, Akademin för ekonomi, samhälle och teknik, Mälardalens Högskola

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Analysis of hourly meter readings in district heating systems

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 systems 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.

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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

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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.

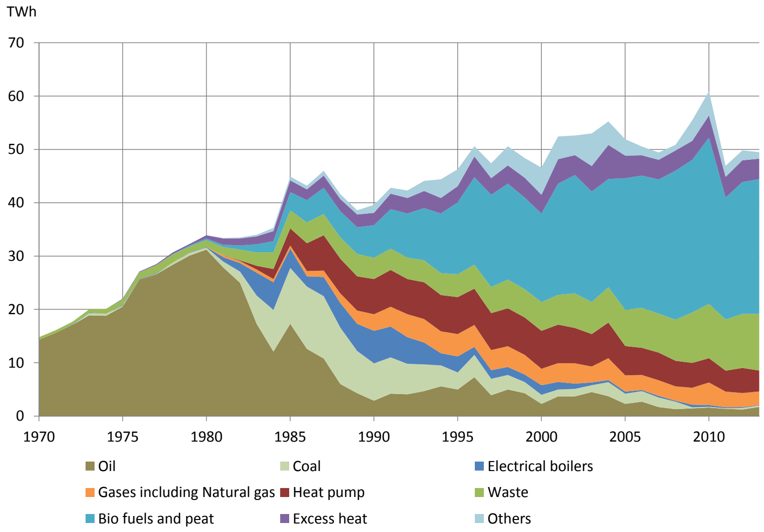

Figure 1. Annual fuel supply to Swedish district heating systems 1970–2013. (Data from [10] and [11])

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.

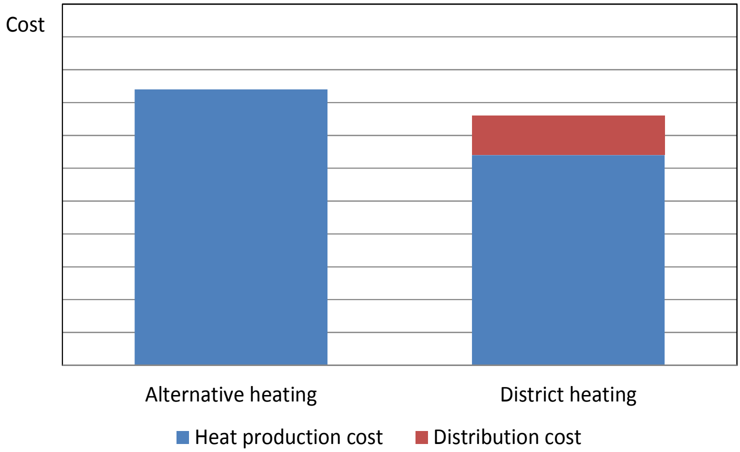

Figure 2. Market condition for district heating illustrating that the heat generation must have essential lower cost than local generated heat.

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.

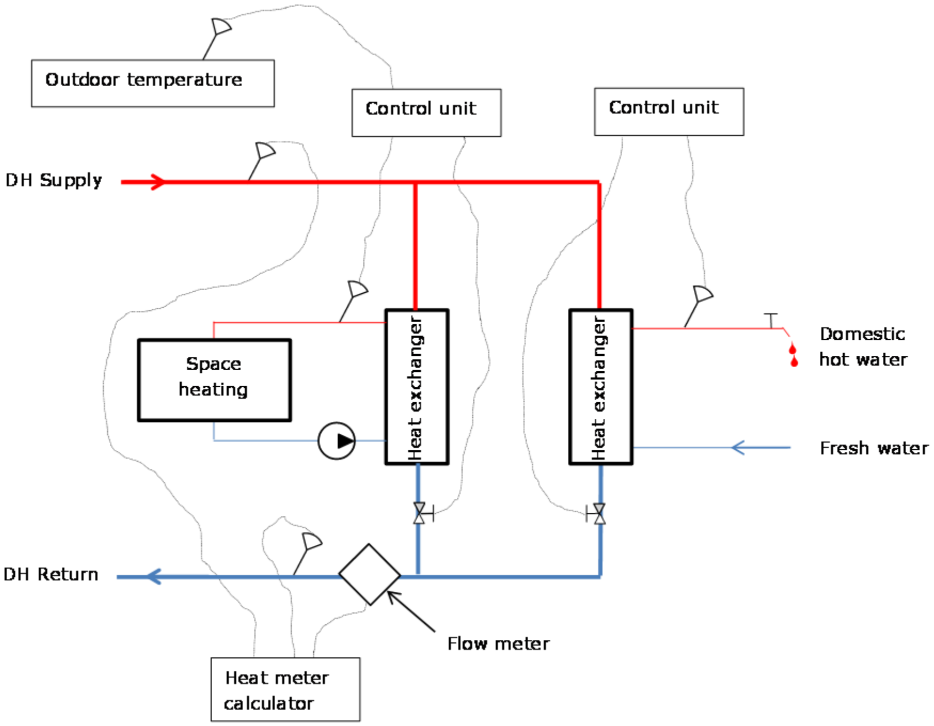

Figure 3. Schematic overview of indirect coupled district heating substation with heat meter.

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.

DATA COLLECTION

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.

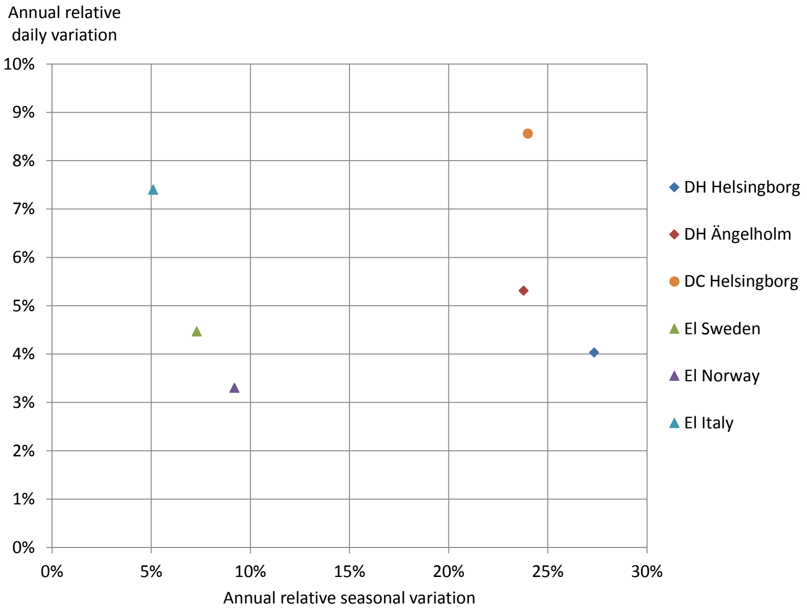

Figure 4. Annual relative daily variation and annual relative seasonal variation for one district cooling system (DC Helsingborg, two district heating systems (DH Helsingborg and DH Ängelholm), and three national electrical grids (El Sweden, El Norway, and El Italy [46]).

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!”

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Paper I

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Daily heat load variations in Swedish district heating systems

Henrik Gadd *, Sven Werner

School of Business and Engineering, Halmstad University, P.O. Box 823, SE-301 18 Halmstad, Sweden

HIGHLIGHTS

- ▶ Novel method for evaluation of daily heat load variations.
- ▶ Daily heat load variations are 3–6% of annual heat supply in Swedish district heating systems.
- ▶ Daily heat load variations is small compared to seasonal heat load variation.
- ▶ Heat storage size to eliminate daily variations is estimated to 2.5 m^3 per TJ supplied heat annual.

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ABSTRACT

Heat load variations in district heating systems are both seasonal and daily. Seasonal variations have mainly its origin from variations in outdoor temperature over the year. The origin of daily variations is mainly induced by social patterns due to customer social behaviours. Heat load variations cause increased costs because of increased peak heat load capacity and expensive peak fuels. Seasonal heat load variations are well-documented and analysed, but analyses of daily heat load variations are scarce. Published analyses are either case studies or models that try to predict daily heat load variations. There is a dearth of suitable assessment methods for more general analyses of existing daily load variations.

In this paper, a novel assessment method for describing daily variations is presented. It is applied on district heating systems, but the method is generic and can be applied on every kind of activity where daily variations occur. The method was developed from two basic conditions: independent of system size and no use of external parameters other than of the time series analysed. The method consists of three parameters: the annual relative daily variation that is a benchmarking parameter between systems, the relative daily variation that describes the expected heat storage size to eliminate daily variations, and the relative hourly variation that describes the loading and unloading capacity to and from the heat storage. The assessment method could be used either for design purposes or for evaluation of existing storage.

The method has been applied on 20 Swedish district heating systems ranging from small to large systems. The three parameters have been estimated for time series of hourly average heat loads for calendar years. The results show that the hourly heat load additions beyond the daily averages, vary between 3% and 6% of the annual volume of heat supplied to the network. Hereby, the daily variations are smaller than the seasonal variations, since the daily heat load additions, beyond the annual average heat load, are between 17% and 28% of the annual volume of heat supplied to the network. The size of short term heat storage to eliminate the daily heat load variations has been estimated to a heat volume corresponding to about 17% of the average daily heat supplied into the network. This conclusion can also be expressed as an average demand of 2.5 m^3 of heat storage volume per TJ of heat supplied by assuming a water temperature difference of 40 °C. The capacity for loading and unloading the storage should be equal to about half of the annual average heat load for heat supplied into the network.

1. Introduction

Heat deliveries in Swedish district heating systems are mainly used for space heating and domestic hot water preparation. Some industrial applications exist, but in many cases, the supply temperature in the district heating systems is too low to be used in industrial processes.

Heat load in district heating systems is the aggregated heat load from the heat customers connected to the district heating network and the distribution losses. The heat supply is controlled by four independent factors: the first one is the hot water taps and valves

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* Corresponding author. Tel.: +46 35 167757.
E-mail address: henrik.gadd@hh.se (H. Gadd).

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in radiators and ventilation air heating systems which control the heat demand. The second one is the control valves in the primary side of the substation which keeps constant temperature of hot water and supply temperature to heating systems depending on outdoor temperature by controlling the primary flow. The third one is differential pressure control on the primary side where the differential pressure has to be kept at a set point at the periphery of the network. The fourth one is the supply temperature on the primary side depending on outdoor temperature, i.e. it is the heat users that are in control of the heat demand. The district heating operators deliver a possibility for a proper heat supply. Since the heat load at the customers' end is not constant, heat load variation at the customers results in heat load variation in the heat plant.

The heat demand from a district heating system is fulfilled by a water mass flow and a temperature difference, i.e. there are two ways to satisfy changes in heat demand: changing the flow through all district heating sub-stations or changing the temperature difference between the supply and return pipes. If a customer increases the heat demand by increasing the mass flow, the increased heat demand propagates to the heat plant by the speed of sound in water, i.e. approximately 1000 m/s. But, if the customers increase the heat demand by increasing the temperature difference, the heat demand propagates to the heat plant with the flow rate of the water in the district heating pipes, i.e. 1–3 m/s. Hence, changes in heat demand, due to changes in flow rate, propagate to the heat plant in a few seconds, while heat demand due to changes in temperature difference will propagate to the heat plant in minutes for the customers close to the heat plant and in hours for customers at the periphery of the district heating network, at least in large district heating systems. This is called geographical diversity. For further information about district heating system functions, see [1].

Large variations in the outdoor temperature between summer and winter generate large heat load variations over the year, seasonal heat load variations, but there are also heat load variations between, and within single days: daily heat load variations.

In published analyses, several papers with case studies or suggestions to predict or control the heat load in the heat plant can be found.

In a model of heat load forecasting it is stated that especially the fast changes in heat load is difficult to predict [2]. Heat load prediction would make it possible to take action in advance. A prediction by simulating a repetitive heat load pattern is presented in [3] and [4]. A support for actions in the district heating network is described in [5], where a method to predict how a temperature front propagates in a district heating network. By using multi-agent systems, where the substations and the heat plant can communicate with one another, a possibility to control each part of the system, including the substations, and optimise the whole system would be possible [6,7]. One possibility with this method would be if there are deficits of heat, the existing heat could be supplied to all heat customers instead of only to the customer closest to the heat plant. A second possibility would be to use buildings as heat storage as described in [8] and thereby be able to use the entire district heating system, including the connected buildings, as heat storage. Advantages of daily heat load variation elimination are described in [9]. The possibility of optimising and reducing peak loads i.e. decreasing the daily heat load variation is described in [10] by using heat meter measures at the customers as input information.

It is obvious that daily variations can cause load problems. Various actions are being taken in order to decrease daily heat load variations, but there is a dearth of suitable assessment methods for general analyses of how to quantify daily heat load variations in district heating systems. In this paper a generic method independent of system size and parameters other than the time series analysed is described. The method could be used for either design purposes or for an evaluation of existing storage units. This method will then be applied on 20 Swedish district heating systems. More knowledge about heat load variations is needed in order to create smarter heat grids in the future.

1.1. Seasonal heat load variation

Seasonal heat load variation is well-known and obvious. It mainly depends on large differences in outdoor temperatures between winter and summer, combined with the demand to have a more or less constant temperature inside the building envelopes.

Heat loads can be split into two categories: physical heat load and social heat load. Heat loads that depend on physical conditions, like temperature differences and degrees of insulation, is called physical heat load. Distribution losses are also physical losses since they depend on the temperature difference between the district heating water and the surrounding temperature of the district heating pipes. Other physical heat loads is the influence of wind and solar radiation. Wind increases the heat demand because of infiltration. Warm air is replaced with cold air that has to be heated. Solar radiation decreases the demand of external heat in two ways. It increases the temperature of the exposed outer walls and thereby decreases the flow of heat from the inside of the building through the walls and windows acting like a greenhouse where solar radiation is let into the building, but the reflected long-wave radiation cannot pass throughout the window panes. Both wind and solar radiation increase the seasonal heat load variations. The windiest parts of the year are when it is cold outside and solar radiation is the most intense during the warm parts of the year.

Social heat load depends on the social behaviour of the tenants. A typical social heat load is domestic hot water preparation. This preparation is an important factor for daily heat load variation as will be described hereafter. There is a seasonal component in hot water preparation as well. In winter, people spend more time indoors and thereby use more hot water. In summer and during holidays, some people leave their urban dwellings temporarily and do not use hot water at all. Hence, domestic hot water preparation increases the seasonal heat load variation. One part of the physical heat load in domestic hot water is that the temperature of the incoming water changes during the year. This is especially true in cities where fresh water is taken from a surface water reservoir. In this case, the seasonal heat load variation will increase since the incoming cold water is colder in winter than in summer. Further description of seasonal heat load variations in district heating system can be found in [11].

In Fig. 1, a typical seasonal heat load pattern can be observed with high heat loads during winter and low heat loads during summer.

1.2. Daily heat load variation

Heat demands in a district heating system are generated at the customers' end. These heat demands are not constant during the day. Even though district heating systems even out daily heat load variations as a result of geographical diversity and also that heat load peaks at the customers' end do not occur at the same moment, there are still daily heat load variations. There are several reasons for daily heat load variations in district heating systems. Most of them are social heat demands. When a person chooses to turn on a hot water tap to wash their hands it will result in an increased heat demand in the building that will reach the heat supply plant through the district heating network. Social heat demands are heat demands caused by both individual and collective social behaviours. One example of individual social behaviour is hot water

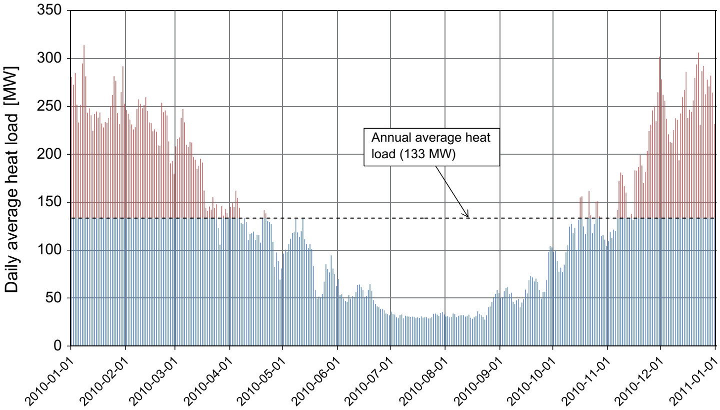

Fig. 1. Seasonal heat load variation illustrated by the daily average heat load during a year in a district heating systems with an annual heat supply of about 4400 TJ.

consumption. Harmonised working hours is an example of collective social behaviour. In offices and schools, where no people are present in the buildings at nights and weekends, no or lower ventilation rates can be applied. Hereby, time clock operation of ventilation should be used in all ventilated spaces that are not in use 24 h a day. This action will decrease the heat demand, but it will also create daily heat load variations.

In residential dwellings, tenants normally sleep at night and do not use domestic hot water, but when they wake up, the first thing they do is to go to the bathroom and turn on the hot water tap. This behaviour will increase the heat demand and create daily heat load variations. The same thing will occur when people come home from work in the evening and start using hot water. Night setback mode is still available in heating control systems; even though it does not decrease the total heat use it increases the heat load variation in a way close to time clock operation of ventilation [12].

In domestic hot water preparation, two different methods are used: direct hot water preparation and hot water storage. In direct preparation, the hot water is heated momentarily at usage in a heat exchanger, which has the capacity to fulfil all peak demands directly. The hot water storage method has a heat exchanger with a lower capacity for loading the storage. At peak demands, the storage of domestic hot water is unloaded. When stored hot water is used, the hot water is replaced with cold water. When using direct preparation, the preparation coincides with the use, creating some daily heat load variations. When hot water storage is used, the daily load variations will not be so pronounced.

There are also physical heat loads that generate daily heat load variations. The fact that night-time outdoor temperatures are normally lower than daytime temperatures generates daily heat load variations. Solar radiation also decreases the daytime heat loads. A typical heat load pattern can be observed in Fig. 2. Three characteristics can be identified:

1. Two peaks during a day, one heat power peak in the morning and one peak in the afternoon.
2. The influence of large differences in outdoor temperature during night and day in spring and autumn gives a significant dip in the heat load in the middle of the day.
3. No or small weekly heat load variations, i.e. variations between different days of the week.

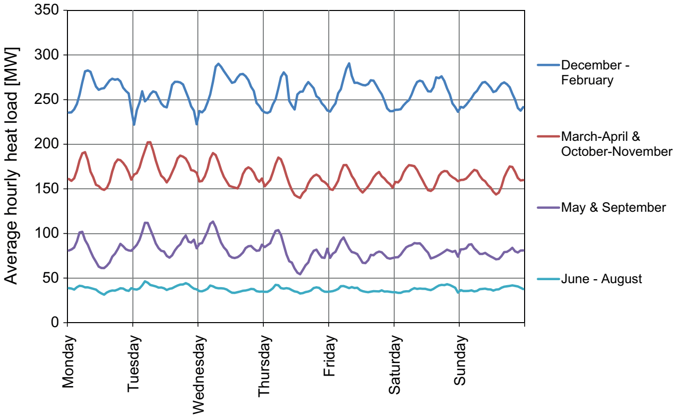

Fig. 2. Daily heat load variation illustrated by the aggregated average hourly heat load during weekdays for four different seasons in a district heating systems with an annual heat supply of about 4400 TJ.

1.3. Consequences of heat load variation

Heat load variations, both seasonal and daily, generate increased costs in district heating systems. Heat plants must always generate and supply the customer's aggregated heat power to the district heating network. A problem in district heating systems is that if not enough heat power is supplied to the network it does not affect all customers equally, but only the peripheral customer in the district heating network. If the heat supply to the district heating network is less than the heat demand, the customer closest to the heat plant will not notice any lack of heat, but customers at the periphery of the district heating network will not get any or very little heat. The reason for this is that the differential pressure between supply and return pipe is highest close to the heat plant and then decreases at the periphery of the district heating network. At the customers' end, it is the differential pressure between supply and return pipe that drives the flow through the district heating substation. The differential pressure control is managed by the main distribution pumps in the district heating network and there are normally no local pumps at the customers' buildings. Therefore the customers closest to the heat plant will have the highest differential pressure and use it to increase the flow of district heating water through the district heating substations to increase the heat power while the customers at the periphery will suffer from a lack of heat. As a consequence of this fact, most of the time an overcapacity of heat power has to be available to secure the heat supply to all heat customers.

One way to handle the variation, and the one that is mostly used, is to have heat storages. In the 1980s, investigations and some tests were performed to have seasonal storages to store heat in summer to be used in winter, but so far no competitive technology exists [13,14]. The cost of the seasonal heat storage is too large compared to alternative heat costs. The only seasonal heat storage in operation known by the authors is located in Marstal, Denmark, where heat storage for a solar district heating system is in use [15].

For daily variations though, there are a number of possible methods to decrease peak load capacity and thereby also reduce the heat load capacity need in the district heating systems. Often it is a part of the optimisation of heat storage where other influences like increased electricity generation and maximization of industrial excess heat are included. Various examples of heat storage sizing are presented in [16] and [17]. It is stated in [17] that the optimal heat storage is strongly connected to the relative amount of relative peak load, i.e. how large the heat load variation is. The district heating network contains a large mass of water. By increasing the supply temperature above what is necessary for the present heat supply, heat can be stored in the network. Another solution is to use heavy buildings connected to the district heating network as heat storage [8]. In heavy buildings with time constants of a few hundred hours, it would be possible to increase the heat supply during low load in the district heating system and decrease the heat supply during high load without a reduction of the customers' heat comfort.

If daily heat load variations could be eliminated in district heating systems, it would make the operation of the district heating system less costly and more competitive. There would be several advantages in the operation such as:

- Less use of expensive peak load power where often expensive fuels are used.
- Less need for peak load power capacity.
- Less need for electricity for district heating network pumping.
- Improved utilisation of industrial excess heat.
- Easier to optimise the operation that leads to higher conversion efficiencies.
- Less need for maintenance because of a smoother operation of the plants.

Before water accumulators are built or devices installed to store heat in the district heating network or customers' buildings, the heat load variations and existing storages need to be characterised and quantified. Even though daily heat load variations are often mentioned as something that is desirable to eliminate, no work has been found that more closely describe nor quantify daily heat load variations.

In this paper a novel assessment method to describe daily variations is presented. It is applied on district heating systems but is generic and could be applied on every kind of activity where daily variations occur. Daily heat load variations in district heating systems can be characterised by giving answers to these three questions:

- Which magnitude has the daily heat load variation in a district heating system?
- Which heat storage volume is needed in order to eliminate the daily heat load variations?
- Which capacity is needed for loading and unloading this heat storage?

2. Methods

The requirements when developing the method described below were to have a generic method independent of system size and parameters other than the analysed time series.

Time series of heat supplied into 20 Swedish district heating networks have been collected in order to analyse the daily heat load variations. The resolution in these time series is 1 h, giving 8760 hourly average heat load values for 1 year for each system.

In order to describe the daily heat load variations, three different variables have been defined:

1. Annual relative daily variation (G_a).
2. Relative daily variation (G_d).
3. Relative hourly variation (G_h).

To be able to compare daily variations with seasonal variations, a fourth variable for seasonal heat load variations has been defined:

1. Annual relative seasonal variation (D_a).

The annual relative daily variation, G_a, is a measure of the daily heat load variation during a year. The value itself expresses the annual proportion of the sum of all heat loads supplied over each daily average heat load over 1 year. It is used to compare different district heating systems with each other.

The relative daily variation, G_d, is a measure of the daily heat load variation for a single day. This variable expresses how much heat that needs to be stored each day in order to eliminate each daily heat load variation. A heat storage that stores as much heat as the highest value of the year will give the possibility of eliminating all daily heat load variations. The sum of all relative daily variations divided by 365 becomes the annual relative daily variation.

The relative hourly variation, G_h, is the daily variation each hour. It expresses the heat transport capacity for loading and unloading the heat storage each hour. In order to be able to eliminate all daily heat load variations, a heat transport capacity to and from the heat storage equal to the highest relative hourly variation is needed.

The annual relative seasonal variation, D_a, is a measure of the seasonal heat load variation during a year. The value itself expresses the sum of all daily average heat loads supplied over the annual average heat load in 1 year.

All four variables are relative variables related to the annual average heat load multiplied by the number of hours related to the variable: 8760 h for the annual relative daily variation, and the annual relative seasonal variation, 24 h for the relative daily variation, and 1 h for the relative hourly variation. The four variables are determined from hourly average heat load (P_h), daily average heat load (P_d) and annual average heat load (P_a).

2.1. Annual relative daily variation (G_a)

Annual relative daily variation is defined as:

$$G_a = \frac{\frac{1}{2}\sum_{h=1,d=1}^{8760,365}|P_h - P_d|}{P_a \cdot 8760} \cdot 100\ (\%) \qquad (1)$$

where P_h is hourly average heat load (W); P_d is daily average heat load (W) and P_a is annual average heat load (W).

The annual relative variation is the accumulated positive difference between the hourly average heat loads and the daily average heat loads during a year divided by the annual average heat load and the number of hours during 1 year. The division with the annual average heat load is introduced in order to get a measure independent of system size. The annual relative daily variation is expressed with one single value per system and year. The value itself expresses the annual proportion of all heat loads supplied over the daily average heat loads. These annual values can be used to compare the daily heat load variations from various district heating systems.

2.2. Relative daily variation (G_d)

Relative daily variation is defined as:

$$G_d = \frac{\frac{1}{2}\sum_{h=1}^{24}|P_h - P_d|}{P_a \cdot 24} \cdot 100\ (\%) \qquad (2)$$

The relative daily variation is the accumulated positive difference between the hourly average heat load and the daily average heat load divided by the annual average heat load and the number of hours during a day. The relative daily variation is expressed with 365 values per system and year.

Relative daily variation is determined for each day and is a variable that quantifies the amount of heat that is diverted from the daily average heat load. A heat storage size equal to the largest value of relative daily variation during a year is enough to eliminate all daily variations over the year.

2.3. Relative hourly variation (G_h)

Relative hourly variation is defined as:

$$G_h = \frac{|P_h - P_d|}{P_a} \cdot 100\ (\%) \qquad (3)$$

The relative hourly variation is the absolute difference between the hourly average heat load and the daily average heat load divided by the annual average heat load. The relative hourly variation is expressed with 8760 values per system and year.

The relative hourly variation is the heat power capacity for loading and unloading the heat storage to eliminate the daily variations. A heat power capacity of loading and unloading the heat storage equal to the largest value of relative hourly variation is the amount of heat load capacity to eliminate daily heat load variations over the year.

2.4. Annual relative seasonal variation (D_a)

The annual relative seasonal variation is defined as:

$$D_a = \frac{\frac{1}{2}\sum_{d=1}^{365}|P_d - P_a|}{P_a \cdot 8760} \cdot 100\ (\%) \qquad (4)$$

The annual relative seasonal variation is the accumulated positive difference between the daily average heat loads and the annual average heat load during a year divided by the annual average heat load and the number of hours during 1 year. The division with the annual average heat load is introduced in order to get a measure independent of system size. The annual relative seasonal variation is expressed with one single value per system and year. The value itself expresses the annual proportion of all heat loads supplied over the annual average heat load.

3. Gathered data

The data sets that are used to determine the daily heat load variations have been collected from 20 district heating systems in Sweden. It is the heat supply to the district heating network, i.e. distribution losses are included in the measuring values. The sizes of the analysed district heating systems are between 32 TJ and 13,300 TJ heat supplied annually to the networks.

The data sets consist of 1-year series from 1st of January to 31st of December, i.e. 8760 values each year. The unit of the values from the meter reading system is MW h/h. Most of the data sets are from 2008 and 2009, but a few are from the years 2004–2007.

For most district heating systems a 1-year data set is collected, but for two district heating systems 5 and 6 years of data sets respectively are collected. This multiyear data is used to analyse the daily heat load variation between different years, later presented in the result section.

The hourly average heat load is often called heat power, but it is actually delivered energy during 1 h. The heat is continuously measured every whole hour. The present meter value minus the preceding meter value is the hourly value for the present hour.

District heating systems with an annual heat supply of more than 700 TJ are normally measured hourly. For district heating networks with an annual heat supply of less than 350 TJ, the number of systems that measure hourly is fast decreasing.

For most of the data series, no or only single values are missing, but in a few cases, values in the annual data series are not complete. For single values and up to five values in a row of missing values are reconstructed by interpolation. Since district heating network systems are thermally slow, changes in the heat power are also slow. If there are more than five values missing, an analysis of the day before and the day after was made to see if there is a typical heat load pattern. Sometimes it is possible to interpolate more than five values. If the pattern does not show a linear behaviour the values from either the day before or the day after are copied. Which day that is used depends on which of the days that looks most like the day with the incomplete data series. The amounts of corrected values are less than one per thousand and have thereby no impact on the results.

4. Results

4.1. Annual relative daily variation

As can be observed in Fig. 3, the annual relative daily variation does not differ much between the different district heating systems. In the studied district heating systems, the annual relative daily variations are between 2.6% and 5.7% of the annual volume of heat supplied into the district heating networks with a mean value of 4.5%. It is only two large systems that have somewhat lower annual relative daily variation.

If the same method is used for seasonal heat load variation as for daily variation the annual relative seasonal variation is in average 24% with a spread of between 17% and 28%. The annual relative seasonal variation for system in Fig. 1 is 27% which corresponds to the area over the mean value divided by the total annual heat supply.

Compared to the seasonal heat load variation, daily heat load variation is very low. The reason for this is that the main part of heat demand is caused by the difference between outdoor and indoor temperatures.

An expected result would be that large district heating systems have smaller relative daily variations (G_a) than small district heating systems. There are two reasons for that:

1. In large district heating networks, customers are geographically spread over different pipe distances from the heat supply plants. Hereby, the water in the return pipe arrives to the heat supply plants at different times compared to when the return water leaves each substation. This is called geographical diversity in the district heating network and should reduce the daily heat load variation.
2. In large district heating networks, you would expect that the operators are more actively involved in the heat distribution network with respect to temporary heat storage in the district heating network.

But as can be observed in Fig. 3 it is not as simple as that. The daily heat load variation is more or less the same for most district heating systems. For district heating systems larger than 4000 TJ annually delivered heat seems to have smaller daily heat load variations.

The annual relative daily variation for of the Swedish total electricity use in 2008 was as a comparison 4.5%, with a total delivered amount of electricity of 497 PJ [18]. In other words, about the same size of daily heat load variation as the district heating systems. One district cooling system with 72 TJ of annually supplied cold has

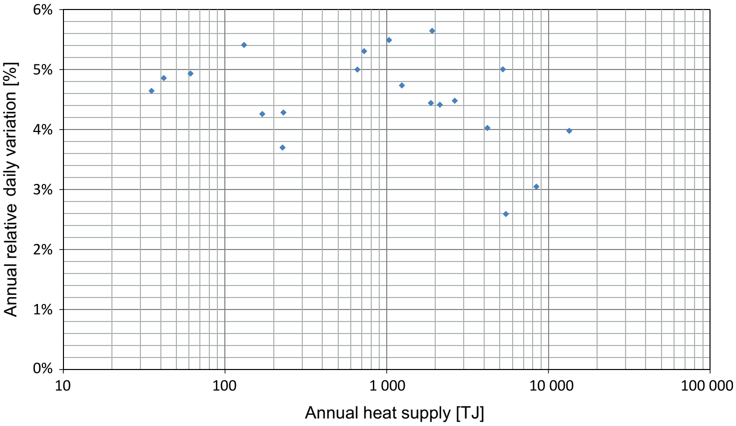

Fig. 3. Annual relative daily variation for the 20 Swedish district heating systems analysed.

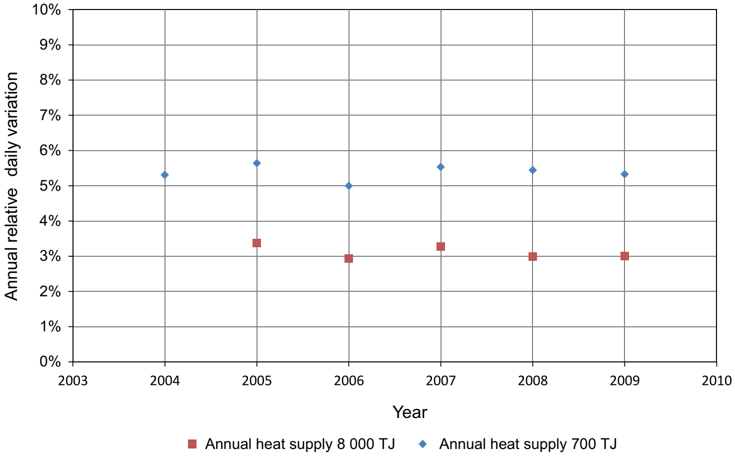

Fig. 4. Annual relative daily variation over a number of years for two Swedish district heating systems with an annual heat supply of about 700 TJ and 8000 TJ respectively.

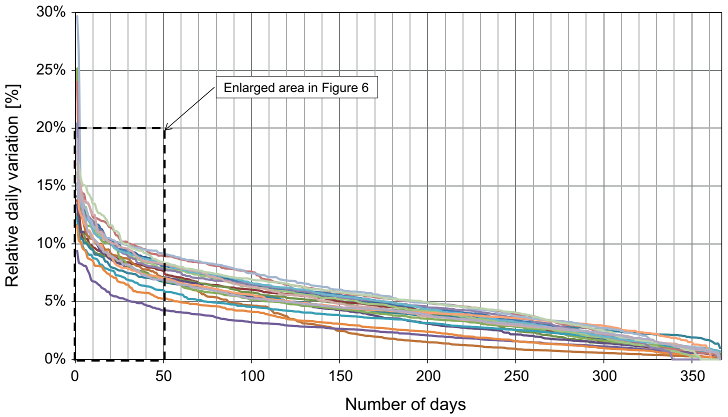

Fig. 5. Relative daily variation for the 20 Swedish district heating systems analysed.

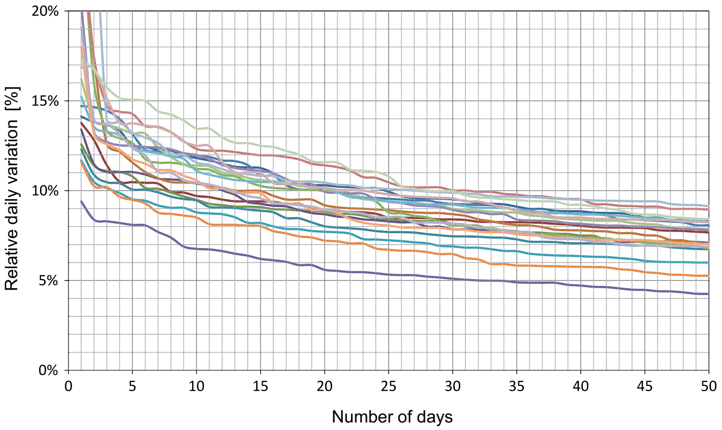

Fig. 6. Enlarged part of Fig. 5 showing the peak parts of the relative daily variation.

also been evaluated. The annual relative variation in this system was 8.6%, which is twice the daily variation estimated for the district heating networks.

To investigate if the annual relative daily variation differs from 1 year to another, multiyear data series were gathered for two district heating systems. Both district heating systems are located in the south of Sweden, one with an annual heat supply of 700 TJ and one with an annual heat supply of 8000 TJ, Fig. 4. The difference is 0.44% units for the larger system and 0.65% units for the smaller system; in other words, the difference in annual relative daily variations between different years is small.

4.2. Relative daily variations

In Fig. 5, the relative daily variation is calculated for each day during the year and sorted by magnitude for the 20 Swedish district heating systems analysed. Fig. 6 contains the same information, but focuses on the highest values obtained.

Maximum value for the largest daily heat load variation is 30% of daily average heat supply and minimum value is 9%. Average value is 17%. This corresponds to 0.05% of the annual heat supplied. In the absence of an economic evaluation the 99th percentile could be used as design condition to exclude extreme values. For the 99th percentile, corresponding to 3.65 days, the maximum value has decreased to 15%, minimum value to 8%, and average value to 12%.

With an effective heat storage size corresponding to 12% of daily average heat load, almost all daily heat load variations are possible to eliminate.

The conclusion above can also be used for estimating the specific demand of a heat storage volume. For each TJ of annual heat supplied, the annual average heat load becomes 32 kW, so with 3.6 h of operation (15% of 24 h), this will give a demand for storing 410 MJ. Assuming a 40 °C temperature difference for the heat storage, the requested water volume becomes almost 2.5 m^3 for each TJ of heat supplied during a year. The corresponding heat storage volume for the relative daily variation of 12% is 2 m^3/TJ of annually supplied heat.

A brief study has been performed for existing heat storages in Swedish district heating systems. The result is that the sizes of heat storage installed are between 4% and 250% with an average of 47% of average daily supplied heat; i.e. the average heat storage in Swedish district heating systems is three times larger than the heat

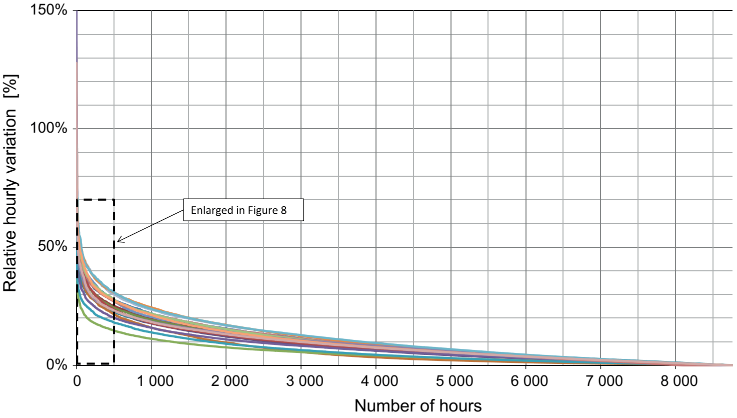

Fig. 7. Relative hourly variation for the 20 Swedish district heating systems analysed.

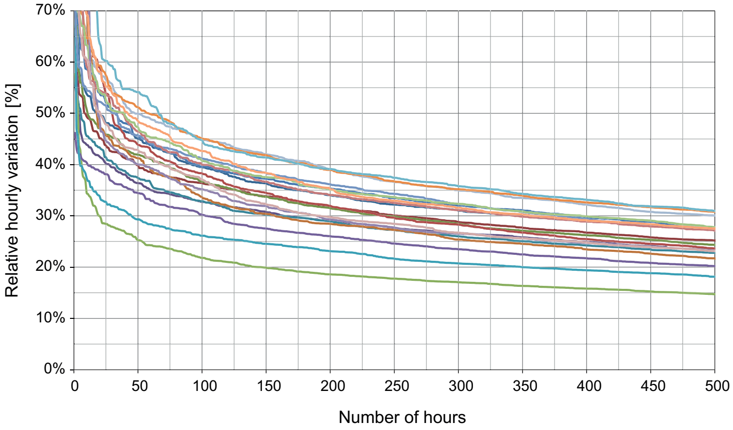

Fig. 8. Enlarged part of Fig. 7 showing the peak parts of the relative hourly variation.

storage size demand to eliminate daily heat load variations. This indicates that heat storages are used to do more than eliminate daily heat load variations.

4.3. Relative hourly variation

In Fig. 7, the relative hourly variation is calculated for each hour over a year. Note that it is the absolute value, i.e. it can be either loading or unloading capacity. Fig. 8 contains the same information but magnified for the high values.

Highest value of all 20 district heating systems is 196% of annual average heat load and the lowest is 46%. Average value is 91%. With the same reason as for relative daily variations, i.e. absence of economical evaluation, the 99th percentile could be used as sizing condition to exclude extreme values. In the 99th percentile the max value has decreased to 47%, min has decreased to 23% and the average value to 38%.

On the analogy of relative daily variation a specific heat loading and unloading capacity for the heat storage to eliminate heat load variations can be quantified. An hourly relative variation of 38% results in a loading/unloading capacity of 12 kW for each TJ supplied.

5. Conclusions

A novel assessment method for describing daily variations is presented. It is a generic method independent of system size and other parameters than the analysed time series. Three parameters have been defined: annual relative daily variation, which is a benchmarking parameter between systems; relative daily variation, that describes the expected storage size to eliminate daily variations; and relative hourly variation, which describes the load and unload capacity of the storage. The parameters can be used for at least two purposes: design and evaluation of existing storages.

This novel method is used to perform an analysis of 20 Swedish district heating systems. The average annual relative variation has been estimated to 4.5% for the 20 district heating systems evaluated, while the average annual relative seasonal variation is 24%. Thus, the magnitude of annual relative daily variation is small compared to annual heat supplied and compared to seasonal heat load variations.

The size of heat storage in order to eliminate daily heat load variations is in the magnitude of 17% of average daily heat supplied or 0.05% of annual heat supplied. The size of existing heat storages installed in district heating systems in Sweden are in average three times greater than the necessary size in order to eliminate daily heat load variations. This indicates that heat storages are used for more services than elimination of daily heat load variations. Two examples could be storage as a reserve between days or to increase electrical power generation at high prices.

Hourly heat load variation is just below 40% of the annual average heat load. This corresponds to a loading and unloading time of 7 h from full to empty or empty to full heat storage.

Two possible direction of further work would be: first, to analyse district heating systems outside Sweden using other control strategies and/or other daily social patterns; and second, to better understand daily variations in district heating systems by analysing corresponding variations for the customer substations in order to identify if and how these variations can be eliminated. Otherwise there is a risk that central heat storages are installed for a problem that can be solved locally at the variation source.

Acknowledgments

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Heat load patterns in district heating substations

Henrik Gadd *, Sven Werner

School of Business and Engineering, Halmstad University, P.O. Box 823, SE-30118 Halmstad, Sweden

HIGHLIGHTS

- ▶ Heat load patterns vary with applied control strategy, season and customer category.
- ▶ Time clock operation of ventilation is the most important factor of daily variations.
- ▶ It is possible to identify outliers by only using two descriptive parameters.
- ▶ A resolution of 1 h in heat meter value analysis is enough.

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ABSTRACT

Future smart energy grids will require more information exchange between interfaces in the energy system. One interface where dearth of information exists is in district heating substations, being the interfaces between the distribution network and the customer building heating systems. Previously, manual meter readings were collected once or a few times a year. Today, automatic meter readings are available resulting in low cost hourly meter reading data. In a district heating system, errors and deviations in customer substations propagates through the network to the heat supply plants. In order to reduce future customer and heat supplier costs, a demand appears for smart functions identifying errors and deviations in the substations. Hereby, also a research demand appears for defining normal and abnormal heat load patterns in customer substations. The main purpose with this article is to perform an introductory analysis of several high resolution measurements in order to provide valuable information about substations for creating future applications in smart heat grids. One year of hourly heat meter readings from 141 substations in two district heating networks were analysed. The connected customer buildings were classified into five different customer categories and four typical heat load patterns were identified. Two descriptive parameters, annual relative daily variation and annual relative seasonal variation, were defined from each 1 year sequence for identifying normal and abnormal heat load patterns. The three major conclusions are associated both with the method used and the objects analysed. First, normal heat load patterns vary with applied control strategy, season, and customer category. Second, it is possible to identify obvious outliers compared to normal heat loads with the two descriptive parameters used in this initial analysis. Third, the developed method can probably be enhanced by redefining the customer categories by their indoor activities.

1. Introduction

Future smart energy grids will require more information about the energy flows in various interfaces in the energy system according to [1]. This information is not always available today for most interfaces. One interface where dearth of information exists is substations in district heating systems. These substations constitute the interface between the distribution network and the customer building heating systems. This existing dearth of information can be explained by the previous lack of measurements, since large amount of data required to perform these analysis have not, by reasonable cost, been possible to collect. Previously, manual meter readings were collected once or a few times a year. However, automatic meter reading systems are now being installed which makes hourly meter readings available at low cost.

The main purpose with this article is to perform an introductory analysis of high resolution measurements in order to provide valuable information about district heating substations for creating future applications in smart heat grids. This is a novel area of research with a very low availability of articles in international scientific energy journals.

In the past, efforts have been performed to optimise the operation of heat supply plants and district heating networks and

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* Corresponding author. Tel.: +46 35 167757.
E-mail address: henrik.gadd@hh.se (H. Gadd).

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to discover and eliminate corresponding errors and deviations. Heat load patterns from customer substations have often been taken for granted, both in design and in operation.

However, the heat load in a district heating system is the aggregated heat load from all customer substations connected to the network and the heat losses from the network. Errors and deviations in customer substations and internal heating systems in buildings will propagate through the district heating network to the heat supply plants. In order to reduce future customer and heat supplier costs, a demand has appeared for more intelligent functions identifying errors and deviations in customer substations and heat supply systems in connected buildings. Hereby, a research demand appears for defining normal and abnormal heat load patterns in customer substations.

The operation of the heating and ventilation systems in a building is shifting depending on the activity in the building. In schools, where no or few people are present during nights and at weekends, no or little ventilation is necessary at these times. During school holidays, the indoor temperature can be reduced. But multi-dwelling buildings need to be heated and ventilated 24 h a day, 7 days a week, all year round. Hence, the heat load pattern is different from building to building depending on what kind of activity that takes place in the building.

The best would of course be to make sure that the customers' facilities are working well, but with hundreds or thousands of customer substations, it has until now been economically impossible to monitor all customer substations. Today, with automatic meter reading systems installed in most district heating systems in Sweden, new opportunities arise to systematically identify errors in the heat supply or control settings at the customers. If an error in a customer substation can be identified and eliminated, it may of course lead to less heat being sold, but the risk is that if it is not eliminated, the company may lose the total heat sales to the customer depending on the fact that other heating alternatives can be more competitive.

Very few studies have been performed concerning horizontal analyses of the heat load pattern in a large number of substations. The reason is that before the large amount of data required to perform these analysis have not, by reasonable cost, been possible to collect. Automatic meter reading systems now installed makes hour meter readings available at low cost.

One work where heat load patterns have been analysed for 50 buildings is [2], where the main aim was to estimate heat load capacities for billing purposes. In order to increase energy efficiency in multi-dwelling buildings, heat loads has been monitored and evaluated in [3]. There are works about indoor comfort like [4] were thermal inertia in a building is evaluated, which indirect is about heat load patterns. Characteristic for [2–4] is that expensive specific equipment had to be installed in the substations in order to collect hourly measurements.

A method of error detection in district heating substations by using information from billing systems is presented in [5].

There are studies performed in order to optimise the substation, often with the goal to decrease the primary return temperature as in [6–9]. There is also a study to identify faults in substations where a method to identify temperature sensor fault is described [10]. In that study, there is also a method described for separating hot water use from space heating, which from a heat load pattern point of view is very interesting. By using multi-agent systems, where the substations and the heat plant can communicate with one another, a possibility to control each part of the system, including the substations, and optimise the whole system would be possible [11,12].

This introduction forms a background to answer three research questions in a field of research which in many ways is a white spot on the district heating knowledge map:

- How do heat load patterns vary in substations?
- Can heat load patterns be simplified to identify outliers by using heat meter readings?
- In what plausible directions can this early research on substation heat load be enhanced?

2. Method

Heat load patterns are not the same in all buildings. It depends on the building properties, but also of the type of activity that takes place in the buildings. To be able to evaluate if a heat load in a building is normal or not, it is necessary to know what heat load pattern is to be expected. From the customer records at two district heating systems, 141 buildings have been selected to be analysed. In the company customer records, seven customer categories are available of which five are used in this study. Two descriptive parameters and four heat load patterns are identified for each data set and plotted in diagrams presented in the results section.

2.1. Gathered data

The collected data sets are meter readings from 141 buildings connected to the district heating systems in Helsingborg and Ängelholm in the south-west of Sweden. In total, there are about 13,000 buildings connected to the two district heating systems from which about 10,000 are one- and two-dwelling buildings. The data sets are hourly measured 1-year series from 1st of January to 31st of December, i.e. 8760 values annually for each building. All data sets are from the year 2010.

The metering data sets come from databases in the automatic meter reading systems. In a few cases, single unreasonable 1-h-values appear in the data sets. They have been corrected by interpolation from the surrounding values. The unit of the values from the meter reading system is kWh/h. The values are often called heat powers, but it is actually delivered heat during 1 h. They could also be referred to as hourly average heat loads.

2.2. Customer categories

In the company customer records, the customer buildings are split into different types of customer categories depending on the activity in the buildings. The subdivision is made due to governmental demands to report statistical data that is collected each year. The national categories for customer categories in the national district heating statistics are: Manufacturing industries, one- and two-dwelling buildings, multi-dwelling buildings, ground heating, public administration, and others.

In this study one- and two-dwelling buildings and ground heating have been excluded. The reason for excluding one- and two-dwelling buildings is that they use less heat per building. It takes the same effort to eliminate a fault in a small building as in a large building, but there is probably less to gain. Ground heating deliveries differ from other usage of district heating since it is the heat in the return pipe that is used in the application and only less than 0.5% of the district heating deliveries in Sweden are supplied for ground heating purposes [13].

In the company customer records for the used heat meter data, the subdivision in different categories has in some cases a higher resolution.

The main part of the buildings in the group "Others" in the national statistics is in the company customer records sorted under the category Commercial buildings. Public administration from the national statistics is split into Public administration and Health and Social Services. In this study, the analysis is split into the following five different customer categories:

- Multi-dwelling buildings.
- Industrial demands.
- Health and Social Services buildings.
- Commercial buildings.
- Public administration buildings.

2.3. Two descriptive parameters

In this paper, two descriptive parameters determined from heat energy metering values will be evaluated for different customer categories: Annual relative daily variation and annual relative seasonal variation.

Annual relative daily variation is a variation in the heat load compared to the daily mean heat load and is defined and described in [14]. Annual relative daily variations occur mainly because of social heat loads such as domestic hot water preparation and time clock operation control of ventilation, but also some physical heat loads that generate daily variation such as wind, solar incident radiation and daily temperature variations between night and day.

Annual relative seasonal variation is the consequence of large variations in outdoor temperature between winter and summer, while the indoor temperatures are expected to be constant.

The first descriptive parameter, annual relative daily variation, is defined as:

$$G_a = \frac{\frac{1}{2}\sum_{i=1,j=1}^{8760,365}|P_{h,i} - P_{d,j}|}{P_a \cdot 8760} \cdot 100\ [\%] \tag{1}$$

where P_h is the hourly average heat load (W), P_d is the daily average heat load (W), P_a is the annual average heat load (W).

The annual relative daily variation is the accumulated positive difference between the hourly average heat loads and the daily average heat load during a year divided by the annual average heat load and the number of hours during 1 year. The division with the annual average heat load is introduced in order to get a measure independent of building size.

The second descriptive parameter, annual relative seasonal variation, is defined as:

$$W = \frac{24 \cdot \frac{1}{2}\sum_{j=1}^{365}|P_{d,j} - P_a|}{P_a \cdot 8760} \cdot 100\ [\%] \tag{2}$$

The annual relative seasonal variation is the accumulated positive difference between the daily average heat loads and the annual average heat load during a year multiplied by the number of hours in 1 day and divided by the annual average heat load and the number of hours during 1 year. As for annual relative daily variation, the division with the annual average heat load is introduced in order to get a measure independent of the magnitude of each heat demand.

2.4. Heat load patterns

Different types of buildings have different heat load patterns depending on the activity in the building, but the heat load pattern is also changing because of outer temperature and impact of solar incident radiation. For this reason, each 1 year sequence meter data set is split into four different season periods:

- Winter: December, January, February (average hourly values from 12 or 13 week-hour values).
- Early spring, late autumn: March, April, October, November. (Average hourly values from 17 or 18 week-hour values).
- Late spring, early autumn: May, September. (Average hourly values from 8 or 9 week-hour values).
- Summer: June, July, August. (Average hourly values from 13 or 14 week-hour values).

For each period the average value is for every hour during a week, where Monday 00.00–01.00 is the first hour and Sunday 23.00–24.00 is the last in each week, plotted in a diagram. One diagram for each building has been plotted. The result is a weekly heat load pattern. Since it is an average value for between 8 and 18 values only recurrent heat load behaviours will appear. From the heat load pattern diagrams four different heat load patterns have been manually identified: Continuous operation control, Night setback control, Time clock operation control 5 days a week and Time clock operation control 7 days a week, which are described below.

The reason to use weekly heat load patterns is because the heat load pattern at a large extent is social heat loads, i.e. are dependent in the social behaviour of people inside the buildings. Since the society in most cases are organised weekly, the social part of the heat load pattern can be expected to recurrent weekly.

Time clock operation of ventilation settings is what most affects heat load patterns. This is the reason why the defined heat load patterns are most characteristic during the winter period. When the outdoor temperature is low, the ventilation air needs more heat. In spring and autumn, the heat load peaks in daytime is less but one can also observe a decreased heat demand after noon due to solar incident radiation. In the summer, domestic hot water is the main part of the heat demand, and no or very small difference in heat load pattern can be observed.

These heat load patterns presented below have not been verified by substation visits or inspections of heat control settings.

2.4.1. Continuous operation control

No additional control is applied other than keeping the indoor temperature at the set point in the building heating control system. For a well-insulated and not too small building, it will mainly be domestic hot water preparation that causes the heat load variations in the hourly time scale. Ventilation is in operation 24 h a day. This is the typical control situation for residential buildings and some Health and Social Services buildings.

A typical heat load pattern for continuous operation control can be observed in Fig. 1. Small differences in heat load appear especially in winter and summer. In autumn and spring, reduced daytime heat loads can be observed. These are the results of additional heat contributions from solar incident radiation to space heating.

2.4.2. Night setback control

Night set back control is when the set point for the indoor temperature is lowered during the night. The traditional thought behind this control strategy is to get a lower indoor temperature during nights and thereby decrease the total heat demand. But most buildings have nowadays high time constants, giving a slow reduction of the indoor temperature due to appropriate insulation and airtight building envelopes. The indoor temperature will not decrease so much that a noticeable heat demand reduction will occur. The only result of night set back applied to energy efficient buildings is to move some heat load from nights to mornings. Hence, night setback control is only suitable and profitable for buildings with high specific demands and short time constants due to bad insulation and non-airtight building envelopes.

A typical heat load pattern for night setback control can be observed in Fig. 2. Lower heat loads during nights are followed by high peak heat loads in the mornings, but these peaks vanish quite fast. The peaks are the results of the reheating of the cooled off heating system during the preceding nights.

2.4.3. Time clock operation control 5 days a week

Ventilation in a building does not necessarily have to be in operation 24 h a day 7 days a week. Schools, for example, only have

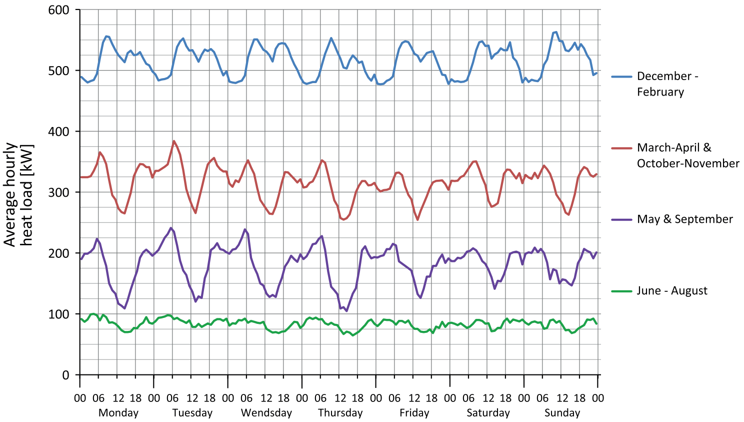

Fig. 1. Average weekly heat load patterns for continuous operation control during four season periods: multi-dwelling buildings with an annual heat supply of 2484 MWh or 8940 GJ.

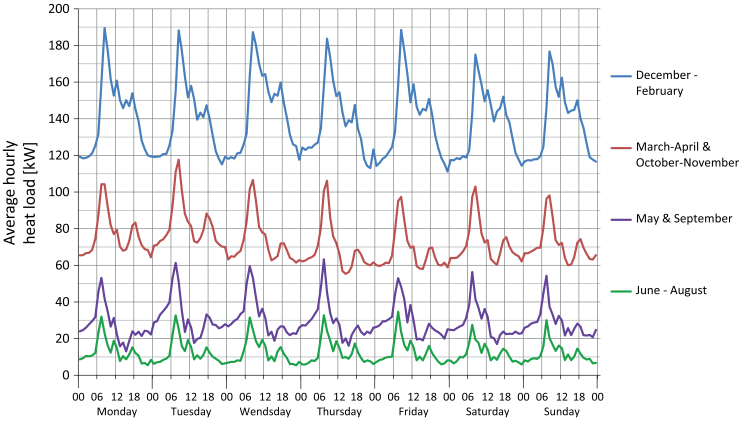

Fig. 2. Average weekly heat load patterns for night setback control during four season periods: public administration building with an annual heat supply of 583 MWh or 2100 GJ.

daytime activities from Mondays to Fridays. At nights and weekends, no or few people are in the buildings and no or reduced ventilation will be appropriate. Full operation of the ventilation systems just increases the amount of used heat energy for the customer. For working days activities only, time clock operation control can be applied 5 days a week.

A typical heat load pattern for time clock operation control 5 days a week can be observed in Fig. 3. Note that the heat load during nights and weekends is the same. During these periods the ventilation is turned off or reduced and the radiator system is supplying heat to keep the indoor temperature at a desirable level.

2.4.4. Time clock operation control 7 days a week

Some buildings have a daytime use 7 days a week. One example is a shopping mall that is open 7 days a week in daytime. Still the ventilation can be shut off during the night since no or few people are inside the building at these times.

A typical heat load pattern for time clock operation control 7 days a week can be observed in Fig. 4. The pattern is similar to time clock operation control 5 days a week, but the ventilation is also in operation at the weekends as well and not only during working days.

3. Results

The relative seasonal variation for heat loads in buildings is most dependent on customer category, and the type of activity in the buildings. Industrial, commercial, and public administration buildings have a relative seasonal variation of around 30–40%, independent of the annual relative daily variation. Health and Social Services buildings have around 30% and multi-dwelling buildings have the lowest relative seasonal variation between 20% and 30%.

The annual relative daily variation has a large range in industrial, commercial and public administration buildings. Since most of these buildings should have time clock operation control of ventilation, they should also have large annual relative daily variations. The results in Figs. 5–9 indicate that time clock operation control of ventilation generates high annual relative daily variations. Still,

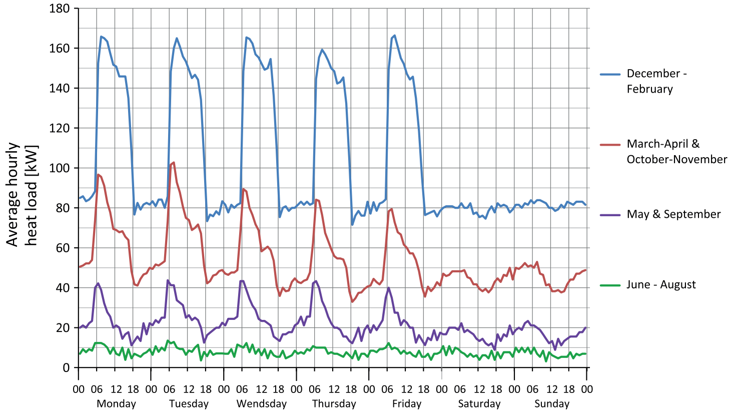

Fig. 3. Average weekly heat load patterns for time clock operation control 5 days a week during four season periods: public administration building with an annual heat supply of 432 MWh or 1560 GJ.

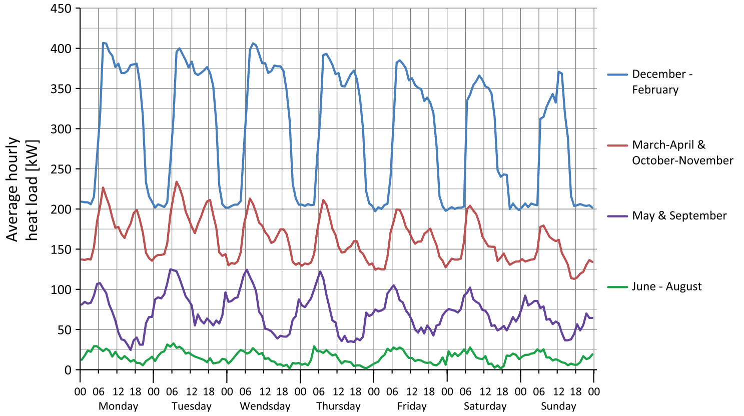

Fig. 4. Average weekly heat load patterns for time clock operation control 7 days a week during four season periods: commercial building with an annual heat supply of 1246 MWh or 4490 GJ.

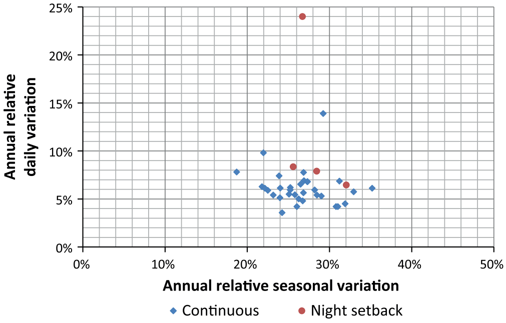

Fig. 5. Annual relative daily variation as a function of annual relative seasonal variation for 37 multi-dwelling buildings.

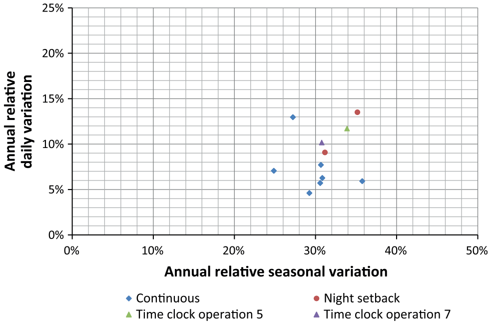

Fig. 6. Annual relative daily variation as a function of annual relative seasonal variation for 11 Health and Social Services buildings.

there are in every group of building types some that seem to have too low or too high annual relative daily variation. Notable are the outliers that deviate from what seems to be a normal heat load pattern.

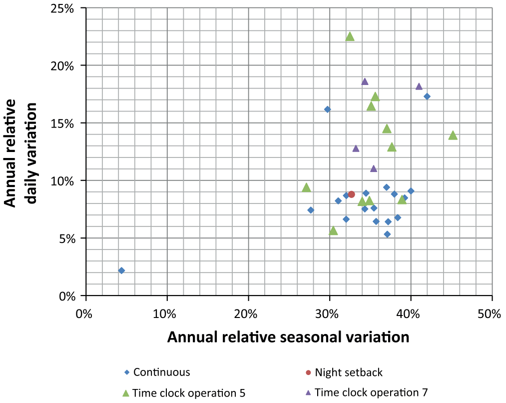

Fig. 7. Annual relative daily variation as a function of annual relative seasonal variation for 36 industrial customers.

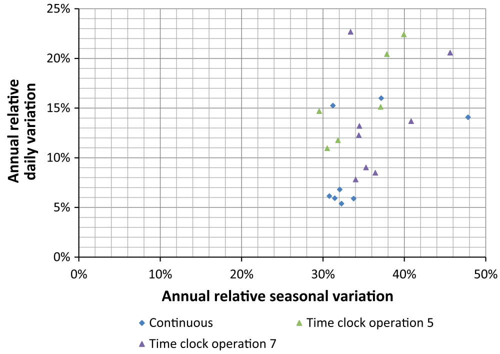

Fig. 8. Annual relative daily variation as a function of annual relative seasonal variation for 22 commercial buildings.

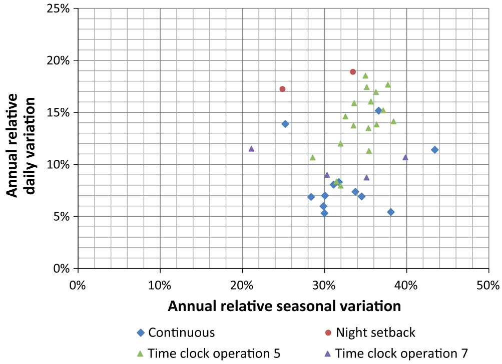

Fig. 9. Annual relative daily variation as a function of annual relative seasonal variation for 35 public administration buildings.

3.1. Multi-dwelling buildings

Multi-dwelling buildings are relatively homogeneous types of buildings with respect to heat load patterns. They are in use 24 h a day all year around and domestic hot water share of the heat load is relatively high, about 20% of the annual heat demand according to [15].

Multi-dwelling buildings are characterised by low annual relative daily variation. As can be seen in Fig. 5, most of the multi-dwelling buildings have heat load patterns from continuous operation control. Only a few buildings seem to have some kind of night setback. Typical values for annual relative daily variation are between 4% and 8%. The relative seasonal variation is in the upper range compared to the other types of buildings in this study. The multi-dwelling buildings have an annual relative seasonal variation in the range of 22–32%. Most of the buildings are well gathered in the diagram, but there are 4 outliers. Most notable is the building with night setback heat load pattern with 24% annual relative daily variation but also the buildings with low annual relative seasonal variations are notable. It indicates a low correlation between heat load and outdoor temperature.

3.2. Health and Social Services buildings

Health and Social Services buildings can be anything from a hospital to an office for the administrators and are thereby a very heterogeneous group. Some buildings like hospitals have a heat load pattern close to multi-dwelling buildings with 24 h activity every day. Other buildings have just daytime activities and have heat load patterns close to traditional office buildings with time clock operation control of ventilation and low domestic hot water use.

Remarks in Fig. 6 are as follows: one building with a heat load pattern from continuous operation control and an annual relative daily variation of 13%, and one building with a heat load pattern from time clock operation control 7 days a week, but only 10% of annual relative daily variation.

3.3. Industrial demands

The definition of industrial buildings is that they are used for the manufacture of materials or products. Their heat demands are more diversified than multi-dwelling buildings. There can be between one- to five-shift operations and thereby everything between 8 and 24 h per day of activity. Heat demands can appear for both space heating and industrial processes. Some industries have excess heat and can thereby decrease their external heat demands partly. In most industrial buildings, there is no or less activity during nights and weekends which is why time clock operation control of ventilation is appropriate. Domestic hot water use is normally low compared to multi-dwelling buildings, i.e. summer heat load when no space heating is required ought to be low.

As can be observed in Fig. 7 fewer than half of the industrial customers seem to have time clock operation control of ventilation. A large portion of continuous heat load pattern indicates that the ventilation or other heat demands are running 24 h a day in lots of industrial buildings. Most notable is the building with 4% annual relative seasonal variation and 2% annual relative variation. It is a more or less constant heat load over the year.

3.4. Commercial buildings

Few commercial buildings are in operation at night. This is confirmed by the fact that most commercial buildings have heat load patterns from time clock operation control during 5 or 7 days a week. Still, there are some customers with a heat load pattern from continuous operation control.

Commercial buildings consist of trading companies, restaurants, hotels, service companies, amusement and recreational services. These are buildings where activities take place mainly during the daytime 5–7 days a week. These buildings should have time clock operation control of ventilation. The use of domestic hot water is low. An exception is hotels that have a heat load pattern close to multi-dwelling buildings with 24 h operation and a rather high share of domestic hot water of the heat load.

Notable buildings in Fig. 8 are three buildings with a heat load pattern of continuous operation control, but with relatively high annual relative daily variations. There are also three buildings with heat load patterns of time clock operation control during 7 days a week with notably low annual relative daily variation.

3.5. Public administration buildings

Typical public administration buildings are schools and municipal administration buildings that are mainly in use during office hours 5 days a week, gymnasiums, public baths, that are also used at weekends, but also fire stations and police stations with a 24 h operation. In Fig. 9 this is confirmed by heat load patterns from Continuous operation control, Time clock operation control 5 days a week and Time clock operation control 7 days a week.

The use of domestic hot water is shifting, but it is low compared to multi-dwelling buildings. Three buildings are noteworthy with low annual relative seasonal variation. Also one building with a continuous heat load pattern of 15% annual relative daily variation is notable.

3.6. Cross-cutting results

The different types of buildings can be divided into three different larger groups depending on variation in annual relative daily variation.

- Low annual relative daily variations: Multi-dwelling buildings.
- Intermediate annual relative daily variations: Health and Social Services buildings.
- High annual relative daily variations: Commercial, Industrial, and Public administration customers.

The most important cause for high annual relative daily variation is time clock operation control of ventilation. In buildings with activity only parts of the day or week, ventilation is reduced or shut off when no indoor activities take place. In an office, normally no or very few people are in the building at nights and weekends. In a multi-dwelling building though, tenants are using heat 24 h a day all year around.

Another setting that increases annual relative daily variation is night setback control. Even though, night setback control does not have an influence on heat demand reduction, it is still not unusual that night setback controls are applied. A heavy building with a thermal time constant of at least 100 h, which is the case with all the buildings in this study, will not cool off during a few night hours. The only results are large heat load peaks when the set point for the indoor temperature changes. The only thing that cools off is the ventilation and heating system, and in the morning, when the set point changes, a high heat load peak is a consequence to warm up the heating and ventilation system.

To enhance the method in this paper, an inventory of the buildings to confirm the settings for Continuous operation control, Time clock operation control 5 days a week, Time clock operation control 7 days a week and Night setback control should be performed. This inventory together with a more suitable subdivision of customer categories that merge with an expected heat load pattern would increase the resolution of the method. It could either be a finer subdivision of the existing customer categories or an entirely new subdivision. In this work, heat load patterns were identified manually. In practice use, the heat load patterns must be identified automatically e.g. by using some kind of clustering data mining method.

3.7. Methodology use in practice

The method presented in this paper is used to analyse the heat load pattern for 141 buildings. For this method to be usable, expected heat load pattern for each building must be determined. For some buildings, this is easy such as for multi-dwelling buildings and school buildings. For others buildings, a more explicit knowledge of the activity in respectively building can be necessary. In city centres for instance, shops, offices and dwellings can occur within the same building.

Well working multi-dwelling buildings should have a continuous heat load pattern resulting in low daily heat load variations. A brief study of the analysed buildings shows that in some multi-dwelling buildings fast heat load fluctuations occur with high daily variations as a result. I.e. high daily variations in buildings with continuous heat load pattern, indicates bad performance of the substation. In school buildings, time clock operation is expected since there is activity in the building daytime, working days, only. Ventilation should be shut off during nights and weekends resulting in high daily heat load variations. If the daily variations are relatively low, one could expect that the ventilation is only reduced to a small extent or only shut off in parts of the school. Hence, schools should have time clock operation 5 days a week heat load pattern and high daily variations. Low seasonal heat load variations indicate low correlation between outdoor temperature and heat demand. For a building with mainly space heating heat demand, low seasonal heat load variations could indicate that heating is turned on even when it is not needed.

The two variables annual relative daily variation and annual relative seasonal variation in combination with existing and desirable heat load pattern could be used in order to identify heat load demands that are disadvantageous for the heat customers. The result could be used as an input to develop a method to automatically identify district heating customers with a non-correct or a disadvantageous heat demand pattern.

4. Conclusions

The three major conclusions are associated both to the method used and the objects analysed.

First, normal heat load patterns vary with applied control strategy, season, and customer category. High annual relative daily variation in a multi-dwelling building would indicate that something is wrong, but on the contrary, on commercial premises and in industries there is something wrong, if there is not a high annual relative daily variation. But as can be observed in the results section, it is not an unambiguous result. A large variation of heat load patterns among various buildings implies that a standard heat load pattern for customer substations does not exist.

Second, it is possible to identify obvious outliers compared to normal heat loads with the two descriptive parameters used in this initial analysis. This makes it easy to systemize the identification of customers with a disadvantageous heat load pattern for both the customers and the district heating companies.

Third, the developed method can probably be enhanced by redefining the customer categories by their indoor activities. The best example is Health and Social Services buildings that should be split into groups depending on the activity and the duration of activity in the buildings.

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Paper III

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Achieving low return temperatures from district heating substations

Henrik Gadd *, Sven Werner

School of Business and Engineering, Halmstad University, PO Box 823, SE-30118 Halmstad, Sweden

HIGHLIGHTS

- Fast detection of differential temperature faults in district heating substations by new method.
- Temperature difference faults can be identified within a single day.
- The novel method can also be used in quality assurance of eliminated faults.
- Temperature difference fault frequency in substations is about 5% annually.

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ABSTRACT

District heating systems contribute with low primary energy supply in the energy system by providing heat from heat assets like combined heat and power, waste incineration, geothermal heat, wood waste, and industrial excess heat. These heat assets would otherwise be wasted or not used. Still, there are several reasons to use these assets as efficiently as possible, i.e., ability to compete, further reduced use of primary energy resources, and less environmental impact. Low supply and return temperatures in the distribution networks are important operational factors for obtaining an efficient district heating system. In order to achieve low return temperatures, customer substations and secondary heating systems must perform without temperature faults. In future fourth generation district heating systems, lower distribution temperatures will be required. To be able to have well-performing substations and customer secondary systems, continuous commissioning will be necessary to be able to detect temperature faults without any delays. It is also of great importance to be able to have quality control of eliminated faults. Automatic meter reading systems, recently introduced into district heating systems, have paved the way for developing new methods to be used in continuous commissioning of substations. This paper presents a novel method using the temperature difference signature for temperature difference fault detection and quality assurance of eliminated faults. Annual hourly datasets from 140 substations have been analysed for temperature difference faults. From these 140 substations, 14 were identified with temperature difference appearing or eliminated during the analysed year. Nine appeared during the year, indicating an annual temperature difference fault frequency of more than 6%.

1. Introduction

District heating systems can substantially contribute to a more efficient energy system. Heat and fuel resources difficult to use individually can be used for heat supply in these systems. Still, there are several reasons to increase efficiency in district heating systems such as: increase in ability to compete, decrease use of primary energy resources and less impact on the environment.

One of the most important factors in running a district heating system with high efficiency is low distribution temperatures. Low supply temperatures have several benefits in a district heating system such as: increased electrical output from CHP-plants, increased heat recovery from industrial excess heat and geothermal heat, and an increased coefficient of performance if heat pumps are used in heat generation. Lower return temperature increase heat recovery from flue gas condensation. Lower distribution temperatures also result in less distribution losses [1]. The economic value of reduced return temperature can vary from 0.05 to 0.5 €/MW h, °C [1]. A decrease in distribution temperatures will be essential for district heating systems to play role in future sustainable energy systems [2]. To achieve decreased supply temperatures, faults increasing return temperatures in substations and customer secondary systems, have to be detected and eliminated. While existing systems, normally referred to as third generation district heating systems, have a supply temperature of 80 °C, future

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* Corresponding author. Tel.: +46 35 167757.
E-mail address: henrik.gadd@hh.se (H. Gadd).

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systems, fourth generation, will perhaps have a supply temperature of as low as 50 °C [3]. Then it will be necessary to have low return temperatures and to have as large temperature difference as possible. Otherwise the efficiency gains from low supply temperature will not compensate enough for increased cost of pumping and larger network diameters due to increasing distribution water flow. To reach and maintain low distribution temperatures, continuous commission in one way or another will be necessary for substations but also for customer secondary systems. This requires fast fault detection in the district heating substations and the ability to control the quality of fault elimination.

Increased temperature difference and low distribution temperatures in district heating systems have for a long time been a research field of district heating. Publications referred to in this paper have an overrepresentation of Swedish and German origin. This is a result of a unique Swedish continuous district heating research programme since 1975, and the German trade journal Euroheat & Power, earlier named Fernwärme International, that has published research and knowledge about district heating in Germany since 1972.

The optimal supply temperature for a district heating system with CHP is investigated in [4] from 1975. In an article from 1977, the importance of large temperature differences and low supply temperatures in order to be able to increase the generation of high value electricity is being described [5].

Regarding system efficiency it has been shown not only that large temperature differences reduce both energy and exergy losses [6–10], but also that the distribution temperatures, i.e., both supply and return temperature, over all should be decreased from an energy and exergy point of view to increase the total system efficiency [11].

1.1. By-passes

To avoid service pipes to cool off in summer time in district heating networks when there is no heat demand for space heating , by-pass valves are mounted in substations between the supply and return pipes. The resulting by-pass flow decreases the temperature difference, but this is necessary in order for the substation to be able to deliver domestic hot water at the requested temperature. An evaluation to decrease this loss by a new control strategy is developed in [12]. The thought was that the by-pass could be shut off parts of the day when no hot water was used. But the fact was that there was hot water taping all hours of the day. By-pass valves can also be necessary in some parts of the network to prevent freezing, or to keep an entire part of the network with no or low heating demand hot. An evaluation of the cost for by-passes is estimated in [13] where it is concluded that thermostatic by-passes have a payback period of less than 2 months. How to operate by-pass valves to minimize decreased temperature differences is discussed in [14], and the conclusion is that there is not one single solution that fits all.

1.2. System efficiency

Temperature difference in the customer secondary system is a result of both the mass flow chosen and the installed heat transferring areas, but large heat transferring areas result in increased system costs. An evaluation of the system efficiency should also include the customer secondary systems at the customers' end. A distribution temperature optimisation based on the total system including a CHP-plant and customer secondary supply temperature demand dependent on radiator size is presented in [15]. The relation between cost and return temperature in customer secondary systems is discussed in [16] but, on the other hand, two studies indicate that radiators often are oversized and can perform well with lower supply temperatures without decreased thermal comfort [17,18].

1.3. Existing substation technology

It is not new technology that has to be developed to achieve low distribution temperatures, which is well described in [19], but with the existing substation technology a return temperature of 32 °C with a supply temperature of 70 °C is possible. In a technical report from 2005 from the Swedish District Heating Association, old and new substations have been compared resulting in no major differences. The same conclusion can be noticed in a report from 1987 [20]. The only difference that could be observed was in the cases when the heat exchanger was fouled [21], and an evaluation of how ten-year-old district heating substations performed in 2009, showed that they performed well. Only a small increase in return temperature at the hot water preparation could be noticed [22]. Hence, district heating substations have, for decades, been designed for large temperature differences and low distribution temperatures and the existing installed substations are not a problem. But the systems have to work correctly. This is valid both for the substations and the customer secondary systems in the buildings.

1.4. Control

It is not only valves and other components that have to work well but also the control system and the settings. By changing the control of a substation from a traditional reconnected control-loop to an alternative control strategy where the primary flow is determined by calculating the demand, a decrease of up to 10 °C could be possible according to [23]. The supply temperature is in summer normally about 70 °C. When the outdoor temperature decreases the supply temperature is increased to be able to supply increased heat demand in the network. By using multi-agent system described in [24,25], peak load could be decreased and thereby, a possibility exists to decrease the distribution temperatures [26].

1.5. Customer secondary systems

The lower limit for return temperature is determined by the customer secondary systems at the heat users' end. To attain low return temperatures, it is important to control the radiator flow and the supply temperature and different methods are described in [27–33]. One way to decrease the return temperature is to have a cascade coupled secondary system and not only in parallel which is the traditional arrangement [34]. In [35] it is stated that it is important to adjust the radiator flow but there is not one method that is significantly better than another. To have total control of the flow to all parts of the customer secondary system, individually circulating pumps on each heat emitter can be used instead of a centralized pump and thermostatic valves to control the flow in a building which is described in [36]. This solution would also eliminate the need for balancing the radiator distribution system. Normally the supply temperature to the radiators is determined by the outdoor temperature. A possibility to use primary supply temperature instead is presented in [37,38]. The conclusion is that it is possible to maintain comfort by using primary supply temperature instead of outdoor temperature to control radiator supply temperature. Theoretically it would be possible to increase the temperature difference but in practice it turned out to be difficult to realize.

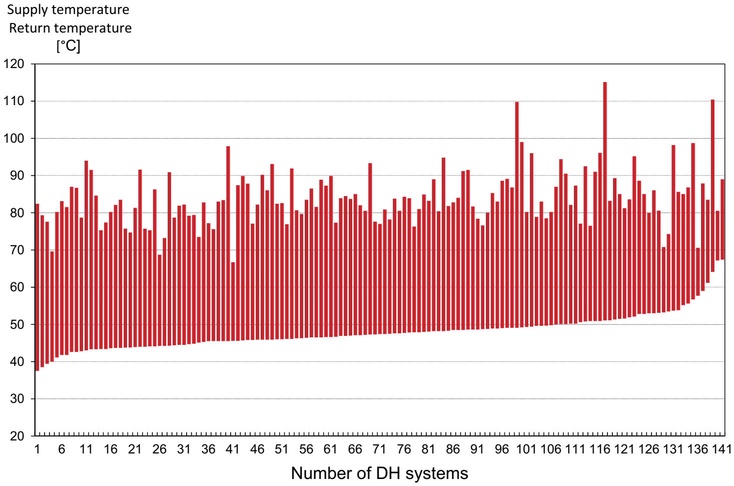

Fig. 1. Supply and return temperatures (top and bottom of each bar respectively) in 142 Swedish district heating systems from 2004 to 2010. Each bar represents one district heating system and is sorted by return temperature. Annual average supply temperature was 86.0 °C and annual average return temperature was 47.2 °C. Source: Stefan Peterson, FVB, Borås, Reproduced with permission.

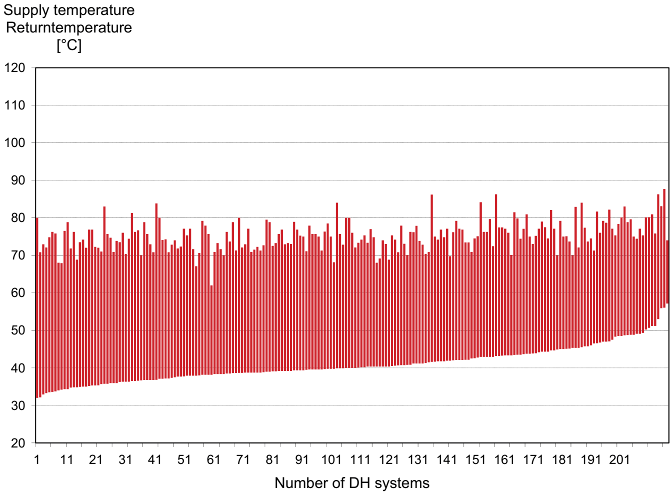

Fig. 2. Supply and return temperatures (top and bottom of each bar respectively) in 207 Danish district heating networks during 2010/2011. Each bar represents one district heating system and is sorted by return temperature. Annual average supply temperature was 77.6 °C and annual average return temperature was 43.1 °C. Source: Generated by data from [39].

1.6. Existing supply and return temperatures

Even if the advantage with low distribution temperatures is well-known among the district heating companies, temperatures in many district heating systems are still high. In Figs. 1 and 2, annual average distribution temperatures for 142 Swedish and 207 Danish district heating systems can be found. Each bar represents one district heating system with the annual average supply temperature as the top value and the corresponding return temperature as bottom value. The bars are sorted by the return temperature. The national average supply temperature in Sweden was 86.0 °C and 77.6 °C in Denmark. The corresponding return temperatures were 47.2 °C for Sweden and 43.1 °C for Denmark.

What is notable is that district heating systems in Denmark have somewhat lower distribution temperature levels compared to Sweden. There are at least two explanations why this is the case:

1. Most district heating systems in Denmark are direct-coupled systems, i.e., there are no heat exchangers, and thereby no temperature degradation, between the district heating network and the customer secondary systems.

2. Some of the Danish district heating systems have large solar heating collectors as part of the heat supply and have thereby an incentive to have low distribution temperatures in the district heating systems.

The importance of low distribution temperatures and large temperature differences is well-known and methods are available, but many district heating systems obviously do not prioritize work to increase temperature differences and to decrease distribution temperature. There are three major causes according to [40]:

1. Lack of resources and competence in the district heating companies.
2. Company organisation. Large parts of the company have to be involved which can lead to internal discussions.
3. Uncomfortable contact with customers where technical personnel take on a sales role and sales personnel get involved in technical discussions.

1.7. Temperature fault detection methods

To eliminate faults in substations and customer secondary systems, they have to be detected and this is a critical step [41]. Eliminating faults could involve a large amount of work and there is a risk that the cost reduction from the efficiency gain of the improved substations would be erased by the cost of man-hours.

Traditionally, work to identify low temperature differences has been organized as campaigns using annual meter readings of heat and flow. The work has been performed manually which results in a large amount of man-hours. Another problem is that the time from when a fault appears until it is detected a lot of time elapses using this method. The result is that a campaign is performed, the temperature difference increases, but then the work stops, and after a while, new faults appear and the temperature difference slowly decreases. The main reason for working like this is that the methods have been developed, when only annual meter readings were available. This is probably also the reason why the frequency of fault detection in district heating substations is not available since no documentation exists about if or when faults appear.

Faults in district heating substations can be divided into three major groups: Construction faults, component faults and operational faults. Construction faults are most likely a decreasing problem. Previously substations were manually built on site, but for several years now, most substations are prefabricated which is why the risk for construction faults is much lower. Component and operational faults can appear almost at any time. In most cases the components and the whole substation are performing as they should at installation and the operation settings are correct. But as time goes by, components can break and operation settings can be changed. In a report about work to increase the temperature difference in the district heating system in Gothenburg between 1995 and 2004 [42], malfunctioning or broken actuators for the heating and hot water valves, control curve for the heating system and the control of the hot water temperature constituting more than 50% of the faults.

A major problem in fault detecting in substations is that there is not one typical heat demand pattern for all substations that is performing well, i.e., there is a difficulty when developing a method to separate faults from normal deviations.

1.8. Automatic meter reading systems

Since 1 July 2009 there is a decree [43] for monthly meter reading for actual electricity use in Sweden. Previously most energy meters were read manually once or a few times a year. Since manual meter reading once a month is too expensive, this has resulted in the installation of automatic meter reading systems. These systems have a metering resolution of at least one hour. Since most district heating systems are owned by energy companies that are also the owners of the local electricity grids, a majority of the companies have installed automatic meter reading systems for district heating customers as well. As a result of the Energy efficiency directive from 2012 [44], the Swedish district heating act [45] has been changed and from 1 January 2015 there will be a new regulation for all district heating companies to charge for the actual use monthly, i.e., from 2015 hourly meter reading will be available for all district heating customers in Sweden. To go from meter reading once a year to once an hour opens up an opportunity for continuous commissioning of substations, with the purpose of detecting faults as they appear.

1.9. Research questions

Continuous methods of how to use hourly meter readings in fault detection is currently missing. Presented in this paper is a novel method for fast detection of low temperature difference faults in district heating substations. This introduction forms the background for the following three research questions:

- How can faults regarding temperature differences be detected when they appear?
- How can the quality of fault elimination be checked?
- What is the frequency of substation temperature difference faults?

2. Method

In this study, 140 district heating substations from two district heating systems have been individually analysed. The method is based on temperature difference signatures, where the temperature differences in substations are plotted as a function of outdoor temperature. The method can be used both for fault detection and quality assurance of eliminated temperature faults.

2.1. Gathered data

The origin of the analysed data is automatic meter reading systems from two district heating systems in the south of Sweden; Helsingborg and Ängelholm. The Helsingborg system has approximately 10,000 connected substations and a total annual heat supply of 3.6 PJ. The Ängelholm system has approximately 3000 connected substations with an annual heat supply of 0.7 PJ. Meter readings from a total of 140 large district heating substations have been collected, out of which 85 are located in Helsingborg, and 55 in Ängelholm. These substations constitute 12% of all heat deliveries performed in the two district heating systems. No small substations installed in single family buildings were included in the study.

The data sets used are 1 h values for a period of one year for heat delivered and circulated flow. In some cases, data values are missing or are obviously wrong in the data sets. If a single or some data is missing in a way that affects the result, the data have been reconstructed by interpolation. If more than 5 data values are missing or are obviously wrong, data from the previous or the following day has been used. Which data set that has been used for reconstruction depends on which of the days had an outdoor temperature closest to the day with the missing data values.

The annual average supply temperatures were 83.8 °C in Helsingborg and 85.8 °C in Ängelholm and the annual average return temperatures were 46.9 °C in Helsingborg and 47.8 °C in Ängelholm. Referring to Fig. 1, the two systems can be considered as

Table 1
Number of substations and heat demands for each of the selected five customer categories used in this study.

Customer categories	Number of substations	Total annual heat demand (TJ)	Average annual heat demand (TJ)	Lowest and highest annual heat demand (TJ)
Multi-dwelling buildings	35	220.7	6.3	2.9–15.6
Industrial demands	37	77.6	2.1	0.2–10.0
Health and social services buildings	10	17.2	1.7	0.5–4.1
Commercial buildings	23	66.1	2.9	0.3–14.1
Public administration buildings	35	147.5	4.2	0.4–27.0
Sum total	140	529.1	3.8	0.2–27.0

typical for Swedish district heating systems in terms of annual distribution temperature differences. All data are annual data sets and all data sets are from the year 2010, 1 January–31 December.

The selection of data sets is based on customer categories and amount of annually delivered heat per substation. In the customer records, customer buildings are divided into eight different consumer categories due to governmental demands to annually report heat statistics. The heat statistics contain six customer categories: manufacturing industry, one-and two-dwelling buildings, multi-dwelling buildings, ground heating, public administration and others. The customer records have in two cases higher resolution. Others in the national statistics are in the customer records divided into commercial buildings and others. Public administration in the national statistics is in the customer records divided into health and social services and public administration. In this study, one and two-dwelling buildings, ground heating and others are excluded. The selected customer categories include approximately 3000 of the total 13,000 substations in the two district heating systems. The excluded substations are mainly single family buildings. From each customer category, the customers with the highest annual heat deliveries have been selected for the analysis (see Table 1).

2.2. Conventional method

There are several reports with different methods to increase temperature difference, e.g., [42,46–48]. Most common and effective is the overflow method, first introduced in 1992 by Sven Werner, then active at Borås energy. The annual overflow is calculated from annual heat and flow readings by defining an expected annual average temperature difference. Using the overflow method automatically results in an order of priorities for substations which most affects the temperature difference in the whole district heating network. A strong advantage with the overflow method is that the annual additional cost associated with a high return temperature is directly proportional to the annual overflow, giving the possibility of performing very simple cost-benefit analyses.

The overflow method is illustrated in Fig. 3, where the 140 analysed substations are presented and isolines showing the annual amounts of different annual overflows, depending on heat demand and annual average temperature difference, are plotted in the same diagram. Zero overflow in this figure is defined as a circulated flow with an average annual temperature difference equal of 45 °C.

2.3. Novel method, temperature difference signature

The method presented in this paper uses temperature difference signatures for fault detection. A temperature difference signature is a diagram where daily average temperature difference is plotted as a function of daily average outdoor temperature.

To determine the temperature difference, heat and flow meter readings from heat meters are used. A heat meter consists of a flow meter, a pair of temperature sensors and a calculator. The heat energy is determined by the calculator from flow and temperature readings. It would be possible to use the temperature meter readings from the heat meter, but a problem with the temperature readings is that it is only momentary temperature, and not an average over a period of time, and single temperature meter readings can differ quite a lot from the average and are therefore not representative. The spread would be larger and the offset line distance would have to be wider to not get false alarms. But, increased offset line distance result in less sensitivity for fault detection. If heat and flow meter reading values are used to determine the temperature difference, the detection method becomes more stable.

In Figs. 4 and 5, temperature difference signatures from the two district heating systems can be observed. In Fig. 4, the temperature difference signatures based on 23 substations in Helsingborg district heating system are plotted and in Fig. 5, the temperature difference signatures based on 22 substations in Ängelholm district

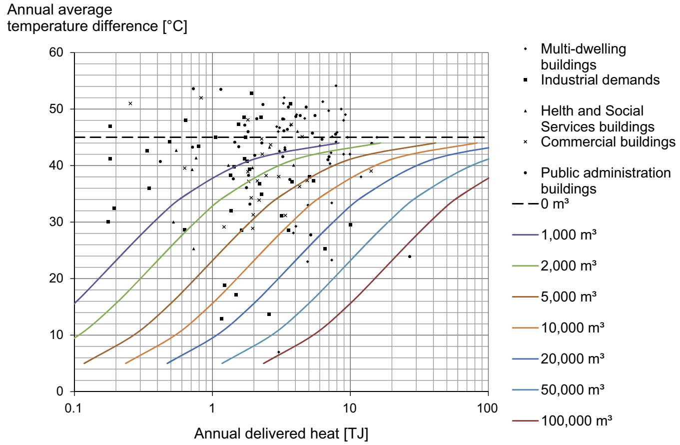

Fig. 3. Annual average temperature difference as a function of annual delivered heat for 140 substations divided into five different customer categories (dots). Isolines for seven different annual overflow volumes have been added for comparison, where the overflow is estimated from an annual average temperature difference of 45 °C.

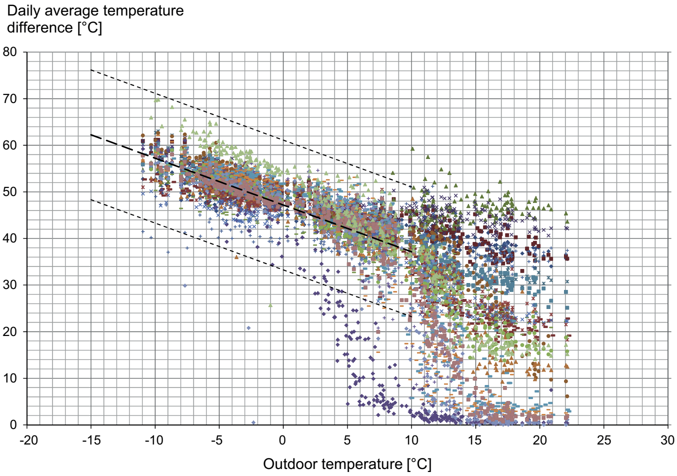

Fig. 4. Temperature difference signature based on 23 well working substations in the Helsingborg district heating system. The thick dashed line is the average line and the thin dashed lines are ±3 standard deviations.

heating system are plotted. All substations in Figs. 4 and 5 are well-performing and have an annual average temperature difference equal to 45 °C or more i.e., none of the substations from Table 2 are present in Figs. 4 or 5.

An aggravating circumstance of temperature difference fault detection in district heating substations is that the temperature difference changes over the year. For a proper performing substation, the temperature difference is higher in the winter, approximately 50–70 °C, and then decreasing with increasing outdoor temperature. To identify faults in the temperature difference it is necessary to know which temperature difference is desirable for a well-performing substation.

The temperature difference signature consists of an average line and two off-set lines. The average line is calculated by the least squares method on meter readings for well-working substations with an annual average differential temperature equal to 45 °C or more. From this average line, two threshold offset lines are defined in this study by using three standard deviations from the average line. One offset line over and one offset line under the average line. The interval between the two offset lines is considered as normal operation. One temperature difference signature must be defined for each single district heating system.

To determine the distance of the off-set lines is a question which needs careful weighting up. Too tight off-set lines will result in too many alarms while to wide distance will result in faults not detected.

When space heating is the dominating heat demand in a building, the temperature difference between supply and return pipes is inversely proportional to outdoor temperature. But, as can be observed in Figs. 4 and 5, at outdoor temperatures exceeding about 10 °C, no general correlation between outdoor temperature and temperature difference is present, i.e., the method described in this paper can only be applied as a general method when outdoor temperature is below 10 °C.

While the overflow method is a way to prioritise existing faults, i.e., there is an acceptance for faults, a requirement to use the presented method is that most substations perform well with a correct temperature difference. It is a method for continuous commissioning to quickly, within one day, identify faults in substations and customer secondary systems.

3. Results

3.1. Fault detection method

In this study, 140 substations from two district heating systems have been manually analysed. Fourteen of the 140 substations have faults resulting in decreased temperature difference during the year presented in Table 2.

The faults are divided into four types:

A: Faults from the beginning of the year, but eliminated during the year.

B: Faults appeared during the year and not eliminated by the end of the year.

C: Faults appeared and eliminated during the year.

D: Faults appeared during the summer period when outdoor temperatures were >10 °C.

The data sets only contain meter readings for one year: 1 January–31 December 2010. In four cases faults appeared at the beginning of the year, but were eliminated during the year, fault type A. In three cases, faults appeared during the year 2010 but were not eliminated by the end of the year, fault type B. In six cases, faults both appeared and were eliminated during the year, fault type C, from which three appeared during a period of outdoor temperatures of >10 °C, fault type D. One substation (No. 8) seems to perform well from 2 April until 16 September but not before or after. On average the fault duration was at least 57 days, most probably even longer since eight substations had faults when the data sets started or ended.

In Fig. 6, an example of a detectable fault in substation 11 from Table 2 is illustrated. The substation has initially a large temperature difference and all daily average temperature differences are in between the temperature difference offset lines until 6 December. On 7 December something happens and the temperature difference decreases substantially. The presented detection method should catch this fast change of annual temperature difference.

Apart from the fourteen substations in Table 2, several of the 140 substations included in this study performed badly in terms

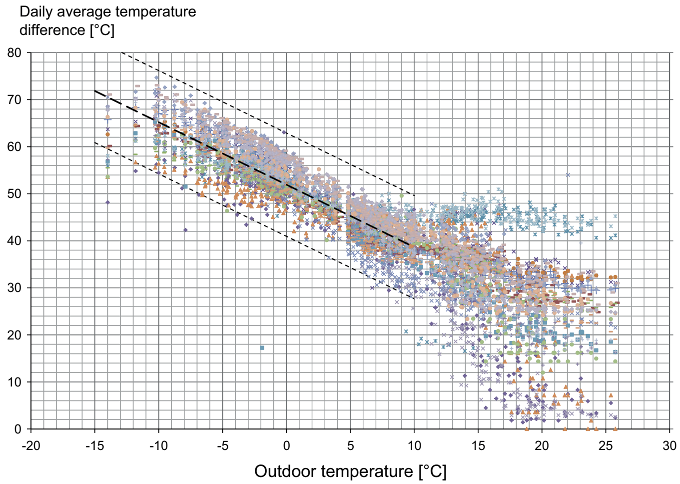

Fig. 5. Temperature difference signature based on 22 well working substations in the Ängelholm district heating system. The thick dashed line is the average line and the thin dashed lines are ±3 standard deviations.

Table 2
14 Substations with major temperature difference faults appearing during the year 2010. Average duration of fault was at least 57 days.

Substation Number	Type of fault	Duration of fault (days)	Detectable by novel detection method
1	C	42	Yes
2	B	>141	Yes
3	C, D	13	No
4	C, D	23	No
5	A	>6	Yes
6	C	21	Yes
7	A	>136	Yes
8	A, B	>142	Yes
9	B	>44	No
10	C, D	34	No
11	A	>24	Yes
12	C	83	Yes
13	B	>56	Yes
14	A	>34	Yes

of temperature difference, i.e., faults existing the entire year. Twenty-one of the 140 substations, apart from the fourteen substations in Table 2, had an annual average temperature difference of less than 30 °C.

3.2. Quality assurance of faults eliminated

The presented method is not only valid for fault detection. As a result of the fast fault detection, the presented method can also be used for quality assurance of faults eliminated. In Fig. 7 below, the temperature difference signature for a substation that had an initial large temperature difference until 7 September, when a fault appeared. On 3 December, the fault was eliminated. But, as can be observed, the substation does not perform as well as before the fault appeared on 8 September. A substation that used to perform excellent turns to a substation that is average in its performance. Either there was more than one fault, the fault has not been eliminated correctly, or new faults have appeared when eliminating the initial fault.

3.3. Fault frequency estimation

From Table 2 it can be noticed that in nine substations, temperature difference faults appeared during the year, i.e., 6.4 % differential fault frequency during 2010.

4. Conclusions

The current distribution temperatures in district heating systems are set from a combination of customer temperature demands and temperature difference faults giving higher return temperatures. Frequent temperature difference faults also increase the supply temperatures, since the overall distribution temperature difference must be kept, when the return temperatures are increased. By eliminating current temperature difference faults, the current distribution temperatures can be reduced to only consider the customer temperature demands. The temperature difference faults can be eliminated by applying a proper fault detection method, using a proper quality assurance method, through monitoring the fault frequencies, and with further improvement of the novel fault detection method presented here.

4.1. Fault detection method

This paper presents a novel method for fast detection of temperature difference faults in district heating substations. The method is based on temperature difference signatures, using daily readings of heat and flow. From 140 analysed substations, fourteen substations were identified with temperature difference faults appearing or eliminated during the analysed one year data sets. Ten of these faults could be identified with the novel method. Of the remaining four substations, three had faults appearing during the summer, when the outdoor temperature exceeded 10 °C, which is outside the range of the applied method.

4.2. Quality assurance of faults eliminated

It has been shown that the novel method presented also can be used as a quality assurance method for eliminated temperature faults. Since man-hours are expensive, it is of the utmost

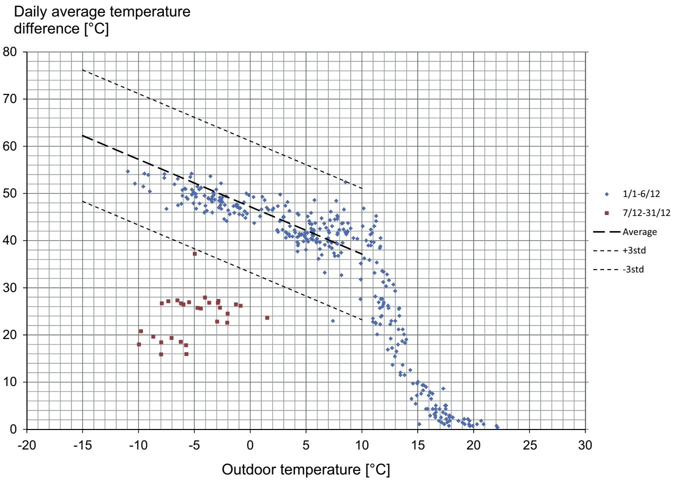

Fig. 6. Temperature difference signature for a commercial building in Helsingborg with an annual heat demand of 3.06 TJ with a temperature difference fault that appeared on 7 December (Substation No. 11 in Table 2.).

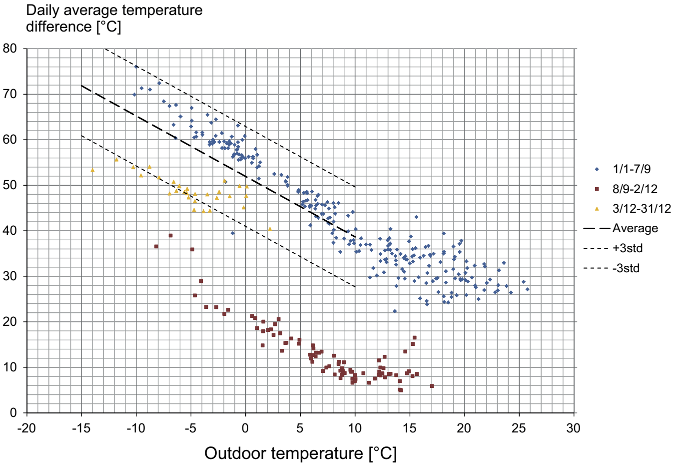

Fig. 7. Temperature difference signature for an industrial demand in Ängelholm with an annual heat demand of 1.36 TJ. A fault appeared on 8 September and was eliminated on 2 December. The temperature difference has not reached the same level after the fault was eliminated as before the fault appeared (Substation No. 12 in Table 2.).

importance that measures implemented in substations and customer heating systems really result in higher actual performances.

4.3. Monitoring fault frequencies

Nine of the temperature difference faults appeared during the year, indicating an annual frequency of temperature difference faults of more than 6%. This implies that more than 150 substations will have temperature difference faults appearing annually from the 3000 substations located in the two district heating systems selected in this study. In Sweden, about 100,000 district heating substations exist [49], one and two-dwelling buildings excluded, implying 6000 substations annually in Sweden will obtain some temperature differential faults. Roughly 1,000,000 substations within the EU, single dwelling buildings excluded, would indicate over 60,000 temperature differential faults appearing annually.

4.4. Future improvement of the novel detection method

To increase the resolution in the method, each substation should have its own temperature difference signature. This is also valid for the offset lines. In this study, the offset lines were chosen as 3 standard deviations from a range of well-performing substations but when individual temperature difference signatures are introduced, the offset lines can in most cases most probably be much narrower. For some substations, also a temperature difference signature for outdoor temperatures above 10 °C can be introduced. Individual temperature difference signatures and more narrow offset-lines will be even more important to apply in the next fourth district heating generation systems with essentially lower distribution temperatures.

4.5. Overall conclusions

Hourly meter readings, now available, open up for continuous commissioning of substations. Historically only heat supply and distribution have been properly commissioned continuously. Now we have a new opportunity to monitor all heat deliveries in district heating systems. Temperature fault detection has changed from being slow and expensive to becoming fast and inexpensive. This is a basic condition for more efficient district heating systems in the future.

Acknowledgements

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Paper IV

Fault detection in district heating substations.

Henrik Gadd[1]
Sven Werner

School of Business and Engineering
Halmstad University, PO Box 823, SE-30118 Halmstad, Sweden

Abstract

All efficiencies in district heating systems with respect to both heat supply and heat distribution increase when lower distribution temperatures are used. The customer heat demands in district heating systems are normally 20 °C to heat buildings and 50 °C for domestic hot water. Current systems have supply temperatures of about 75-90 °C and return temperatures of about 40-50 °C as annual averages. These levels are used in order to cover both the current customer temperature demands but also temperature faults appearing in the system. Future system design now discussed includes supply temperatures of 50 °C, since customer temperature demands will decrease as customer heat demands will decrease in the future. Then the margin and acceptance for temperature faults will radically decrease. This implies that temperature faults occurring must be detected quickly. All substations in Sweden will in 2015 have devices for automatic meter reading installed due to governmental demand for monthly billing of actual heat use. This implies that hourly metering readings for heat, flow, supply and return temperatures will be available from all district heating substations. These heat meter readings can also be used for the detection of usage, temperature, and control faults appearing in the heat deliveries. Entirely new information, never reported before, is presented about these faults. In this study, one-year time-series of hourly heat meter readings from 135 district heating substations was analysed. Faults were identified in 74% of the substations. Hence, only 26% of the substations worked correctly. The identified faults have been divided in three different fault groups: Unsuitable heat load pattern, Low annual average temperature difference and Poor substation control. The most important conclusion from this early study of big data volumes is that automatic meter reading systems can lead to future proactive fault detection instead of the current reactive fault detection in district heating substations and secondary customer systems.

Keywords

District heating, fault detection, big data, substations, temperature difference

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1. [1] Corresponding author: henrik.gadd@hh.se +46 35 167757

1 Introduction

District heating systems contribute substantially to a sustainable supply of energy. Heat and electricity can be generated by energy resources otherwise difficult to utilise, like waste, geothermal heat and industrial excess heat [1]. In order to stay competitive in the future, there are two major challenges for district heating systems: The first is competing of renewable energy resources and the second is decreased heat demands in new and existing buildings.

Decrease of available energy sources

To reach a sustainable society others than today bio mass is of interest in applications where oil is used today, e.g. liquid fuel as biodiesel or ethanol[2] or for plastic production[3], resulting in increased competition of. This will probably also result in somewhat decreased industrial excess heat because of increased energy efficiency measures in the industry. There is also a general objective to work towards decreased amount of waste by less usage and more recycling, i.e. the energy assets used in today's district heating systems will either not be available or too expensive in the future.

Decreased heat demands

In countries with small possibilities to expand district heating deliveries due to the saturation of the market, heat demand will decrease in the future due to energy efficiency measures in the connected buildings. The answer for district heating companies to this scenario can be to identify new applications for district heating and to generate more electricity [4]. This could seem contradictory since decreased heat demand ought to result in decreased generated electricity from CHP, Combined Heat and Power Plants, but according to [5], this is not the case since most of the energy decrease will be with heat-only boilers. Another and even more important measure in order to maintain the competitiveness in district heating systems is to increase the system efficiency. One of the most efficient ways to increase efficiency is to decrease distribution temperatures. The gains from decreased distribution temperatures are lower heat losses, increased efficiency, higher electricity output from CHP plants, and increased utilisation of geothermal and solar heat and industrial excess heat [1].

System boundary

District heating systems are often divided into three major parts: Heat generation, District heating network and Substations. But the system efficiency can only be optimised if the system boundary also includes the heated buildings. Faults in secondary systems will be transferred via the substation to the district heating network and heat generation, and will decrease system efficiency. Hence, customer secondary heat supply systems must be included when working with district heating system efficiency.

Traditionally heat generation and distribution have continuously been monitored to detect and solve faults immediately or within a few days, while substations have often been regarded as well-functioning as long as customers' comfort is not affected. The fault detection at the customers' end has at a large extent been reactive. This implies that mainly faults affecting customer comfort, and not faults decreasing system efficiency, are being detected.

Heat load patterns

Previously fault detection analysis based on meter readings had to be based on annual meter readings since it was what was available. In an IEA report from 2003 [6], it is stated that high resolution heat meter readings could be used for customer analysis. Still, analysis of a large number of substations with high measuring resolution is rare. The reason is that, in the past, the collection of heat meter readings has been performed manually and was thereby very expensive. In a thesis from 1996 [7], the heat load patterns of 50 substations were analysed with a measuring resolution of 15 minutes during a period of 18 months to learn more about heat demands in buildings. The lack of knowledge of the actual performance was the reason for the analysis of one building in [8], where a resolution of 5 minutes were used. A method to separate domestic hot water from space heating using the existing heat meter is presented in [9] and is interesting from a heat load pattern point of view.

Distribution temperatures

Current water-based district heating systems, referred to as third generation of district heating technology with a primary supply temperature of 80-110 °C, are used to heat air to 20 °C and domestic hot water to 50 °C. Why do we need 80 °C to heat air to 20 °C and domestic hot water to 50 °C? See Figure 1. There are two reasons for having a temperature level of 80/45℃ (supply/return temperature). The first reason is that the secondary systems in existing buildings are normally designed for high temperatures. Design supply temperatures have previously been 70-90 °C in Europe. With increasing demand for efficient energy use, the supply temperatures in secondary systems have gradually decreased and the design temperature in Sweden today is 55-60 °C which it has been for the last 30 years [10]. On the other hand, it has been shown that both in Sweden and internationally, the secondary systems are often oversized [11-15] and thereby capable to supply heat enough to obtain comfortable indoor temperatures at lower supply temperatures than design values. The second reason for high primary supply temperatures is that all temperature faults in substations and secondary systems and district heating operators only option in order to maintain the heat supply to all customers is to increase the supply temperature. Heat exchangers and substations do not need these high supply temperatures. If all substations and customer secondary systems worked as they were supposed to do, current system temperatures could be decreased to about 70/35 °C, which was shown in [16]. Hence, the high temperatures in current district heating systems are combinations of old design, tradition, and a compensation for temperature faults in substations and secondary systems. These temperature faults are not noticed by the customers, since the buildings are warm and hot water are available from the water taps.

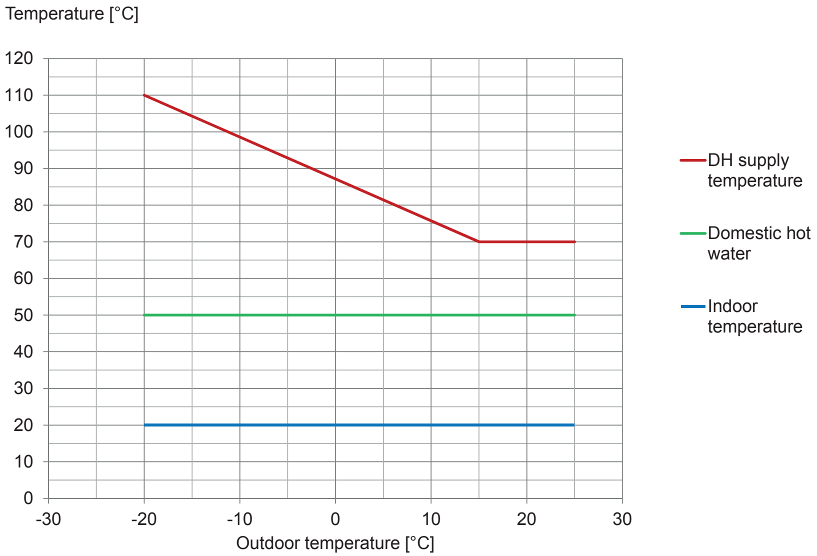

Figure 1 **Temperature levels in existing district heating systems. The primary supply temperature is 20-90°C higher than the temperature demands.**

For future district heating systems, 4GDH with system temperatures of 50/20 [17], the margin for faults will radically be decreased since faults will affect customer comfort. This is also one of the main conclusions in a Danish report that has evaluated low temperature district heating demonstration projects[18]. Then, continuous commissioning of substations and secondary systems will probably be necessary not only to detect faults quickly, but also to make service visits governed by needs and not, as is common today, by following the calendar in order not to spend man-hours to check equipment that is already working well.

Fault detection

A preconceived idea today is that most heat demands in district heating systems are working well. This paper will show that this is not the case. When running an air handling unit, continuous commissioning is essential to ensure and maintain optimal operation, which is a major conclusion in [19], where a lot of work in the area has been analysed. There is no reason to believe that other secondary systems and substations would work for years without any faults occurring. Hence, secondary customer heating systems do not function correctly.

Many fault detection methods described in the literature for district heating application are based on statistical methods e.g. [20-24], when a deviation from an expected heat demand is detected. These methods require a correct heat demand to compare with. However, a problem is that a large proportion of the substations do not work excellently or even well, i.e. there are no correct heat meter readings to compare with.

Excuses for not working with fault detection in substations and secondary systems

Energy companies have historically put a lot of effort into improving the efficiency of the energy supply and distribution. In the district heating field it is heat supply plants and networks that have not only been improved but also continuously supervised in order to detect faults quickly and eliminate detected faults. But substations and customer secondary systems have been of less interest. It has been regarded as the customers' problem. If only customer comfort is taken into consideration, this is a working strategy, but from a system efficiency and competitiveness point of view, it is not.

Reasons for not working with fault detection in substations and customer secondary systems are, in the first place, probably because there are so many and you have to do a lot of work to see the results. There is a large number of different possible faults that are occurring unsystematically [25-27]. In a 2005 report [28], three major reasons were identified why work to improve efficiency was not carried out: Lack of knowledge, internal problems to handle a job where a large part of the company has to be involved and difficult customer relations where technical personnel get into a sales role and sales personnel get into technical discussions.

The only way to override the mentioned problems above is to start working with hidden faults. In the same report there is advice of how to manage the problems, e.g. split the work in small projects, label the projects as system efficiency projects so that people understand that it is affecting the whole district heating system and decide how customer contacts should be realized and if possible, involve the customer and even to get them to pay for part of the investment.

Another problem is that when work has been performed to decrease system temperatures, it has often been organised as campaigns. Since new faults will appear in substations and secondary systems, work to decrease system temperatures must be an ongoing process as part of the day-to-day work. Otherwise, the system temperatures will slowly increase as new faults appear.

Current faults

Faults in substations and secondary systems could be divided into three categories: First, faults resulting in comfort problems such as lack of heat or domestic hot water and physical faults such as water leakage or sound emissions. Second, faults known but not solved due to the need of too many man-hours to identify them and third, faults where new fault detection methods must be developed. The third category includes faults caused by the human factor such as faulty settings in building operating systems. This paper only deals with the last two categories. In order to identify and solve faults in the last two categories, and thereby increasing the system efficiency, continuous commissioning of substations and secondary systems is necessary. Then fault detection can go from being reactive to becoming proactive.

Introduction of automated meter reading systems

On 1 July 2006 a change in the Swedish law [29] made it mandatory from 1 July 2009 to charge the customers for their actual use of electricity monthly and not as it used to be, based on prior usage. To fulfil this demand, automatic meter reading systems have been installed in the electric grids, but also in the district heating systems, since a major part of the district heating systems in Sweden is operated by companies that also operate the electric grids. From 1 January 2015 it will also be mandatory for district heating companies to charge their customers for the actual use of district heating [30]. Even though the demand is for monthly readings, the automatic meter reading systems are designed for a resolution of one hour or higher, i.e. hourly meter readings from all district heating substations can be available in 2015 in Sweden, meter readings that could be used for fault detection purposes.

Research questions

This paper will show that the introduction of automatic meter reading systems in the district heating systems not only opens up for a possibility of identifying faults that have previously been hard to detect, but also for information about fault frequencies that has never previously been published. The literature review in this paper has an overrepresentation of Swedish references due to 30 years of unique Swedish research programmes in the district heating field. In this paper, hourly heat meter readings from 135 substations have been analysed and the obtained results will give answers to the following three research questions:

-What types of faults can be identified in substations?
-What are the proportions of different fault groups?
-What is the proportion of substations that work correctly?

2 Method

2.1 Gathered data

The data sets in this study come from the automatic meter reading systems in two district heating systems in the south of Sweden: Helsingborg, with approximately 10,000 connected substations and an annual heat supply of 3.6 PJ, and Ängelholm, with approximately 3,000 connected substations and an annual heat supply of 0.7 PJ. The annual average supply temperature in 2010 was in Helsingborg 83.8 °C and in Ängelholm 85.8 °C. The corresponding return temperatures were 46.9 °C in Helsingborg and 47.8 °C in Ängelholm. From the two district heating systems, meter readings from 135 substations were selected for analysis, 82 from Helsingborg and 53 from Ängelholm, see Table 1 below. The data sets are the same as in [31], apart from six substations that have been excluded due to incomplete data sets. All data sets are hourly meter readings of heat, flow, supply and return temperatures on the primary side of the substation during one year. All data sets are from 2010, 1 January to 31 December.

Table 1 Number of substations and heat demands for the each of the five customer categories analysed in this study.

Customer categories	Number of substations	Annual heat demand [TJ]			
		Total	Average	Lowest	Highest
Multi-dwelling buildings	35	220.7	6.3	2.9	15.6
Industrial demands	33	68.9	2.1	0.2	10.0
Health and Social services buildings	10	17.2	1.7	0.5	4.1
Commercial buildings	22	63.8	2.9	0.3	14.2
Public administration buildings	35	147.5	4.2	0.4	27.0
Total	135	518.0	3.8	0.2	27.0

The selection is based on the amount of annually delivered heat, and customer category. In the customer records, customers are divided into eight different customer categories due to governmental demand to report energy use statistics. The energy statistics contain six customer categories: Industrial demands, One and two-family dwellings, Multi- dwelling units, Ground heating, Public administration and Others. In the customer records, the resolution is higher in two cases: Public administration is, in the customer records, split into Health and Social Care buildings and Public administration buildings. Others in the statistics are, in the customer records, split into Trade buildings and Others. In this study, the customer categories One and two-family dwellings have been excludes due to low share of the total heat demand (~20%) split to a large amount of substations. I.e. each substation in one- and two dwelling building has a very small impact of the system efficiency. Ground heating and Others from the customer records are also excluded. Ground heating due to it is only single installations and others due the subscriptions are undefined and thereby impossible to evaluate. The customer categories, from which the analysed substations originate, include approximately 3,000 of a total of 13,000 substations existing in the two district heating systems. From each customer category, the substations with the highest volumes of annual heat delivery were selected.

2.2 Analysis

In this study, meter readings from substations are analysed manually. It is a theoretical analysis, but is based on meter readings observed from real substations in continuous operation. Three types of faults or symptoms of faults have been identified:

- Unsuitable heat load pattern
- Low annual average temperature difference
- Poor substation control.

Unsuitable heat load pattern

In order to be able to identify unsuitable heat demand pattern the activity in the building has to be known. In this study, the information can partly be found in the customer records by using the customer categories, but there are two major problems. Firstly, the information is manually inserted in the customer records and thereby there is a risk for errors. Single errors have been discovered but are of a different magnitude than unsuitable heat load patterns. Secondly, the customer categories are set for reporting statistics and are only partly suited for determining expected heat load patterns, e.g. multi-family dwellings, which is the most homogeneous customer category while public administration buildings, on the other hand, is a very heterogeneous group. The heat load pattern used in this study is Continuous, Night setback (NSB), Time clock operation 5 days a week (TCO5) and Time clock operation 7 days a week (TCO7). The heat load patterns are studied as an average for four seasons. The heat load patterns and seasons are defined in [31]. The selection criteria for unsuitable heat load patterns in this study are all multi-family dwellings which do not have a continuous heat load pattern, industrial demands that do not have time clock operation of ventilation 5 days a week (TCO5) and commercial buildings that do not have any time clock operation of ventilation at all. All buildings with pronounced night set back control are also considered as unsuitable heat load patterns.

Health and Social Services buildings are mainly building owned by the county council and can be anything from hospitals with 7-24 operation with an expected Continuous heat demand to an office building with an expected TCO5 heat load pattern. Public administration buildings are municipal building e.g. schools, gymnasiums, public baths, libraries with day time activity but also service buildings for elderly people. I.e. Health and Social service buildings and Public administration are because of their heterogeneous heat load patterns, not possible to evaluate for unsuitable heat load patterns apart from night setback.

Low annual average temperature difference

The annual temperature difference is calculated from meter readings for delivered heat and flow on an annual basis. All substations with an annual average temperature difference of ≤ 45 °C are in this paper regarded as Low annual average temperature difference. In the analyses, substations were divided in groups depending on annual average temperature difference. One group for every 5 °, see Table 4. A combination of that the perfect building and substation do not exist and that all district heating customer are different, a limit for annual average temperature difference that is good enough as a general value had to be defined. It would be more correct to have individual limits for low annual average temperature difference, but because of lack of knowledge of each customer, this is not possible. I.e. an annual average temperature difference exceeding 45 °C is regarded as good enough.

The calculations are based on a constant density of 990 kg/m³, corresponding to a return temperature of 45 °C, since the flow meter is normally mounted in the return pipe. The heat capacity factor used is 4.18 kJ/kg, K, corresponding to a temperature of 65 °C that is the average temperature of supply and return temperature. Low annual average temperature difference is symptom of faults rather than faults and belongs in fault category two or three.

Poor substation control

Abnormal heat demand indicating poor substation control is manually analysed from four different diagrams for each substation: Heat power signature for daily and hourly averages and weekly analysis of energy and flow. Two selection criteria were identified: major irregular oscillations and bad correlation between heat demand and outdoor temperature. In Figure 2 below an example of a multi dwelling building with irregular oscillations in energy and flow is present and the heat power signature for hourly averages show bad correlation between heat demand and outdoor temperature. Figure 3 show a multi dwelling building that works correctly. Poor substation control is just as low annual average temperature difference is symptom of faults rather than faults and belongs in fault category two or three.

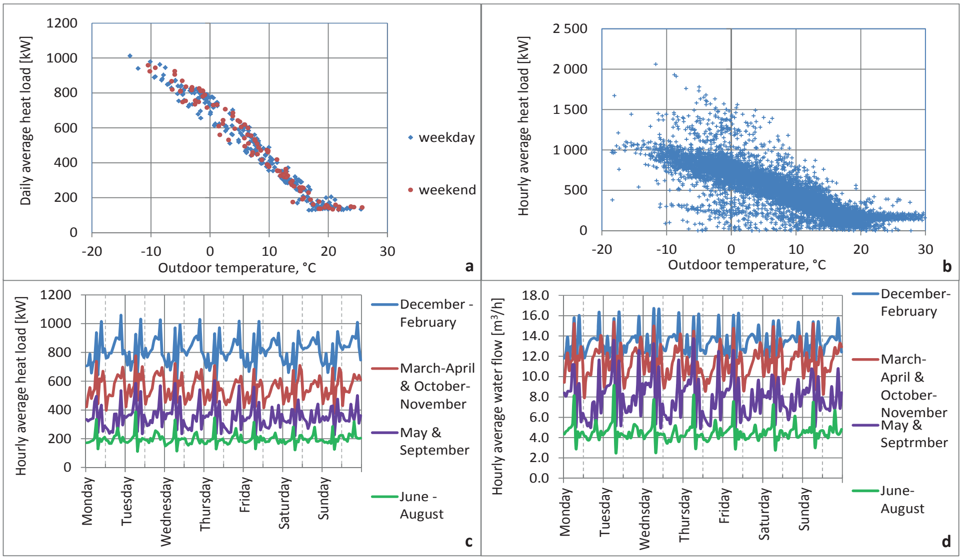

Figure 2 Heat power signature for daily(a) and hourly(b) averages and weekly analysis of energy(c) and flow(d) for a multi dwelling building with bad correlation between heat demand and outdoor temperature and irregular oscillations in energy and flow. Annual heat demand of 15.6 TJ and annual average temperature difference is 45 °C

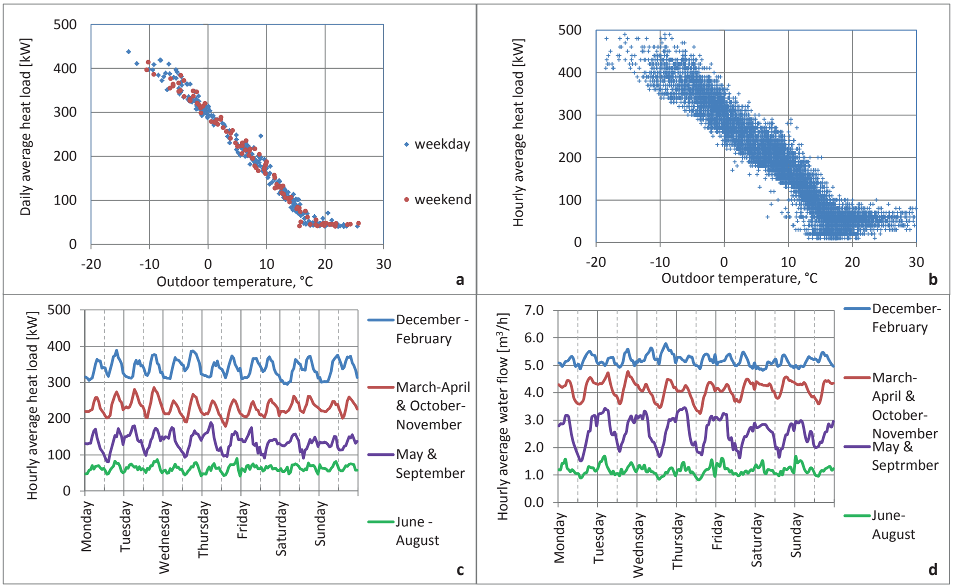

Figure 3 Heat power signature for daily(a) and hourly(b) averages and weekly analysis of energy(c) and flow(d) for a multi dwelling building that work correct. Annual heat demand is 6.3 TJ and annual average temperature difference is 51 °C.

3 Results

Heat demands in buildings are unique for each building. This is an aggravating circumstance in fault detection in district heating substations due to the difficulty in separating deviating heat demands from normal heat demands. Three fault groups are identified by manual analysis, but they could easily be automated which is a prerequisite for future district heating systems in order to maintain competitiveness.

In Table 2, a summary of the results from the analysis of the 135 substations can be found. 100 or 74% of the analysed datasets show faults or symptoms of faults in substations or secondary systems. Most common is Low annual average temperature difference with 92 or, 68% followed by Unsuitable heat load pattern that is identified in 30 or 22% of the substations. Poor substation control was identified in 16 or 12% of the substations. Only 35 or 26% work correctly, i.e. have large temperature difference, proper control and seem to have a correct heat load pattern. Health Care and Social Services buildings and Public administration buildings were not evaluated for Unsuitable heat load patterns. For the remaining 90 substations 22, or 24 %, are regarded as well-performing substations.

The result shows a large number of faults in the substations but no or low correlation between different types of faults. All fault groups are identified in all the customer categories and no systematic faults can be identified.

Table 2 Summary table for the 135 analysed substations split into identified faults and well-performing substations for five customer categories.

	Multi-family dwellings	Industrial demands	Health and Social Services buildings	Trade buildings	Public administration buildings	Total
Total number of substations	35	33	10	22	35	135
Unsuitable heat load pattern	4	23	2*	8	2*	39
Low annual average temperature difference	19	27	9	18	19	92
Poor substation control	3	3	2	3	5	16
Well-performing substations	15	3	1	4	12	35
Proportion of well-performing substations	43 %	9 %	10 %	18 %	34 %	26 %

*Health and Social services buildings and Public administration buildings are only regarded having unsuitable heat load pattern if Night set back is applied due to heterogeneous heat load pattern for these two customer categories.

3.1 Unsuitable heat load pattern

The heat load patterns used in this study were Continuous, Night setback control (NSB), Time clock operation 5 days a week (TCO5), and Time clock operation 7 days a week (TCO7). The heat load patterns for the five customer categories were identified, see Table 3.

Depending on the activity in the buildings, different heat load patterns are expected. Health and Social Services buildings and Public administration buildings are very heterogeneous from a heat load pattern point of view, so, apart from the four substations with Night setback control, they are not possible to evaluate without the knowledge of the activity in each building.

Total number of substations with unsuitable heat load patterns was identified in 35 (Shaded in Table 3) out of 90 analysed substations, or almost 40 % in the three customer categories: Multi-family dwellings, Industrial demands and Trade buildings. A drawback in identifying unsuitable heat load patterns is of course that the expected suitable heat load pattern in this study is set as a general pattern for all of the customer categories and not as it should be, individually for each building.

Unsuitable heat load pattern, the second most common fault, however, is easily identifiable and uncomplicated to correct.

Table 3 The 135 analysed substations sorted by four heat load patterns and five customer categories. Shaded numbers are identified as substations with unsuitable heat load patterns

Heat load pattern	Multi-family dwellings	Industrial demands	Health and Social Services buildings	Trade buildings	Public administration buildings	Total
Continuous	31	17	6	8	12	74
NSB	4	1	2	0	2	9
TCO 5	0	10	1	6	17	34
TCO 7	0	5	1	8	4	18
Total	35	33	10	22	35	135

3.2 Low annual average temperature difference

Even though for decades, it is well-known that a large temperature difference is advantageous, many substation temperature differences in district heating systems are low. In this study, the annual average temperature difference has a range from 7°C to 54°C. In Table 4, the 135 substations are divided by customer category and intervals of annual average temperature difference.

Almost 70% of the substations have a temperature difference of ≤ 45 °C and 15% have less than 30°C. Only 7% of the substations have a temperature difference exceeding 50 °C.

All customer categories contain substations with both large and small temperature differences, which indicate that it is a general problem. Hence, low annual average temperature differences are not systematic faults associated to customer category, but have individual explanations in each substation. This conclusion was drawn already in 1987 [25].

Table 4 The 135 analysed substations sorted by six annual average temperature difference intervals and five customer categories.

Annual average temperature difference	Multi-family dwellings	Industrial demands	Health and Social Services buildings	Trade buildings	Public administration buildings	Total	
<30	5	9	2	2	2	20	15%
30-35	2	4	0	4	1	11	8%
36-40	2	7	4	9	4	26	19%
41-45	10	7	3	3	12	35	26%
46-50	12	5	1	2	13	33	24%
>50	4	1	0	2	3	10	7%
Total	35	33	10	22	35	135	

3.3 Poor substation control

Poor substation control has been identified in all customer categories and in all temperature difference intervals. Out of 135 substations analysed, 16 substations or 12% were identified with Poor substation control, see Table 5. Four substations had bad correlation between heat demand and outdoor temperature. All of them also had irregular oscillations.

No general correlation between Poor substation control and Low annual average temperature difference can be identified, but the substations with a temperature difference of < 30 °C are over- represented in Poor substation control, see Figure 4.

Table 5 16 out of 135 analysed substations observed to have bad substation control sorted on selection criteria.

Poor substation control	Multi-family dwellings	Industrial demands	Health care and Social service buildings	Trade buildings	Public administration buildings	Total
Irregular oscillations only	2	2	2	3	3	12
Irregular oscillations and bad correlation between heat demand and outdoor temperature	1	1	0	0	2	4
Total	3	3	2	3	5	16

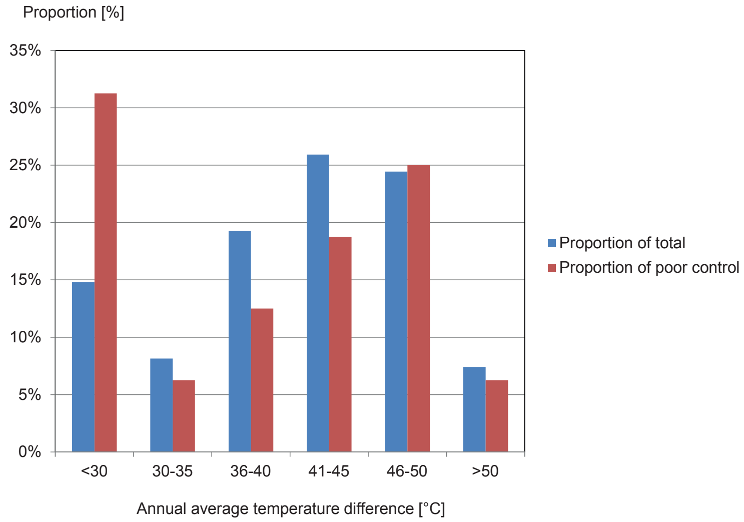

Figure 4 **Proportion of total amount of analysed substations (in blue) and proportion of poor substation control (in red) for six different temperature difference intervals.**

4 Discussion

In the fourth generation of district heating systems, 4GDH, 50°C supply and 20°C return temperature are discussed. A reduction of system temperatures increases system efficiency with reduced cost and emission as a result. Today faults can be, and are, compensated for by increased system temperatures. This study has shown that the district heating system does not work correctly. Almost 3/4 of the analysed substations in this study would be considered to have some kind of fault. The distribution temperatures in the two district heating systems where the analysed substations are situated, Helsingborg and Ängelholm, are in the midrange of district heating systems in Sweden. This makes it probable that the results are representative for at least Swedish conditions. In 4GDH-systems, today's faults will be unacceptable. In this study, all analyses are performed manually. However when applied in district heating systems to identify and eliminate faults quickly, automatic fault detection, in the form of continuous commissioning in one way or another, will become necessary.

The quality of the present customer records, automatic meter reading systems, substations and secondary systems are not better than what is needed for today´s DH-systems. To be able to introduce 4GDH, all system parts mentioned have to be improved. A difficulty when it comes to fault detection in district heating substations is that there are large differences between well performing substations. Different customers have different heat demands and different heat load patterns. A normal heat demand for one customer is abnormal for another.

To implement fault detection in the district heating systems, district heating companies must have a large amount of knowledge about their customers and their behaviour on an individual level from a heat demand point of view. It is also necessary to include the customer secondary heating systems in the optimisation of a district heating system, and thereby the work must be performed in close cooperation with the individual customers. To start with, general thresholds can be used, but in the long run, for the 4th generation district heating systems, thresholds for fault detection must probably be set on an individual basis. Many methods found in research literature are based on identifying deviation from previous heat demands, but if 75% of the substations are already more or less faulty this does not work. This is why fault detection based on absolute thresholds rather than relative thresholds is preferable.

Heat meter issues

This study shows that hourly resolution for meter reading is enough. The amount of faults is, at the present, so large that an increased resolution is of no use. For 4GDH, a higher resolution might be necessary, but there might also be a demand for a higher quality in the meter readings.

Traditionally heat meter readings have only been used for billing purposes. The reason for measuring has been to split the cost for a common heat supply system in such a way that the customers regard as fair. The driving force for developing heat meters has been low prices. If heat meters are to be used for fault detection in the future there might be other demands. Development areas for heat meters could be increased accuracy of sensors and measuring systems but also to have additional parameters that should be measured other than heat, flow, supply and return temperatures. For instance, secondary temperatures and flows or differential pressures in both primary and secondary systems could be of interest. A part of this already exists in building supervision systems. Then it is a matter of how to utilise the meter readings and by whom it should be done.

This study shows that hourly meter readings can be used for faults detection in district heating substations that previously would demand great effort in man-hours. It opens up for continuous commissioning that can change service visits to be governed by demand and not by calendar.

5 Conclusions

This study of meter readings from 135 district heating substations was performed in order to identify faults. In the present district heating systems the proportion of faults is high. From the 135 meter reading data sets, 100 have been identified with faults, i.e. only 26 % of the analysed substations worked correctly. Three main groups of faults were identified: Unsuitable heat load pattern, Low annual average temperature difference, and Poor substation control.

Unsuitable heat load pattern

Unsuitable heat load pattern is a result of faulty settings in the buildings’ control systems, i.e. it is not a fault in the equipment but a fault caused by the human factor. It is a fault in the building’s control system and not in the substation. According to this study the proportion of unsuitable heat load patterns is in the range of 30-40 percent, but these faults are easy to identify and uncomplicated to correct. This fault group is probably the most low-hanging fruit in measures to decrease heat use in buildings.

Low annual average temperature difference

About 70% of the substations have a temperature difference of less than 46 °C. Low annual average temperature difference is one of the most important factors working against high efficiency in substations and has been an improvement issue in district heating discussions for decades, but is obviously still a burning issue.

Poor substation control

Poor substation control was identified in 14% of the substations. As for low annual average temperature difference, poor substation control is not a fault but a symptom of faults that can be both physical faults and faults caused by the human factor. It can be faults in the substations or in the secondary systems. But, there is no or little correlation between a low annual average temperature difference and poor substation control.

Overall conclusions

An aggravating circumstance for fault detection in substations and customer secondary systems is that heat demand patterns in buildings are individual. A correct heat demand for one building constitutes a fault for another building.

This study has shown that hourly meter readings can be used to identify faults in district heating substations and customer secondary systems. From the three fault groups, Low annual average temperature differences are still, after decades of discussion, the most important issue to work with to improve the system efficiency in district heating systems. However, unsuitable heat load pattern is probably the fault that is the easiest and most cost-effective to do something about. Generally speaking, all faults are coincidental and have no occurrence pattern and are thereby difficult to predict. The most important conclusion from this study is that automatic meter reading systems can lead to future proactive fault detection instead of current reactive fault detection in district heating substations and secondary customer systems.

In this study all analyses were manually performed for the research purpose. However, automated methods must be developed in order to apply these analyses in district heating systems. The main conclusions from this study can then be utilised when designing appropriate data mining methods.

6 Acknowledgements

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