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District heating and cooling as part of smart energy systems

Licentiate Thesis submitted in partial fulfilment of the requirements for the degree of Licentiate of Science in Technology.

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Abstract

Energy systems are evolving and energy companies are required to take action to achieve higher levels of energy efficiency. Smart cities have been widely under discussion and smart energy systems are considered as the backbone of this approach. District heating and cooling (DHC) businesses are argued to be ‘important tools’ for reaching energy targets. The major objective of this research is to study the special characteristics of smart energy systems and how DHC systems are adapting to them. The most important factors for smart thermal grids are intelligence, efficiency, and flexibility in production and consumption, customer involvement, integration with other energy systems, and reliability. This study will present three case studies to highlight energy efficiency measures on the consumer side of a DHC system. The first study concentrates on the benefits of remote measurements and better implementation of a district heating (DH) forecasting model when consumer’s hourly measurements are utilised. The forecasting model was formed using linear regression, based on outdoor temperature data and the social component of the heat consumption. The study shows that forecasting models are more accurate for bigger customers and aggregated groups of customers and in the best cases a rather simple model predicts heat consumption with good accuracy.

The second case study focuses on the flexibility of the DH network. The demand-side management (DSM) potential of district-heated residential buildings was determined by cutting heat for one hour during the morning consumption peak. Utilising the results of an earlier study, where the thermal behaviour of eight different-aged residential buildings was simulated, the object of this research was to figure out the overall DSM potential of the buildings. The results showed that the thermal behaviour of the buildings varies and that the buildings with the best potential for DSM were the ones built during the years 1940–2002. In the larger scale, the momentary heat effect decreased 80 percent due to DSM actions.

The last case study concentrates on the original idea of the DH system, which is that heat can be recycled from sources where it otherwise would be wasted. A new business model is presented and critically evaluated, in which heat customers can sell their waste heat back to the energy company at a predetermined price. The pricing model is estimated relative to the waste heat suppliers as well as to the energy company. The results showed that, in general, it is profitable for heat customers to sell their waste heat in situations where the price of electricity is low, because then priming the temperature of the waste heat using heat pumps is affordable. System-wide, the results showed that emission levels were increased in most of the cases due to the priming of the waste heat. Despite the results, this concept is an important opening for the energy and heat markets to include more waste heat in an energy system and thus decrease primary energy consumption.

Keywords: thermal energy systems, smart energy systems, district heating and cooling, energy efficiency, consumption forecasting, demand-side management, waste heat utilisation

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Tiivistelmä

Energiajärjestelmät kehittyvät ja energiayhtiöiltä vaaditaan toimia energiatehokkuuden parantamiseksi. Kaukolämpö- ja kaukojäähdytysjärjestelmiä pidetään tärkeinä osina tehokkaita energiajärjestelmiä. Tämän tutkimuksen tavoitteena on tarkastella älykkäiden energiajärjestelmien tärkeimpiä tekijöitä sekä sitä, miten kaukolämpö- ja kaukojäähdytysjärjestelmät sopeutuvat niihin. Älykkäiden lämpöjärjestelmien tärkeimpiä tekijöitä ovat älykkyys, tehokkuus, joustavuus tuotannossa ja kulutuksessa, asiakkaiden osallistuvuus, integrointi muiden energiajärjestelmien kanssa ja järjestelmien luotettavuus. Tässä työssä esiteltiin kolme tutkimusta, joiden lähtökohtana ovat lämmönkuluttajat. Tutkimusten tavoitteena oli lämpöjärjestelmien energiatehokkuuden parantaminen. Ensimmäinen tutkimus keskittyi lämpöenergian etämittauksen hyötyihin. Tutkimuksessa kehitettiin kaukolämmön kulutuksen ennustusmalli, jossa hyödynnettiin asiakkaalta saatua tuntimittausdataa. Ennustusmalli perustui lineaariseen regressioon ja siinä hyödynnettiin ulkolämpötilaa ja lämmönkulutuksen sosiaalista komponenttia. Tulokset osoittivat, että ennustusmalli on tarkempi suuremmille asiakkaille sekä asiakasryhmille. Lämmönkulutusta on mahdollista ennustaa tarkasti melko yksinkertaisella ennustusmallilla.

Työn toinen osa keskittyi kaukolämpöjärjestelmän joustavuuteen sekä lämmön varastointiin. Tässä osassa selvitettiin kaukolämmitettyjen asuntojen kysyntäjoustopotentiaalia silloin, kun lämpöenergia katkaistiin yhdeksi tunniksi aamukulutushuipun aikana. Tutkimus perustui aiemmin tehdyn selvityksen tuloksiin, jossa simuloitiin kahdeksan eri vuosikymmenenä rakennetun kerrostalon lämpökäyttäytymistä lämmönkatkaisun aikana. Tulokset osoittivat, että rakennusten lämpökäyttäytyminen vaihtelee suuresti rakennusvuoden mukaan. Paras kysyntäjoustopotentiaali oli kerrostaloasunnoissa, jotka on rakennettu vuosien 1940 ja 2002 välillä. Kaupungin energiajärjestelmätasolla hetkellinen lämpöteho laski joinakin päivinä jopa 80 prosenttia kysyntäjouston ansiosta.

Työn kolmannessa osassa lähtökohtana oli, että kaukolämpöjärjestelmässä voidaan hyödyntää hukkalämpöä monenlaisista lähteistä. Tässä osassa esiteltiin uusi kaupallinen malli, jossa kaukolämpöasiakkaan on mahdollista myydä hukkalämpöä energiayhtiölle ennalta määrättyyn hintaan. Järjestelmää kutsutaan avoimeksi kaukolämpö- ja kaukojäähdytysjärjestelmäksi (Open DHC). Hinnoittelumallia arvioitiin sekä hukkalämmön toimittajan että energiayhtiön kannalta. Tulokset osoittivat, että hukkalämmön myyminen kaukolämpöverkkoon on kannattavaa silloin, kun sähkönhinta on alhainen. Tällöin hukkalämmön lämpötilan nostaminen (priimaus) lämpöpumppuja käyttäen ei ole asiakkaalle liian kallista. Järjestelmätasolla tulokset osoittivat, että lähes kaikissa tapauksissa hukkalämmön vastaanottaminen nosti energiajärjestelmän päästötasoa, joka johtui hukkalämmön priimauksesta. Tuloksista huolimatta Open DHC on mielenkiintoinen avaus energia- ja lämpömarkkinoille, jonka tavoitteena on tuoda lisää hukkalämpöä järjestelmään ja täten vähentää primäärienergian kulutusta.

Avainsanat lämpöjärjestelmät, älykkäät energiajärjestelmät, kaukolämpö ja kaukojäähdytys, energiatehokkuus, kulutuksen ennustus, kysyntäjousto, jätelämmön hyödyntäminen

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- Kontu, K., Fang, T., Lahdelma, R. Forecasting district heating consumption based on customer measurements. Proceedings of the IASTED International Conference. Power and Energy Systems and Applications (PESA 2012). November 12–14, 2012 Las Vegas, NV, USA.

and

- Jokinen, E., Kontu, K., Rinne, S., Lahdelma, R. Demand side management in the district heated buildings to optimize the heat production. Accepted in ECOS 2014– The 27th International conference on efficiency, cost, optimization, simulation and environmental impact of energy systems. June 15–19, 2014. Turku, Finland.

as well as on the following paper, which has been sent to the journal *Energy*, comments from the journal having been received:

- Kontu, K., Rinne, S., Wirgentius, N., Lahdelma R. Utilisation of waste heat: A market-based approach to a district heating system. Sent for approval to *Energy* journal in 05/2014.

In addition to these, Kaisa Kontu has participated as author in the following academic works:

- Kontu, K., Rinne, S., Olkkonen, V., Lahdelma, R., Salminen, R. Multicriteria evaluation of heating choices for a new sustainable residential area. Approved to *Energy & Buildings* journal (02/2015).
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- Kuosa, M., Kontu, K., Mäkilä, T., Lampinen, M.J., Lahdelma, R. Static study of traditional and ring networks and the use of mass flow control in district heating applications. *Applied Thermal Engineering* 54 (2013) 450-459.

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LIST OF ABBREVIATIONS

CHP	Combined heat and power
COP	Coefficient of performance
cFIR	Conditional finite impulse response -model
DC	District cooling
DH	District heating
DHC	District heating and cooling
DSM	Demand-side management
EU	European Union
ICT	Information and Communication Technologies
HOB	Heat-only boilers

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1 Introduction

1.1 Research theme and background

Thermal energy, i.e., heating and cooling, accounts for 46 percent of global final energy demand (International Energy Agency, 2013). Because of thermal energy's large share of overall energy demand, the future trend in thermal demand will significantly affect global energy need as well as emission levels. At the EU level, district heating (DH) and district cooling (DC) along with combined heat and power (CHP) production are considered as 'important tools' for reaching the energy targets (Connolly et al., 2014; European Commission, 2012). Also, the International Energy Agency (2013) highlights the fact that district heating and cooling (DHC) systems are feasible energy technologies; they will be even more feasible in the future when a projected 6.3 billion people will live in cities around the world by 2050.

In Nordic countries, DH has a long tradition, with a large market share. Yearly DH consumption is approximately 130 TWh (International Energy Agency, 2010a). DC systems in wide scale have a shorter history but their market share is increasing. CHP production has a big role in Nordic DH production. The energy efficiency of a CHP plant is high and the energy company also receives income from selling electricity.

Energy systems are evolving, with pressure from many directions (for example the EU's climate change strategies, national regulations, and energy efficiency directives) to increase energy efficiency. The production of electricity with renewable sources brings challenges to energy systems because production is more difficult to forecast. Also, consumers can produce electricity to be sold back to the network, thus production will be more scattered.

Smart cities have been widely under discussion as expected solutions for energy systems coping with the coming changes. Energy systems in smart cities are assumed to be flexible, adaptable, reliable, and efficient in both production and consumption. Intelligence and utilisation of information and communication technologies (ICT) in smart energy systems are regarded highly as they are helping cities to make better use of their resources. The role of consumers is also becoming more important; they are no longer considered as a single consumption point of the system but as an important part of the energy system having the possible capacity to produce energy for the network as well as to be a flexible consumer.

The DHC business is expected to have the willingness to reply to the changing market as well as the ability to develop new ideas for the heating market. Initially, DHC systems have features which will help energy systems respond to the expectations of a smart energy system. One of these features is that in a DHC network, it is possible to utilise heat that otherwise would be wasted (such as heat from CHP plants, industrial waste heat, and geothermal heat), making the energy system more efficient. Industrial waste heat originates in industrial processes in large quantities, but in many cases the location makes it hard to utilise in existing heat networks. Small-scale industrial companies, such as data centres, ice stadiums, and shopping centres, which need continuous cooling, are usually located close to population centres, but the amount of waste heat generated is smaller and usually the quality is not proper as such.

Another strength of DHC systems is their ability to bring flexibility to energy systems, since storing energy (heat or cold) in the short term is easy. DH networks have already been used as small heat storage systems; beside this, in many cases larger heat storage systems are added to the network. One possibility to make DH systems more efficient is to use demand-side management (DSM), which would help to even out consumption peaks.

A traditional DH system in Finland is presented in Figure 1 (at left). As the figure shows, the base load is produced in CHP plants and the peak load is produced in heat-only boilers (HOB). The imbalance between the production and consumption can be evened out with small heat storage systems; also the heat network is used as heat storage. DHC consumers consist of single consumers (residential buildings, public buildings, offices), small enterprises (such as grocery stores, ice stadiums, data centres located close to residential areas) and big companies (need of process heat in industry). Heat consumers in the DHC business have been seen as an inflexible part of the energy system.

In future, DHC systems need to be developed towards the figure presented at the right in Figure 1 where heat production is versatile, even more so with the addition renewable energy sources. The increase of fossil fuel prices due to climate policy actions requires energy companies to consider other fuel options. The significance of heat storage to even out the imbalance of production and consumption has increased. Consumers have become a more important part of the system in achieving energy efficiency targets. Consumers can be a flexible part of the energy system and their consumption can be forecasted more precisely. Waste heat from larger consumers can be utilised and thus decrease the use of primary fuels as well as emissions. The temperature level of the DH system should be lower to bring more waste heat into the network and to achieve a lower level of heat loss. ICT systems and remote measurements (smart measurements) are an important part of the transition to smart energy systems.

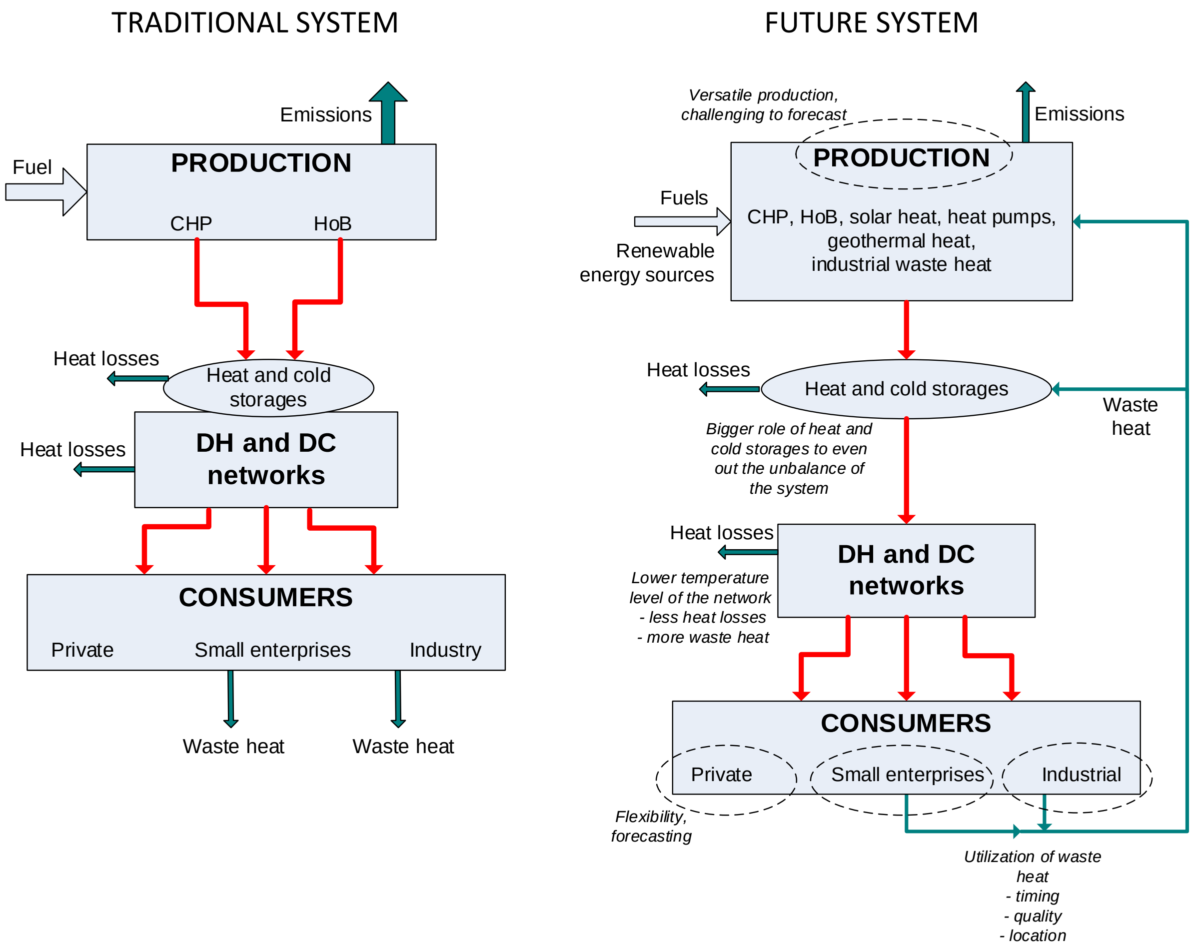

Figure 1. Transition of DH systems. The traditional DHC system is presented at left. At the right, a more efficient and flexible DHC system is presented where production is more versatile, waste heat is utilised in DHC production, and single customers are more flexible as well as permitting more accurate forecasts.

1.2 Research gap

Smart energy systems have been widely studied but the research has mainly concentrated on smart electricity grids. Smart electricity grids have been studied in terms of energy policy and regulation as well as in country-specific reviews (Connor et al., 2014; Crispim et al., 2014; Lin et al., 2013; Muench et al., 2014), ICT technology (Bhatt et al., 2014; Reddy et al., 2014; Wissner, 2011), renewable energy and energy optimisation (Clastres, 2011; Kaygusuz et al., 2013; Mohamed and Mohammed, 2013; Phuangpornpitak and Tia, 2013), and energy storage (Koohi-Kamali et al., 2013; Krajačić et al., 2011).

Also, the term smart grid is almost always used to refer to smart electricity grids. The problem of this one-sided research is that it often leads to researchers concentrating on electricity transmission lines, flexible electricity consumption, and electricity storage as being the main ways to deal with the integration of fluctuating energy sources from renewable energy. The efficiency of the energy system is increased when electricity systems are combined with other energy systems such as heating and cooling systems, gas grids, and transportation (Hvelplund et al., 2014; Lund et al., 2014, 2012).

There are a few research and political papers, however, which concentrate on smart thermal energy systems, including district heating and cooling systems, promoting their benefits as a part of an efficient energy system. In Schmidt et al., (2012) the concentration is on the challenges and opportunities for district heating and cooling systems as necessary parts of smart cities. Some of the same writers have also participated in the policy papers in the EU-level smart city group (Schmidt et al., 2013) where similar work has been done.

Another EU-level series of research studies concentrating on thermal networks as a part of smart energy systems was implemented between the years 2012 and 2014 (Connolly et al., 2014, 2013, 2012; Persson et al., 2014). Heat Roadmap Europe studies concentrate on how local resources can be utilised to satisfy the energy demand. The methodologies used are geographical mapping and energy simulations with the energyPLAN tool. As a result, these reports give recommendations for a redesign of the European heat supply, at the same time achieving the CO_2-emission reductions set by the European Council to be accomplished by the year 2050. The main ideas for achieving these goals involve lowering heat demand in buildings and expanding district heating systems across the EU-28 and candidate countries.

As stated above, smart energy systems have previously been studied widely, but a wider perspective is needed. It will be necessary to combine research concentrating on electricity grids with research into different energy systems to find the most energy-efficient solution. Also, studies where the concentration is on consumers as a flexible part of thermal energy systems (and thus as part of larger smart energy systems) have received less attention.

1.3 Targets and research questions

The central question of this research is what the special characteristics of a smart energy system are and how DHC systems are adapting to them. With different case studies, this research will concentrate on how different energy efficiency measures on the consumer side will affect DHC systems and will proceed from there to examine the efficiency of the whole energy system.

This thesis is aimed to address the following research questions:

- How can DHC markets adapt to the definition of a smart city? What challenges will such adaptation bring to DHC systems? Which DH and DC characteristics will help energy systems become smarter?
- How can DH remote measurements be utilised? Is it possible to develop more specific forecasting models for DH consumption based on hourly consumption data from individual customers? What benefits do remote (smart) measurements bring? Is it possible to make energy systems and DHC systems more efficient with smart measurements?
- How can small consumers such as residential buildings and public buildings function as a flexible part of the energy system? What is the possibility of using demand-side management (DSM) to make energy systems more efficient? What is the DSM potential of district-heated residential buildings for cutting short-term heat demand peaks?

- How can waste heat from different temperature levels be utilised in heat networks and how can the quality of the waste heat be increased to the necessary level? What are the effects of feeding waste heat to the DHC network with regard to the efficiency of the energy system and emission levels? How are the availability of waste heat and the timing of heat demands linked together and what is the role of heat storage in this? What kind of pricing model is convenient for the efficient sale of waste heat?

1.4 Construction of the research

After the introduction, this research is divided into seven chapters. Chapter 2 briefly presents the heating options mainly used for space heating in Finland. After this, the chapter concentrates on examining the basics of DH and DC systems. This chapter describes how DH and DC systems have developed over the years and in which countries these systems can be found. The basic technologies are presented, concentrating on how these systems are executed in the Finnish energy system. Variations in district heating and cooling consumption are described with city wide examples, as well as consumption from one residential block building. Chapter 2 also provides information about measuring and forecasting district heating consumption, supported by a literature review. Finally, Chapter 2 describes the advantages and disadvantages of these systems as well as their future challenges.

Chapter 3 concentrates on common factors of thermal energy systems in smart cities. Because the definitions of the terms ‘smart city’ and ‘smart energy system’ are not unambiguous, this chapter starts by examining different definitions and common factors for these systems. When common factors are found, characteristics of thermal energy systems in smart cities and smart energy systems are examined to ascertain what challenges these will bring to DHC systems and which DHC characteristics will help energy systems to become smart.

Chapter 4 concentrates on optimising heat and cold production in smart energy systems, since this will become even more important for energy systems in the future. This chapter will concentrate on a literature review of heat and cold storage, including waste heat in thermal energy systems, and the modelling of energy systems. The last part will concentrate on presenting the energyPRO energy simulation tool, since this tool is used for optimising energy systems in Chapter 7.

Chapters 5, 6, and 7 each concentrate on a case study which looks at different challenges of DHC systems when adapting to smart energy systems. Chapter 5 focuses on ICT systems and the possibilities of smart metering in DH. There are many possibilities related to smart metering which are still untapped in DH systems, even though, at least in Finnish DH companies, remote meters have been installed giving hourly consumption data. This chapter focuses on building a DH consumption forecasting model based on hourly measurements.

Chapter 6 presents how a DH system can be a flexible part of the energy system, with concentration on DSM. Here it is examined the possibility of residential block buildings to operate as short-term heat storage sites by cutting the heat for one hour in the morning to lower the heat load peaks in the DH system.

Chapter 7 demonstrates the utilisation of waste heat in a DHC network by investigating the Open DHC system in Stockholm. The idea of the Open DHC system is that a DHC network will be opened to customers, giving them the opportunity to sell their extra (waste) heat at a pre-determined price to the thermal network. Differing amounts of waste heat, at various temperature levels, will be recovered in the DHC system. This case study will critically evaluate the opportunities and challenges of the Open DHC system in terms of increasing the energy efficiency of DH systems and decreasing the CO_2-emissions. To be able to do that, the whole energy system is modelled on hourly level.

The individual case studies in Chapters 5, 6, and 7 are discussed in terms of the area of research to which they belong, and the research gaps in earlier studies.

In Chapter 8, a discussion of the whole study, with conclusions, is given. This chapter also makes recommendations for further study.

2 District heating and district cooling systems

2.1 Traditional options for heating

In the traditional heat supply market, heat can be supplied using various technologies and fuels, such as electricity, district heating, oil, or gas (no. 1 in Figure 2). With electric heating, the customer can choose the electricity supplier and thus influence the choice of the fuel. With DH systems, the customer is not free to choose the heat supplier because DH systems are specific to a particular area. Additionally, heat can be supplied with a heat pump from the air (no. 2), from the ground (no. 3), or by circulating heat inside the building (no. 4). From these space-heating options, the dweller can choose either one technology or a combination of the above-mentioned technologies. This is not the case in every country, however. For example, Denmark and Norway have regulations that make it possible to force customers to connect to the DH network (International Energy Agency, 2010a). In the case of Finland, the supporting heating systems, such as solar thermal or heat-storing fireplaces, brings more reliability for the dweller’s heating systems.

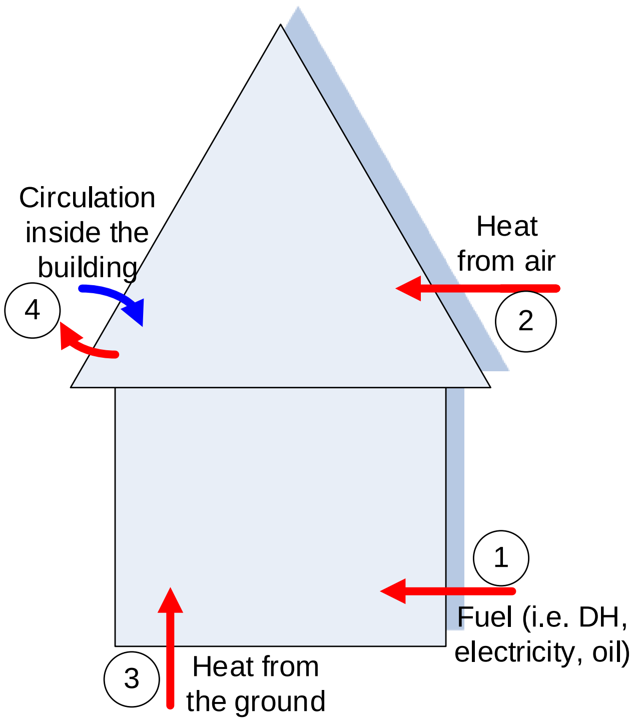

Figure 2. Traditional heat supply market where the red lines represent the heating and the blue lines the cooling.

Customers want a comprehensive service for both heating and cooling. The increased cooling demands in residential buildings result from heat gain due to the number of entertainment electronics and ICT appliances being used. In addition, certain types of service buildings need continuous cooling (Haywood et al., 2012; Uddin and Rahman, 2012). This changes the heat supply market. Heat inside a building must also be delivered elsewhere, and this is the reason why two-way heat transfer is an important part of the heat supply market. Space-heating options (2–4) can be used for cooling as well. In the case of a DH business, two-way heat transfer means that buildings (customers) sell waste heat to the DH system and the energy company pays an agreed price for the heat.

The dweller usually chooses a heating system based on multiple considerations, such as whether the heating system is economical, environmentally friendly, and reliable (Motiva, 2012).

Electric heating

Electric heating can be implemented either as a room-specific system or a water-cycling system. Adjustment for the desired temperature level is quick and easy in both systems. Electric heating is especially suitable for houses, in which heat demand is small (such as small low-energy and passive-energy houses), since the cost of electric heating is higher than for other heating options. Installation costs for a room-specific electric heating system (for a single-family house) is approximately 5000–10000 €; for the water-circulating system, it is 7500–12500 €. The operating costs vary according to the electricity consumed. Delivery reliability of the electric heating system is almost 100 percent and its use is effortless; thus it does not need much maintenance.

District heating

The heat for the DH system can be produced in a heat-only boiler or combined heat and power plant. The environmental effects of the DH depend on the method used for heat production. Typically, the investment costs for the DH system for a single-family house is 10000–15000 €. In addition to this, there are costs for heat consumption. Delivery reliability of the DH system is almost 100 percent and its use is effortless; thus it does not need much maintenance. More information on the DH system is presented later in Chapter 2, sections 2.2 and 2.3.

Ground source heat pump

Ground source heat is typically collected either from bore well in the rock or from the run of pipes installed horizontally at a depth of one metre. Approximately two thirds of the heat produced is the renewable heat from the source and one third is produced with electricity, which is used to run the system. The typical investment cost for the ground source heat pump for a single-family house is 15000–20000 €.

Oil heat

An oil heating system includes the following parts: oil boiler, oil burner, oil tank, flue chimney, and control system. Newly installed oil heating systems are energy-efficient with 94–95 percent efficiency. Measured yearly, the energy efficiency of the oil heating system is approximately 90 percent. Oil heating systems are easy to combine with renewable energy systems such as solar heat or wood.

Beside these, the following supporting heating systems were included in the study:

Solar heat

Solar heat technology is based on the utilisation of solar heat energy to operating a building's heat applications. Solar collectors are used to recover the solar heat. In Finnish weather conditions, solar heat is mainly used for heating domestic hot water but it is also possible to use it for space heating. Measured yearly, a typical solar heat system can produce 50 percent of the heat needed for domestic hot water and 10–15 percent of that needed for space heating. Solar heat is normally used as a supplementary heating system in single-family houses. The size of a solar heat system suitable for a single-family house is 8–20 m^2 and its investment cost is approximately 4000–7000 €.

Heat-storing fireplace

Wood fires have a long tradition in Finland even though fireplaces and wood-fired boilers are rarely the main heating system in buildings nowadays. The fireplaces have some special features when compared with other heating systems. Fireplaces can be used in exceptional circumstances where centralised energy systems are not available. Wood firing requires active procurement and storing of the fuel as well as an active user. Wood firing as a supplementary heating system can result in energy savings as well as being economical. The negative side of wood firing is the particle emissions produced. As a supplementary system in a single-family building, the investment cost of a fireplace is approximately 3000 € and the price of the firewood is 55–95 €/i-m^3 (dry wood).

Because of the cold weather in Finland, space heating of residential buildings is one of the biggest energy consumers. Statistics available from Finnish Energy Industries show that district heating has the largest market share with 46 percent of heating residential, commercial, and public buildings, followed by the market shares of other heating systems in Finland (Energiateollisuus ry, 2014). In Figure 3, the market share of heat pumps (11,6 %) includes the electricity consumed by them. The market share of electricity (18,6 %) includes the electricity consumption of heat distribution equipment and electric sauna stoves; similarly market share of wood (13,1 %) includes the wood used by sauna stoves.

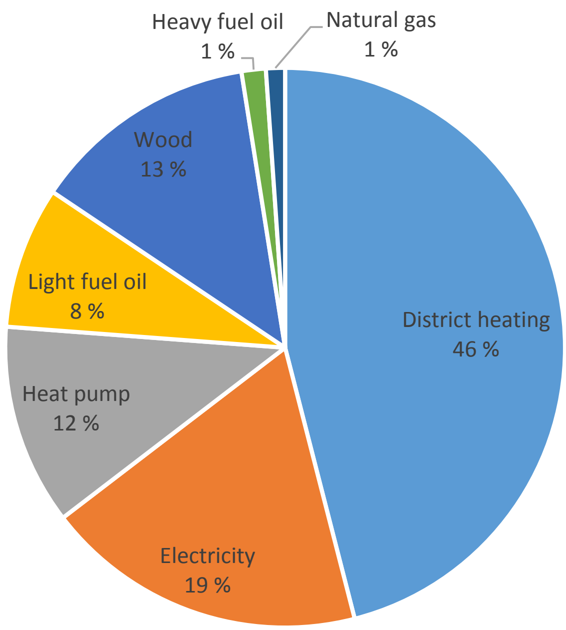

Figure 3. Market share of space heating in residential, commercial, and public buildings in Finland, 2012 (Energiateollisuus ry, 2014)

2.2 Introduction to district heating and district cooling systems

District heating is centralised heat production for heating buildings and service water and distributing the heat to consumers in a wide area. On a global scale, DH is widely used in Western and Eastern Europe, North America, and some Asian countries (Japan, Korea, China, and Mongolia) (Energiateollisuus ry, 2006; Frederiksen and Werner, 2013). The main customers for a district heating system are industry, public buildings, office buildings, apartment buildings, and single-family houses.

District cooling is centrally produced, delivering chilled water from a cooling plant to customers (such as residential, commercial, and industrial facilities) which are connected via a pipeline. DC is mostly used in downtown or commercial areas and can be found in several European countries (such as Finland, Sweden, German, Austria, and France), Japan, Korea, USA, and the United Arab Emirates. DC still has a rather small share in the cooling market (Frederiksen and Werner, 2013). Proper statistics for this

Table 1. Capacities, total sales, and length of pipeline for DH systems, plus percentage of citizens served by DH in selected countries (Euroheat & Power, 2011)

	DH capacity	DH sales	Trench length of DH pipeline system	Percentage of citizens served by DH
	MW_{th}	TJ	km	%
Austria	9 500	73 176	4 376	21
China	338742 [1)]	2 810 220	147 338	
Denmark		10 194	30 288	61
Finland	22 940	11 229	13 060	50
France	16 293	78 502	3 644	7
Germany	49 931 [2)]	279 938	20 151	12
Hungary	7 638	31 647	2 138	
Japan	4 248	21 958	656	
Korea	38 321	187 024	2 037	15
Netherlands	5 600	268		5
Norway	2 893	13 859	1 334	1
Poland	58 300	235	19 621	41
Russia	541 028 [3)]	6 891 293		
Sweden	17 500	182 727	22 800	48
USA	89 600	354 871	3 320	3

1) plus 85 273 t/h steam
2) connected load
3) in 2007

are difficult to get because figures are not systematically collected. Table 1 and Table 2 show the figures for DH and DC systems in selected countries across the world.

Table 2. Capacities, total sales and length of the pipeline for DC systems (Euroheat & Power, 2011)

	DC capacity	DC sales	Trench length of DC pipeline system
	MW_{th}	MWh	km
Austria	35	64 832	7,4
Denmark			
Finland	156	125 880	77
France	668	876 000	145
Germany	161	171 667	54
Hungary	3	602	
Japan	3960	3 460 704	
Korea	194	181 495	33
Norway	126,2	122 711	53
Poland		46	20
Sweden	650 [3)]	900 000	334
USA	16234	24 714 555	596

DH systems have developed over the years. The first DH systems were established in the USA during the 1880s, using steam as a heat carrier. This system also spread to Europe and it is still used in DH systems in Manhattan and Paris. The energy efficiency of a steam-based system is low; such a system is also unsafe due to the possibility of steam explosions. The second generation of DH systems used pressurised hot water at temperature over 100 °C as a heat carrier. CHP production was widely used, which meant more efficient systems. This technology was dominant in most DH systems until the 1970s. The third-generation systems use pressurised water as a heat carrier but at lower temperatures (the supply temperature is often below 100 °C). All DH system extensions as well as most new systems use this technology. The trend in DH system development has been towards lower temperature levels, material-lean components, and prefabrication, leading to lower costs at construction sites.

Similar developments can be distinguished in DC technology, where the main technologies have been developed from centralised condensers and decentralised evaporators with a refrigerant (first generation, introduced in the late 19th century) to large mechanical chillers (second generation). The third generation of DC (many of these having been installed in the 1990s) includes technologies such as natural cooling from sea water or lakes, absorption cooling, and heat pumps (Frederiksen and Werner, 2013; Lund et al., 2014).

There are many advantages of DHC systems when compared to other heating or cooling systems. One of the main advantages is greater production efficiency. When this is combined with the use of heat and cold storage systems, it will promote more efficient use of fuels. A wide range of fuels and technologies can be used for production of district heating; additionally, utilisation of heat that would otherwise be wasted is possible. On the customer side, the benefits of DH system include less space required for heating

Table 3. The advantages and disadvantages of district heating and cooling systems

Advantages	**Disadvantages**
- higher efficiency than in single-house heating or cooling - high production efficiency - greater efficiency accompanies efficient use of fuels and lower emissions - wide range of fuels and technologies - utilisation of heat and cold storage systems - high delivery reliability, comfort, and continuous heat delivery - less floor space and lower capital investment for the customer's own heating equipment	- investment incentive with long pay-back period due to the need for extensive networks of piping - individual customers unable to negotiate prices and delivery conditions in natural monopolies harmful environmental effects during the piping construction - possible widespread interruptions of heat distribution - heat loss from the system - large differences in consumption due to seasonal changes - not suitable for sparsely populated areas

equipment, a high degree of reliability, and the comfort of the system. One of the disadvantages of a DHC system, restricting the spread of such systems, is that DHC systems are structured as investment-incentive systems with long pay-back periods. Customers are also unable to negotiate prices and delivery conditions in DH and DC systems, which are always natural monopolies. DH and DC systems are not suitable for sparsely populated areas due to the heat loss problem. Other advantages and disadvantages are listed in Table 3.

2.3 District heating systems in Finland

The first district heating network in Finland was established in 1940 in Helsinki (Energiateollisuus ry, 2006). As shown in Figure 3, in 2012 approximately 46 percent of Finnish houses were heated with DH, while in larger cities such as Helsinki, the share of DH was more than 90 percent (Energiateollisuus ry, 2013; Helsingin Energia, 2014). The DH network in Finland is a double pipe system (see Figure 4), where heat is delivered to customers as heated water. The heat demands of the customer include both the heating of the residential space and the need for service water. In a double pipe system, a supply

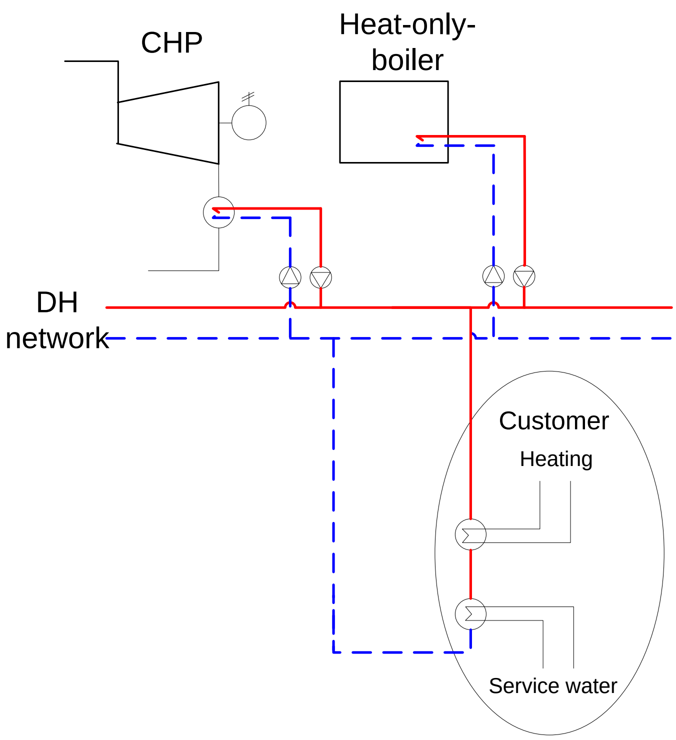

Figure 4. A typical double-pipe DH system where the base heat load is produced at a CHP plant and the peak load is produced with heat-only boilers. The red lines represent the supply pipes and blue dashed lines the return pipes.

pipe takes the hot water to the customers and a return pipe carries the cooled water back to the heating plant. The DH water circulates from the heating plant to the customers and back to the heating plant. The water is circulated with pumps which are located at the heating plant and, in larger networks, also along the DH network. The network's construction pressure is usually 1.6 MPa. The customers are connected to the network with an indirect connection. This means that the heat from the DH system is transferred through heat exchangers in buildings to secondary radiator circuits and to heat domestic water.

The heat producer controls the supply water temperature according to the outdoor temperature, with the maximum temperature being 120 °C. The supply water temperature must be high enough to deliver the necessary heat to customers and to cover heat losses in the network. On the other hand, the temperature should be as low as possible to minimise heat losses in the network and to allow maximal power production at CHP plants. Therefore, the temperature control curve of the heat producer determines the lower limit for the supply water temperature to satisfy customers' heat consumption. The temperature can be increased due to weather conditions such as increased wind speed, air humidity, forecasted significantly lower outdoor temperatures, or if the network is used as heat storage. Similar DH systems can be found in other Nordic countries, except Iceland, where geothermal sources are the main source of heat for DH systems (Energiateollisuus ry, 2006; Frederiksen and Werner, 2013; Kontu et al., 2012).

2.3.1 District heating consumption

DH is used for heating residential space and for heating domestic hot water. Space heating consists mainly of two parts: heating the radiators and heating the air coming in through ventilation systems. The distribution of the heat energy consumed in residential buildings yearly is roughly (Energiateollisuus ry, 2006):

- heating residential space (40%),
- heating air in ventilation systems (35%), and
- heating domestic hot water (25%).

The heat load varies widely throughout the year, following the weather phenomena of the different seasons, especially the changes in outdoor temperature. This is referred to as seasonal heat load variation. The momentary heat load fluctuates more strongly than the seasonal heat load. The DH demand also varies with the weekly and daily pattern; this is called the social component of the heat load. (Dotzauer, 2002; Gadd and Werner, 2013a, 2013b; Kvarnström et al., 2006; Nielsen and Madsen, 2000; Wojdyga, 2008)

The most significant factor affecting the heating of a building is the weather. The difference between indoor and outdoor temperature directly affects the amount of heat that is lost by convection and conduction through walls, floors, and ceilings. Beside this, solar radiation and wind speed and direction affect heat consumption. Direct solar radiation heats up buildings. Strong winds intensify the effects of cold weather. The instantaneous consumption fluctuates more than monthly consumption. Figure 5 presents the DH consumption in 2011 of one medium-sized city in Finland. The seasonal variation of the heat consumption can easily be seen. In summer time, only heat for domestic hot water is needed.

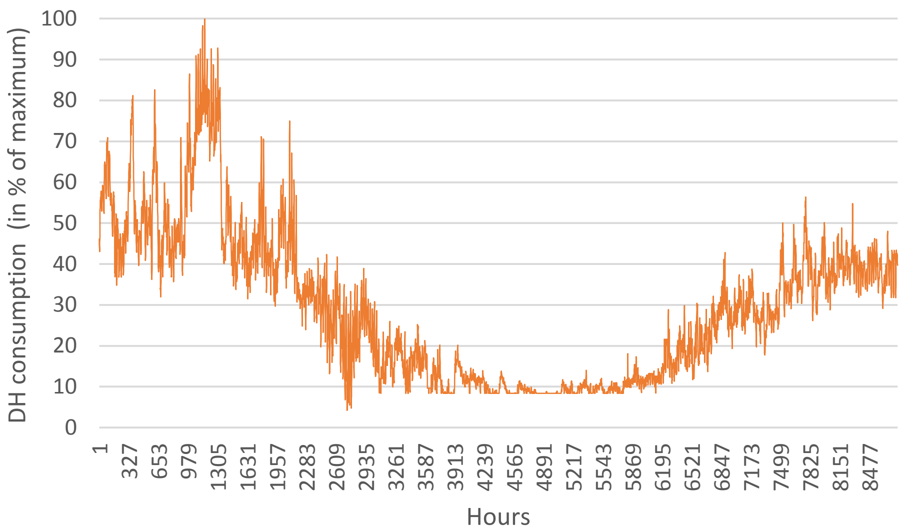

Figure 5. Heat consumption of one city for one year showing the yearly pattern of consumption

The social component of DH consumption means that the consumption has weekly and daily patterns. This is the main factor determining the heat consumption necessary to produce domestic hot water. Typically, the heat consumption decreases at the weekends. Hourly changing DH consumption typically has a morning peak, which is due to the use of domestic hot water and the starting up of ventilation systems in office buildings. The evening peak is mainly due to increased use of domestic hot water. In the night time, the heat consumption is decreased due to less activity. These phenomena can be found in Figure 6, where hourly heat consumption of one residential building for one week is presented. The daily pattern can be seen from heat consumption peaks, with the outdoor temperature also affecting the consumption level. Different types of customers and buildings have different consumption behaviour. The weekly pattern can be more clearly evident for the whole network, which includes different customer types, than for single customers. This is because different customers have different consumption behaviour types which correlate in the larger scale.

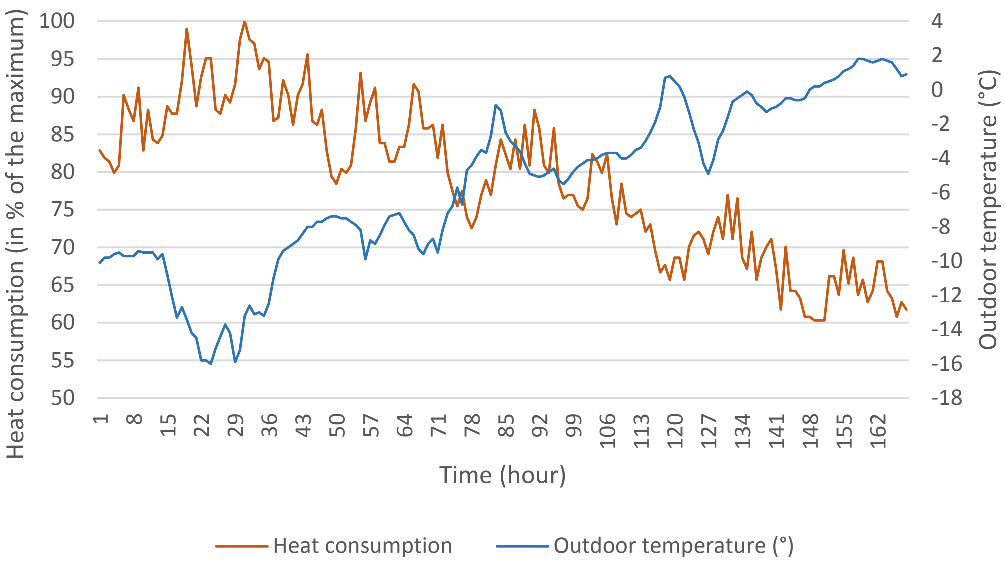

Figure 6. Heat consumption of one residential building for one winter week showing the daily pattern of consumption

2.3.2 District heating production

Transferred heat power in a double-pipe system is calculated with formula (1)

$$\emptyset = \dot{m}c_p\Delta T = c_p\rho V'\Delta T \quad (1)$$

where $\dot{m}$ is the mass flow of the DH water (in kg/s), c_p is the specific heat capacity (in J/(kg*K)), and ΔT is the temperature difference of the water in supply and return pipes (in K). This means that the heat demand changes can be satisfied in two different ways: by changing the flow of the district heating water, or by changing the temperature difference between supply and return pipes. The maximum heat power transmission of the network is defined by the size of the pipe, allowable pressure level, pressure loss and pressure difference, maximum size of the pumps in the heat production plant, and measurement of the customers' DH appliances and possible restriction of water flows.

The heat load variations require a flexible heat production structure. When designing the production for a DH system, the baseline is that the power needed will be divided for at least two different production units, as presented in Figure 7. This is advantageous economically and also for the reliability of the system. The power generated can be divided for the base load and the peak load. The base load is typically produced in the CHP plants; for the peak load demand, separate HOBs are used.

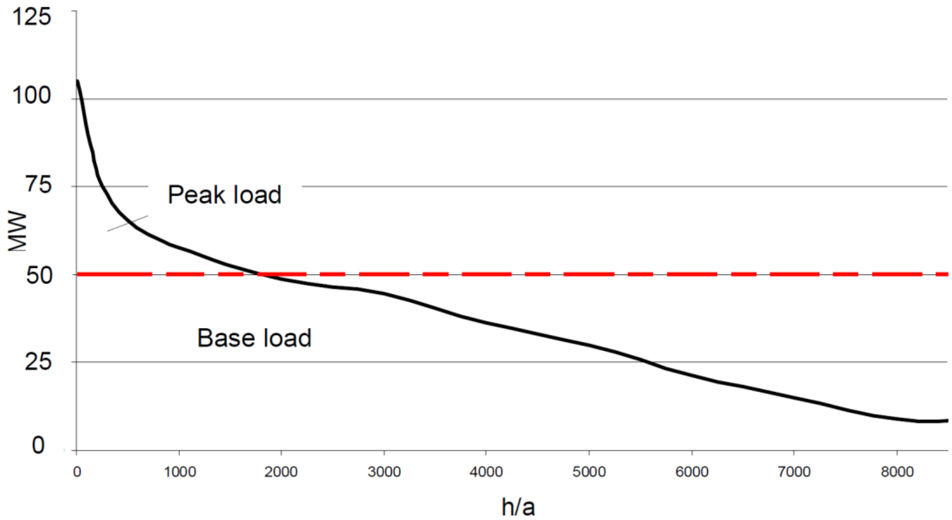

Figure 7. Duration curve for heating power. The heat demand is covered with base load production units (for example, a CHP boiler) and peak load production units (HOB)

To increase the level of flexibility, the DH networks perform as small heat storage systems; in addition to this, many DH systems have separate heat storage capacity to even out the imbalance of the heat demand and production. In the energy systems with

CHP production, heat storage units are also used to optimise the profits from electricity production. Heat storage systems have been suggested as one way of handling the heat load variations.

Seasonal heat storage (i.e., storing heat in summer to be used in winter) have been studied (Gabrielsson, 1988; Nielsen and Möller, 2012; Sibbitt et al., 2012; Tveit et al., 2009), but they are not widespread in many DH systems, since competitive technology does not yet exist. For daily heat variations, heat storage systems have been studied and implemented to decrease peak load capacity and investigate the effects on the whole energy system. The DH networks perform as small heat storages and beside this many DH systems have separate heat storage systems to even out the imbalance of the heat demand and production. Different sizes of heat storage units for DH systems have been studied (Nuytten et al., 2013; Østergaard, 2012; Smith et al., 2013; Verda and Colella, 2011). The use of building mass as heat storage has also been studied (Jokinen, 2013; Jokinen et al., 2014; Olsson Ingvarson and Werner, 2008).

Many advantages could be achieved with elimination of daily heat load variations, such as less use of the peak load boilers, which usually use more expensive fossil fuels, less need for electricity for pumping energy, easier optimisation of the DH system operation, and less need for maintenance because of the smoother use of heating plants (Gadd and Werner, 2013a). The start-up and maintenance costs of the HOBs are also significant additional cost items for DH companies.

2.3.3 Measuring district heating consumption

The thermal energy consumed by customers is measured. The heat meter consists of a flow sensor, temperature sensors, and a heat consumption meter. The flow sensor measures the volume of circulating water flow. The temperature sensors are installed in two locations to measure the temperature of supply and return water. Figure 8 presents a simplified picture of principles of measuring district heating, showing the location of sensors.

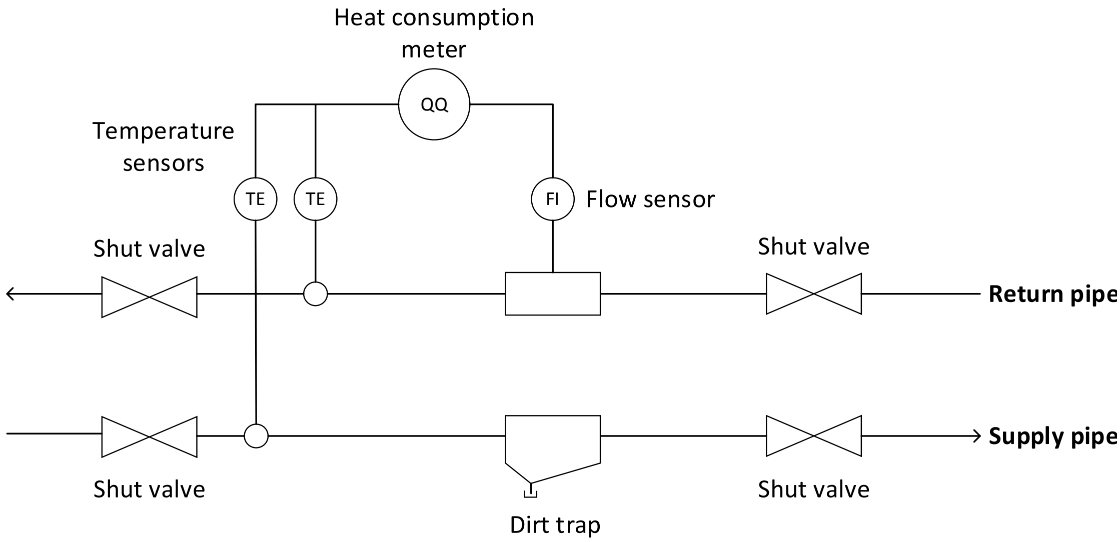

Figure 8. Simplified diagram of the principles of district heating measurement devices

The heat consumption meter calculates the consumed heat energy using the water flow and temperature difference by using formula (2)

$$Q = c_p \int_{t0}^{t1} q_m \, \Delta T dt \tag{2}$$

where Q is heat energy, c_p is the specific heat capacity for water, q_m is the district heating water flow, ΔT is the temperature difference of district-heated supply and return water, t_0 is the beginning time for measurement and t_1 is the finishing time for measurement.

Figure 9 and Figure 10 show hourly measurements of a typical heat meter which consists of flow and temperature sensors. The measurements presented in Figure 9 and Figure 10 are from one residential block building located in Helsinki for one winter week. Figure 9 shows the supply and return temperatures, showing that supply water temperature remained high, almost 100 °C, due to the cold weather that week. The outdoor temperature for this particular week varied from -17,4 °C to 2,2 °C.

Supply water temperature, which is controlled in the power plant, is more stable than the return water temperature. This is because the water temperatures are measured as momentary values and if simultaneous DH water use for domestic hot water is taking place as the temperature measurement is taken, then peaks for return water temperature occur. From these values, the temperature difference is calculated using formula (2).

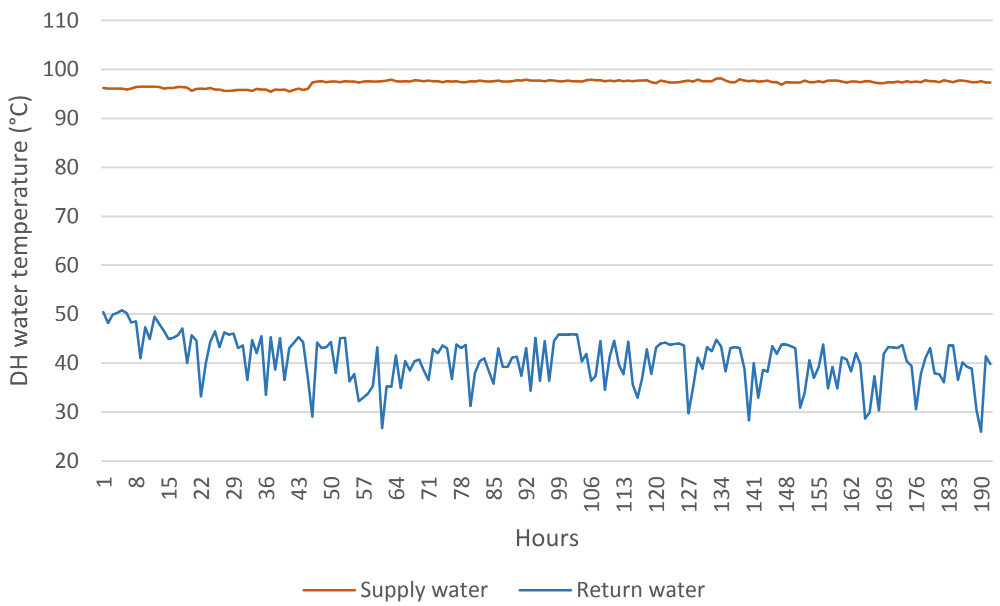

Figure 9. Hourly measurements of DH supply and return water temperatures for one residential block building (same building as in Figure 10)

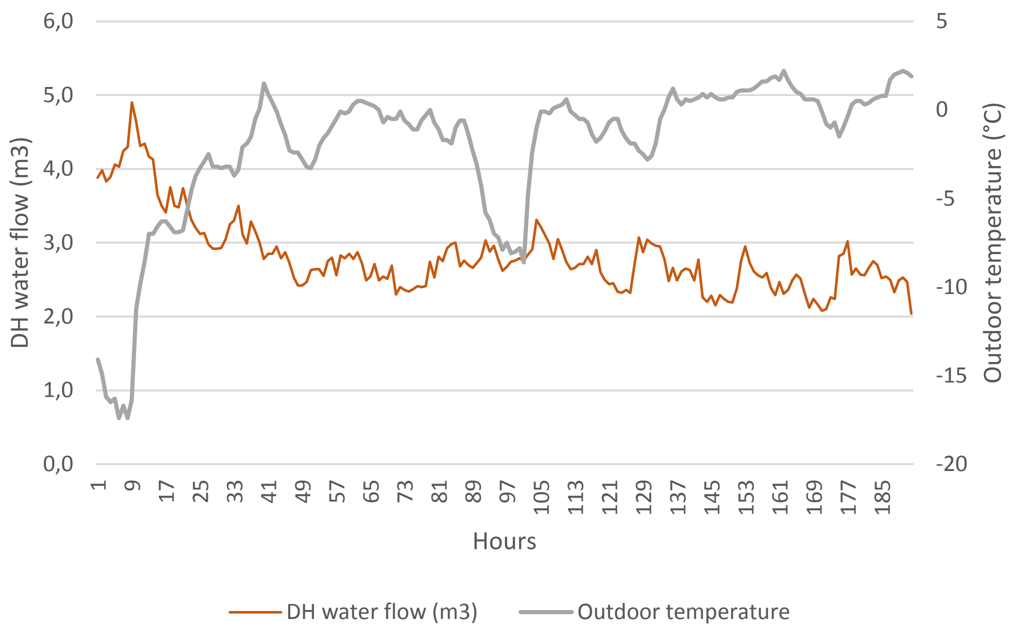

Figure 10. Hourly measurements of DH water flow for one residential block building (same building as in Figure 9), with outdoor temperature measurements taken at the same times

From Figure 10, where DH water flow is presented, the typical daily pattern of the DH system can be seen with morning and evening peaks (see Chapter 2, section 2.3.1).

Traditionally, customers have sent their heat meter readings to the energy company once a year. The problem with this arrangement has been that some readings will always be missing. In addition, the temporal distribution of consumed heat energy cannot be resolved.

In the near future, legislation will guide energy companies and property owners towards more developed measurement operations in the DH and DC business as well as in the electricity and gas businesses (European Union, 2012). Many DH companies are moving towards remote meter reading, which means that the data showing thermal energy consumed is sent to the energy company automatically. In Finland, the biggest DH companies have installed remote meters for almost all of their customers and the installation pace since 2008 has been fast. This was studied in a questionnaire-based research study, where 20 Finnish DH companies were asked about their motivation for remote metering (Piispanen, 2010). In 2008, only 28 percent of the customers of the DH companies in the study had remote meters, whereas in 2013, the DH companies forecasted that almost all of their customers (over 90 percent) would be under remote metering. As of 2014 remote meters have been installed to customers' substations. It would be important to install them also in some medium points of the network. This would allow the development of programs to verify the accuracy of measurement data and to monitor the network's operation.

With remote meter reading, it is possible to get more accurate, real-time energy consumption data from customers. Currently the meter readings are not monitored continuously and they are used mainly for billing purposes. Remote data could also be used by the energy companies to locate faults in the network and to identify inefficient heat-use habits of customers.

In addition to the benefits mentioned above, it is possible to utilise hourly heat energy measurements in many other ways. These possibilities include, for example, verifying the accuracy of measurement data, correcting certain measurement errors automatically, and monitoring the network's operation. In addition, it is possible to develop more accurate adaptive forecasting models, to plan production more accurately and to better optimise the operation of the network. Remote measurement data also enables the use of new dynamic pricing systems.

The study by Piispanen (2010) reveals that the most important benefits from remote metering, in the opinion of DH companies, are better billing processes and faster availability of the readings. A better billing process would include such aspects as abandoning the use of estimation billings, the design and use of faster billing processes, and fewer mistakes. It would also allow for better control of production, easier reporting for customers, and monitoring of consumption.

2.3.4 Forecasting district heating consumption

Remote measurements in DH and DC systems allow development of more specific forecasting models. The literature includes several studies of forecasting models for DH applications. DH forecasting models should normally consider at least two factors: outdoor temperatures and the social component of consumption, As these factors have the greatest influence on heat consumption (Dotzauer, 2002; Kontu et al., 2012; Kvarnström et al., 2006). The social component of heat consumption indicates the behaviour of customers and it mainly concerns the use of domestic hot water. For this reason, the social component consists of annual, weekly, and daily patterns. Inadequate consumption and weather data leads to inaccurate forecasting models which advocates for using simple forecasting models.

More accurate forecasting models have been developed where, in addition to the outdoor temperature and the social component, more specific weather conditions have been taken into consideration (Nielsen and Madsen, 2006, 2000; Wojdyga, 2008). These weather conditions include wind speed and direction, solar radiation, and precipitation. Besides these factors, different DH networks might include other characteristics, such as customers' specific geographic location, which will affect the heating consumption. These factors are called stochastic factors. The effect of these kinds of phenomena at a large scale is small and hard to model explicitly with sufficient accuracy (Dotzauer, 2002).

Different methods to predict DH consumption have been used, such as the linear regression model (Kvarnström et al., 2006), the Grey-box method (Nielsen and Madsen, 2006, 2000), the Box-Jenkins method (Chramcov et al., 2009), and the conditional finite impulse response (cFIR) model (Pinson et al., 2009). Production forecasting models for other applications have also been developed; for example, to forecast electricity consumption. Compared to electricity consumption, DH has a special factor, which is the time delay between production and consumption. Taking time delay into account in the forecasting model improves its accuracy (Dotzauer, 2002). One possibility to consider the time delays in a forecasting model is to model the whole DH network based on information available from the heat production companies. With this, it would also be possible to model and investigate heat losses in different parts of the network.

2.4 District cooling system in Finland

In Finland, the first DC system was established in Helsinki in 1998; since then DC has increased rapidly. As of 2013, DC is available in eight cities in Finland: Helsinki (since 1998), Turku (since 2000), Lahti (since 2000), Heinola in Vierumäki (since 2002), Lempäälä (since 2008), Espoo (since 2012), Tampere (since 2012), and Pori (since 2012). Altogether DC energy was produced 169 GWh in 2013 and the length of the DC piping was approximately 95 km. The production of DC in Finnish systems is mainly based on heat pumps (48,8 % of the production). The other production methods used were as follows: free cooling (26,3 % of the production), absorption cooling (17,1 % of the production), and compressor technology (7,8 % of the production). (Energiateollisuus ry, 2014)

The cooling energy is distributed through a supply pipe as cold water. After delivering cooling for the customer, the warmed water is returned to the power plant through a return pipe and recycled. In most DC systems, the customers are connected to the network by an indirect connection where DC pipes forming one water cycle connect to a cooling system in a different building with another water cycle (similar to a DH system connection, as shown in Figure 4). In a direct connection, the DC water cycles in the cooling system of the building. Direct connection should be used only in networks with few customers (2–3 customers).

One difference between DH and DC networks is the greater width of pipes used for DC. The reason for this is the lower temperature difference between the supply and return temperatures. Large pipe diameters give a larger area for heat transfer to the supply pipe which results in greater cold losses. Still, the magnitude of cold losses is lower in DC networks when compared to heat losses in DH networks because of the smaller difference in temperature between the DC water and the ambient air.

2.4.1 District cooling consumption

Cooling demand exists in various industrial processes and commercial businesses which need cooling continuously. Beside this, citizens need cooling to higher standards of comfort. For space cooling, the cooling demand comes from climatic conditions such as air temperature, solar radiation, wind speed and direction, and air humidity. Besides these, internal heat sources such as machines, computers, and other electric appliances affect the cooling demand. Lighting and the number of people in a building bring more heat to the building. The predominant factor for cooling demand is the outdoor temperature (Euroheat & Power, 2006). The cooling power is chosen so that the inside temperature will stay at a desired level. In the coldest periods of outdoor temperature, cooling demand can occur at the same time as heating demand.

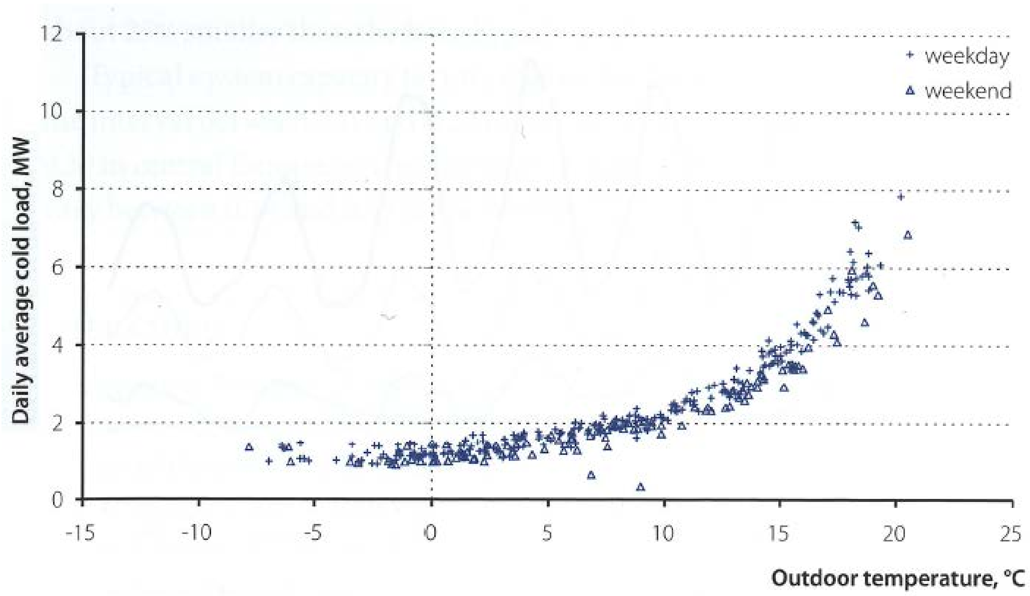

Figure 11. Daily average cold load in Helsingborg, Sweden in 2009 (Frederiksen and Werner, 2013)

Figure 11 shows daily average cold demand in Helsingborg, Sweden for the year 2009. The figure shows that cooling demand exists even in the coldest periods. When the outdoor temperature is higher than 10 °C, the cold demand increases substantially. The cold demand at weekends is slightly lower than for weekdays.

Figure 12 presents typical average daily variations in district cooling load in Helsingborg, Sweden in 2009. The figure shows that cold demand varies widely between summer and winter periods. In seasons when the cold load is high, the daily average cold load is about 30–40 percent smaller than the hourly peak load. This means strong daily variations of cold load and encourages district cooling companies to invest in cold storage systems. (Frederiksen and Werner, 2013)

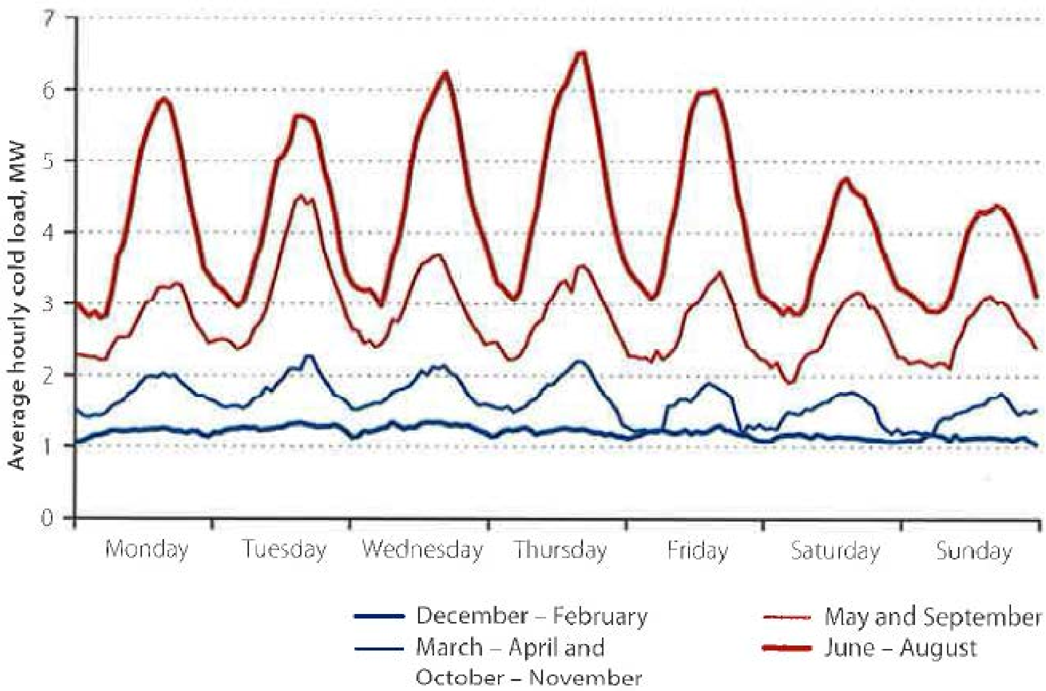

Figure 12. Typical daily district cooling load variations during four seasons in 2009 (Helsingborg, Sweden) (Frederiksen and Werner, 2013)

2.4.2 District cooling production

DC can be produced several ways. The most commonly used methods in Nordic countries are free cooling, absorption cooling, compressor technology, and heat pumps. Free cooling means efficient utilisation of nature’s own energy resources and cooling energy derived from sea water, lakes, or rivers. In winter time, when these waters are cold, the existing cooling energy is enough to meet the cooling demand. In summer and autumn, when the waters are warmer, free cooling can be utilised as an efficient and cost-effective source for the base demand. It is also possible to utilise snow for a DC system; for example, in Sundsvall, Sweden, snow is collected in winter time to be later used during the warm season.

Absorption cooling utilises waste heat that is produced, for example, in CHP production (DH that cannot be utilised in summer time due to low heat demand), industrial processes, or flue gases. Absorption cooling is based on the qualities of refrigerant used, selected based on the needed cooling temperature. The most commonly used refrigerants are lithium bromide, used when the cooling temperature is over 5 °C, or ammonia used when colder temperatures are needed. (Energiateollisuus ry, 2006; Frederiksen and Werner, 2013; Suomen Kaukolämpö ry, 2004)

Compressor technology has four main components: the compressor, the condenser, the evaporator, and the expansion valve. Compressor technology needs electricity to work and the most commonly used refrigerants are ammonia, HFC, or HCFC. Using this technology, lower cooling temperatures are available than with absorption cooling. (Energiateollisuus ry, 2006; Frederiksen and Werner, 2013; Suomen Kaukolämpö ry, 2004)

Heat pumps are a well-known technology used mainly in heat production. To increase the efficiency of the district energy system using heat pumps, it is reasonable to combine the DH and DC systems since heat pumps are able to produce both heating and cooling at the same time. (Energiateollisuus ry, 2006; Frederiksen and Werner, 2013; Suomen Kaukolämpö ry, 2004)

These methods of production can be combined, depending on the local conditions, so that needed energy is produced in the most cost-effective way. Cold storage is a very important part of DC systems since cooling demand usually varies greatly during a 24-hour cycle. In DC networks, the size of the cold storage should be around 1/3 of the cooling load. Cold storage systems bring many advantages for the cooling network, such as smaller need for cooling capacity and thus lower investment costs, greater reliability for the system, and the avoidance of operating the production plants at low efficiency while the demand is low.

2.5 Challenges in future

The role and competitiveness of DH in future energy systems have been studied widely (e.g., Connolly et al., 2014; Lund et al., 2014, 2010; Magnusson, 2012; Persson and Werner, 2011; Pöyry Management Consulting Oy, 2011). In Nordic countries, DH has been growing steadily for decades and it is still increasing in both the length of piping in DH networks and DH production and use. In spite of this, many references predict that DH is increasing at a slower pace than in former decades and will eventually lead to the stagnation or the reduction of DH use (e.g., International Energy Agency, 2010a).

In Sweden, for example, DH grew significantly in the second half of the twentieth century (Magnusson, 2012). After the year 2000, DH production and use were almost static. Similar developments can be seen in the Finnish DH system. It is stated that even though the trend of DH production and use is still positive, the key measure of a system, heat load, is declining, causing the stagnation of the system (Magnusson, 2012). The deceleration of DH growth has been explained by different factors, such as increased energy efficiency of buildings due to climate policy actions, warmer climate due to increased greenhouse effect, and conversion to other heating alternatives due to newly developed heating technologies.

Table 4 compiles the challenges that DH systems will face in future. Many of these challenges are due to the reformation of energy policy at the EU and national levels such as emission trading, increased levels of energy production taxes and fuel prices, and energy efficiency policies for buildings and energy systems. These will affect the allowable emission levels of DH systems, fuel selection, costs of DH due to the increased taxes and fuel prices, and the heat demand due to increased level of energy efficiency in buildings.

Table 4. Challenges for DH systems and reasons for challenges

Challenges for DH system	Comments / Questions
- reformation of energy policy and its effects on the competitiveness of DH	- emission trading, increased heat production taxes, increased fuel prices, EU 2020-policies, energy efficiency policies for buildings, IE-directive (Industrial Emissions) requiring investments for power plants to decrease SOx, NOx, and particle emissions
- emission reduction and renewable energy	- due to climate policy actions
- increased level of energy efficiency in buildings causing lower heat demand	- due to climate policy actions
- taxation policy of DH	- due to climate policy actions
- price and cost variations of different fuels	- competitiveness with other energy systems, diminishing natural resources, climate policy
- conversion to other heating alternatives due to newly developed heating technologies	- more competition in heating markets
- warmer climate due to increased greenhouse effect, leading to lower heat demand	- lower heat demand will decrease the competitiveness of DH systems compared to other possible heating systems
- keep the image of DH system attractive for consumers	- to attract new customers

The heat demand level in buildings is expected to decrease due to energy efficiency policies for buildings as well as in consequence of higher temperature levels since the climate change. In this situation, the level of competitiveness with other heating systems will be higher. Technologies and energy efficiency of other heating systems are developing, which raises the level of competition between different heating systems. It is important to keep the image of the DH system attractive to new customers.

Because of the challenges presented in Table 4, the DH companies have to consider the following questions to stay competitive:

- How to add renewable energy sources and surplus heat for the production of district heat
- How to improve the energy efficiency of the district heating system on the consumer side, including investigation of ways to minimise heat use in buildings
- How to develop a low-energy DH system specifically for use in low-energy building areas

The situation for DC systems is different, since they have a shorter history on the wider scale. DC systems have been growing fast in Finland and other Nordic countries during the past 15 years. Reasons for this are the possibility of using natural cooling sources such as cold sea water for the DC, increased cooling demand to satisfy the need for comfort levels, reliability and freedom from worry of DC systems for customers, and the better energy efficiency of the system compared to individual cooling appliances.

It is expected that climate change will increase the cooling demand in Nordic conditions. Also citizens demand comfort and thus the use of cooling energy will increase because of the increased level of wealth in the community. Some of the future challenges are common to both DH and DC systems (see Table 4), such as reformation of energy policy and emission reduction and energy efficiency targets. The challenges for DC systems in the future are mainly centred on the following topics:

- How will the demand for cooling evolve in future? How will climate change affect it? How will different regulations about the energy efficiency of buildings affect the cooling demand?

- What actions should DC companies take to be able to expand the DC network and make it more accessible for citizens?
- How should DC systems be marketed to citizens in such a way that as many people as possible would be familiar with the system and its benefits?
- How may the technical and financial competitiveness of DC systems be ensured, compared to other cooling systems?

3 Smart cities and thermal energy systems

In recent years, smart cities and smart energy systems have been under discussion in many research and political papers. The drivers behind the development towards smart cities and smart energy systems are varied. Environmental aspects are changing energy systems. Dependency on fossil fuels needs to be reduced. CO_2 emission targets are changing the fuel mix in many energy systems. These reasons will increase the share for energy systems of renewable energy sources with fluctuating characteristics. Energy systems based on decentralised production and various energy technologies need good management systems and ICT technologies to work efficiently. On the other hand, different sources predict that energy demand is increasing, even though many actions have been taken to prevent this. Some reasons for increased energy demand are the growth of population worldwide, industrialisation, and increased living and wealth standards.

The third driver towards development of smart cities is a worldwide trend of urbanisation. For example, in the EU countries 74 percent of the people were living in urban conditions in 2013; while the world-wide share was 53 percent (The World Bank, 2014). It is predicted that there will be 6,3 billion people living in cities around the world by 2050. An urbanised world means that cities will use most of the energy produced. Urban areas have a huge potential to be efficient in many areas, including energy efficiency, since it is easier to provide energy, water, and sanitation to people living closer to each other.

There is no unambiguous shared definition, however, for the term ‘smart city’ on a global scale and it seems difficult to identify common descriptive attributes for it (Neirotti et al., 2014). In the online Business Dictionary (BusinessDictionary, 2014), the term ‘smart city’ is defined as

> *a developed urban area that creates sustainable economic development and high quality of life by excelling in multiple key areas*

Dirks (2009) suggests that smart cities are based on six core attributes (key areas), which are people, business, transport, communication, water, and energy. Giffinger et al.

(2007) highlights the following attributes for smart cities: smart economy, smart people, smart governance, smart mobility, smart environment, and smart living. One thing that is common to all smart city definitions is that smart cities are characterised by a pervasive use of information and communication technologies (ICT), which helps cities to make better use of their resources.

The importance of energy systems in smart cities is acknowledged widely in different sources and smart energy systems are considered as a backbone of the smart city (Net!Works European Technology Platform, 2011). It is also argued that smart grids are needed because of the new characteristics of energy systems: more fluctuating renewable energy is included in the energy systems and there is more bi-directional power flow (consumers producing to the grid) (Lund et al., 2012; Muench et al., 2014). Literature considering smart energy systems can be found widely but the research has mainly concentrated on electricity grids (usually called smart grids). It is argued that smart energy systems should be considered for wider systems where electricity, thermal, and gas grids are combined and coordinated to find synergies between them to produce efficient systems.

The term 'smart grids' is criticised as being too indistinct and overly fashionable (Muench et al., 2014). Smart grids are defined as (Muench et al., 2014)

> *an energy distribution system with the unique features to allow functional interaction of relevant market participants with the implementation of modern technologies such as ICT, to provide the capacity (in kW) that enables smart market applications (in kW/h), and to ensure the stability of distribution grids by securely connecting a large number of small points of intermittent consumption and production*

Another research study defines the term 'smart energy grids' as (Neirotti et al., 2014):

> *automated grids that employ ICT to deliver energy and enable information exchange about consumption between providers and users, with the aim of reducing costs and increasing reliability and transparency of energy supply systems*

Definitions for smart thermal grids or important factors to consider in building one can be found in a few sources (Gaia Consulting Oy, 2011; Schmidt et al., 2013, 2012). From these definitions as well as definitions for smart electricity grids and smart cities, some common factors can be highlighted which future DHC systems should take into account. These are presented in Figure 13 and explained more carefully later. The different factors partially overlap each other.

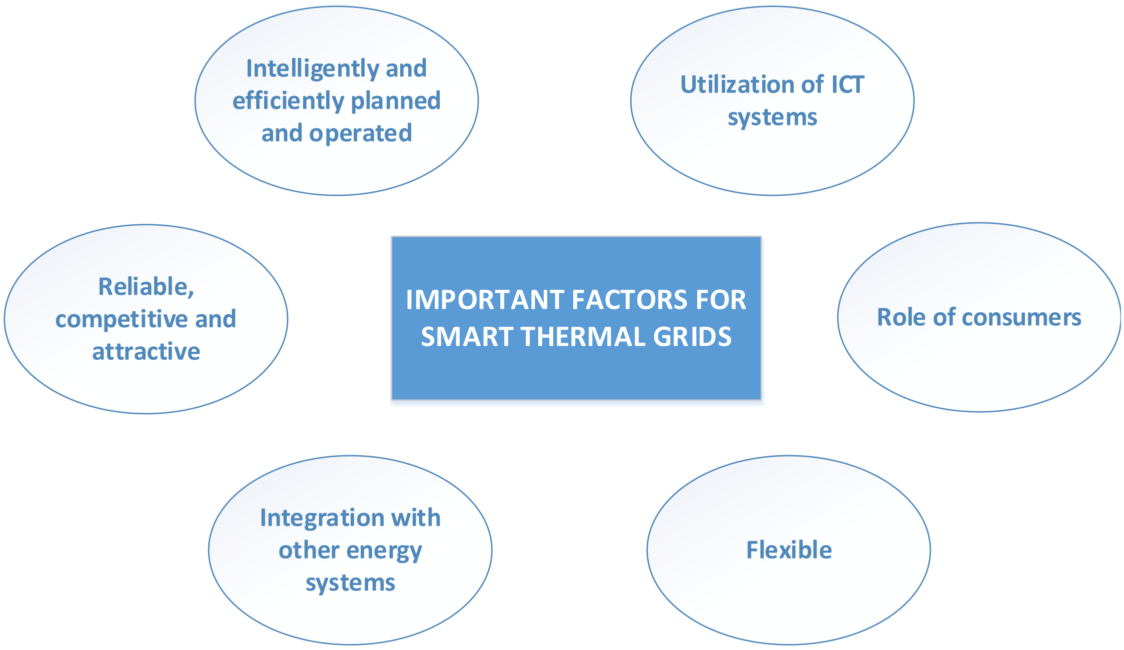

Figure 13. Important factors for smart thermal grids

Intelligently and efficiently planned and operated

Thermal networks should be planned and operated intelligently. Intelligently planned thermal systems utilise efficient technologies such as piping materials, substations, and heat storage systems. The real challenge in intelligent planning is to consider the implications of long-term development scenarios, considering technical possibilities that might not be foreseen in design standards.

Intelligent planning is needed to utilise energy sources efficiently. Initially, DHC systems integrated as a part of an energy system have features which will help energy systems in the transformation towards smart systems. The original idea of the DH system is that heat can be recycled from sources where it otherwise would be wasted. In 2011, for example, 77 percent of DH in Finland originated from recycled heat, including surplus heat from CHP plants, waste-to-energy plants, and industrial processes, as well as energy delivered by heat pump (Euroheat & Power, 2011). This makes a DH energy system more efficient, leading to cost-effectiveness of the system. One challenge is that lower temperature levels for a DH system would require more waste heat to be supplied to the network.

In smart energy systems, energy is produced in versatile production plants where centralised and decentralised plants are integrated. Technology used is efficient, and local energy resources are exploited. Consumers may also sell their extra heat to the network. This will require a flexible and intelligent heat network as well as the use of lower temperature levels. Thermal plants are spatially integrated in the community, taking into account the whole energy system. Efficiency will lead to cost-effectiveness of the system.

Utilisation of ICT systems

One of the most important and most commonly mentioned factors regarding smart cities and smart energy systems is the utilisation of ICT systems. Utilisation of ICT systems is not possible, however, without remote and real time data of the operational state of each part of the network. This means measurement data must be collected from production plants, consumers, and different measurement points in the network.

Beside the data, the possibility of modifying the state of the network (i.e., control) is needed. The data itself does not help to make smart systems intelligent but development of proper programs to efficiently utilise the data is needed. In the case of thermal energy systems, utilisation of ICT systems means, for example, that more data from consumers and different parts of the network will be available from smart meters which should be exploited more efficiently. Finding malfunctions is also possible with more data and proper programs.

Role of consumers

The role of consumers will become more important in smart cities. Consumers will not only be considered as simple consumption points but as consumers which are an integrated part of the smart system. Energy companies should enable the end-users to interact with the heating and cooling systems since the customers can act flexibly in consumption as well as producing heat for the network. This could happen as energy companies develop new business models to encourage better participation by consumers.

Flexible

Thermal networks will be a flexible part of the energy system, bringing adaptability in the short, medium, and long term. Short-term adaptation means adapting energy supply and demand situations with different sizes of storage systems, demand-side management, and peak-load boilers, all of which need to be integrated to the system. Medium-term adaptation means adjusting the temperature level in existing networks and in the long-term, adapting by aligning the network development with urban planning. Smart thermal systems should also be flexible in size, which means they are possible solutions for neighbourhood-level or city-wide systems, according to the demand for heat and cold. Also in the long term, smart thermal systems should be flexible in case heat (or cold) demand decreases due to emission targets.

Thermal networks are a flexible part of the energy system in the short term, with the capability of storing heat or cold. Heat storage systems have been studied widely in different scales (e.g.,Arteconi et al., 2012; Nuytten et al., 2013; Olsson Ingvarson and Werner, 2008; Østergaard, 2012; Sibbitt et al., 2012; Smith et al., 2013; Tveit et al., 2009; Verda and Colella, 2011) and their role in future energy systems with fluctuating energy sources will increase. Advanced thermal storage systems should be developed to be more efficient and applicable (such as seasonal storage for high temperatures, see Schmidt et al., 2013, 2012). After having a functioning ICT system (smart heat meters), the exploitation of heat storage and DSM will make energy systems more efficient.

Integration with other energy systems

Thermal grids need to be integrated into the whole urban energy system from a spatial point of view as well as from an energy system point of view. The spatial point of view is related to urban planning parameters and processes to achieve a techno-economic feasibility. The size and structures of the planned DHC networks (micro networks, city-wide networks, or regional heat transport systems) depends on urban structures and topologies as well as land-use characteristics.

The system level of integration means co-operation with other energy systems. Smart energy systems should be planned for wider systems where other energy systems such as electricity, thermal, and gas grids are integrated, combined, and coordinated to find synergies between them to have the most efficient systems and minimise emissions levels. In the case of a thermal system, this is closely related to the flexibility of the system, since the storage capacity will bring the possibility of optimising electricity use and production (for example, heat pumps and CHP). System-wide energy modelling is important to see the effects of primary energy use as well as emissions levels for the whole energy system. This is shown in a case study in Chapter 7, where waste heat is utilised in a DHC system. Chapter 4, section 4.3 discusses the importance of energy modelling.

Reliable, competitive, and attractive

The reliability of energy systems is an increasingly important factor for consumers. DHC systems have a good track record of being reliable heat and cold suppliers and should remain so in future. Competitiveness of thermal energy systems means that they need to be cost-effective, both for individuals and businesses. DHC systems are competing with other heating and cooling systems in the open market, which is why they need to be shown as an attractive option for consumers and investors.

Despite the high reliability of the heat and cold supply, customers might perceive some negative connotations about DHC systems, such as the necessity of long-term contracts with the utility, the feeling that they are dependent (not possible to choose the heat or cold deliverer), and high connection costs. To increase acceptance in the population, at least the following aspects need to be considered: introducing transparent and adaptive tariff systems, developing new business models to allow customers to participate (including customers of different sizes), and creating possibilities for customers to control their level of comfort by using intelligent control systems.

4 Optimising heat and cold production

The heat and cold loads in DH and DC systems have high seasonal variations (see more details in Chapter 2, section 2.3.1). This results in need for heat supply optimisation with a set of plants with different cost characteristics in order to minimise annual heat supply costs. More information about this is presented in Chapter 2, section 2.3.2. When heat is produced in CHP plants or with heat pumps, the price of electricity affects the optimisation of different power plants.

The future will bring challenges for optimisation of heat and cold production. Integration of renewable energy, such as wind power, solar power, and ocean energy, brings challenges to energy systems. Large hydropower stations are an exception since they are typically well suited for electricity balancing. These challenges are usually regarded as a problem for the electricity grid but other energy systems should not be forgotten, since they can help in the adaption of renewable energy sources. The optimisation challenge depends on the share of renewable energy input (Lund et al., 2012). The higher the share of renewable energy in the energy systems, the more challenges will occur.

Lund et al. (2012) highlights that smart grids with large shares of renewable energy should not be seen as separate from the other energy sectors such as heating systems, gas grids, and transportation systems. Energy systems with a high capability of utilising intermittent renewable energy sources should be designed with CHP and improved efficiency (e.g., in the form of fuel cells). The CHP plants should be operated so that they produce less energy when the renewable energy input is higher and more when renewable energy input is low. Energy storage systems bring more flexibility to the energy systems. Heat storage systems should be preferred since electricity storage systems are inefficient and expensive. It is also important to utilise electricity in transportation systems (such as electric vehicles) to increase the efficiency of the energy system, as well as to invest in flexible demand such as heat pumps, consumer demand, and electric boilers.

4.1 Heat and cold storage

As stated in Chapter 2, section 2.3.2, the variation of the hourly heat demand with morning and evening peaks brings challenges in heat production. The heat load variations require a flexible heat production structure. The daily and hourly heat load variations cause additional costs for the DH system and reduce its efficiency. This is mainly due to the fact that heat for the peak load periods needs to be produced with HOBs, which in most cases are fuelled with more expensive fuels than large CHP plants. The start-up and maintenance costs of the HOBs are also significant additional cost items for the DH companies.

There is a large volume of published studies describing the use of heat storage systems to optimise the DH systems. Simulation models and tools for the heat storage systems have been developed for example in the premise of investment of the new energy systems (Tveit et al., 2009), the optimal use of the heat storage and primary energy consumption (Verda and Colella, 2011), as well as to even out the variations of the renewable electricity production (Nuytten et al., 2013). The operation of the different DH systems (case studies) has been analysed for example in studies conducted by Kiviluoma (2013) and Streckienė et al. (2009). The optimisation of the electricity production with the heat storage systems has been studied for example in a case in Germany (Streckienė et al., 2009). Kiviluoma and Meibom (2010) studied the effect of the heat storage systems in the Finnish energy system where electricity is produced with renewable sources such as wind power.

Demand-side management means the measures which the energy company uses to influence the consumption behaviour of the consumers. In the DH business, the usual goal of DSM is the better management of the energy production in such a way that the consumption level of the heat and its temporal behaviour would be optimal in relation to the whole energy system. With DSM, it is possible to improve the economics of heat production by, for example, cutting the peak loads. Shifting peak-load production to either earlier or later times will make energy production more efficient. Also, it is possible to produce heat for the heat storage at other than peak load times.

The effects of DSM for energy saving in the DH system have been studied for example in office buildings. In Jyväskylä, Finland, it has been estimated that with DSM it would be possible to achieve 25-30 percent savings in heat load (peak load) by exploiting the thermal mass of the building (concrete building) and by properly controlling the heating system (IEA, 2005; Kärkkäinen et al., 2003). This study was conducted for two office buildings, and the effects of DSM were first estimated using a calculation model. Afterwards, experimental tests were conducted for the same buildings and the results were extrapolated to apply to the whole city. In Iowa (United States), DSM has been tested for office buildings, and the energy savings was found to be up to 30 percent (Braun et al., 2002). Using the mass of the buildings as a heat storage device has also been studied in Gothenburg, Sweden (Olsson Ingvarson and Werner, 2008). In this study, the changes in inside temperature were analysed in 12 different types of buildings using a field survey. The results showed that the energy-saving potential with DSM was approximately 25 percent for the whole city.

4.2 Including waste heat in the energy system

One strength of DHC systems is that it is possible to utilise heat that would otherwise be wasted, making the energy system more efficient. Waste heat usually originates from industrial processes. It is defined as energy flow which has

- the wrong quality, such as temperature that is too low,
- the wrong location, so its utilisation in industrial processes is not possible or not profitable, or
- the wrong timing, as for energy demand.

Beside these, waste heat is available in lakes, ground, and waste water from cities.

Despite the high shares of CHP in DH systems in Nordic countries, the amount of industrial waste heat used as a heat source in DH systems is still generally low, even though it is regarded as a vital means of increasing energy efficiency. The figures vary depending on the source.

Persson and Werner (2012) studied the amount of industrial waste heat recovered in DH systems in the EU-27 countries: it was only 0,4 percent in 2008. In the new heat roadmap for Europe, Connolly et al. (2014) mapped the yearly potential of industrial excess heat in DH networks in the EU-27 countries to be 2710 PJ. The amount of industrial excess heat used in DH networks accounted for only 0,9 percent of the mapped potential in the year 2010 (Connolly et al., 2014). In Sweden, the amount of industrial waste heat used in DH systems was the highest out of all these countries in 2011, accounting for seven percent (3852 GWh) of the total fuel input (Svensk Fjärrvärme, 2011).

The reasons for the low amounts of industrial waste heat utilised in DH networks are numerous; they include the low temperature level of waste heat, which is unsuitable for DH networks, and the long distances from the waste heat source to the heat demand, which increases the distribution losses. In addition to these technical limitations, the lack of a proper business model as well as human factors makes it difficult to use industrial excess heat in DH networks.

However, DH collaboration between industries and energy companies has been studied in the literature quite extensively from various perspectives. Grönkvist and Sandberg (2006) and Thollander et al. (2010) have analysed the factors promoting and inhibiting DH collaboration between industries and utilities in several ways. Different case studies on utilising industrial waste heat have been presented from distinct starting points, using various methods. For instance, Ajah et al. (2007) studied the techno-economic feasibility of industrial waste heat using the ASPEN plus tool to recover waste heat from the pharmaceutical industry in DH networks. Svensson et al. (2008) and Jönsson et al. (2008) studied the amount of waste heat available from a kraft pulp mill in Sweden, examining whether the waste heat should be used internally in the pulp mills or externally in a DH network.

Holmgren (2006) studied a municipal DH system using various heat sources. She analysed scenarios for making new investments in the energy system and investigated the energy system as a whole using the MODEST simulation tool. Kapil et al. (2012) took into account the distance between an industrial waste heat facility and a DH system when the profitability of collaboration between the particular process industry and the DH system was evaluated.

Gebremedhin and Moshfegh (2004) and Karlsson et al. (2009) analysed even larger systems where various heat companies and industrial sites might form a shared heat market. Both studies included examples from Sweden, using the MODEST simulation tool to calculate the results. Gebremedhin and Moshfegh (2004) focused on conditions for establishing a joint heat market, analysing which heat plants should be used and how to meet the heat demand in a cost-effective and environmentally reasonable manner. Karlsson et al. (2009) analysed the prospects of three large industrial plants and four energy companies forming a regional heat market. They calculated the economic influence for different operators as well as the environmental impacts of such a heat market.

The above-mentioned studies provide an interesting cross-section on how to best use various amounts of industrial waste heat in different types of DH systems. The general conclusion of these studies is that the benefits of using waste heat in a DH network are dependent on the energy system as a whole, as well as on the geographical distance from the waste heat source to the municipality (heat demand). The studies also demonstrated that the heat trade in the DH business can occur at different levels.

Traditionally, DH networks have been community-based markets, where an energy company sells heat to its customers. In addition to this, heat trade can occur between two or more energy companies where the production units with the lowest marginal price produce heat and the producer receives compensation for this. At the next level, the DH companies and industrial utilities can implement a bilateral agreement where waste heat from industry is fed into a DH system.

The third level of the heat trade, which has not yet been studied in the academic literature, is implemented in a real-life case in a market-based thermal system, Open District Heating and Cooling (Open DHC) (Fortum, 2013a). The idea here is that a DHC network will be opened to customers to give them the opportunity to sell their extra (waste) heat to the thermal network. The waste heat, at different temperature levels and amounts, will be recovered in the DHC system. The novelty value of this system is that the energy company develops an open-pricing model for waste heat and, based on that model, a waste heat supplier can sell the waste heat to the DH network whenever it is profitable for them to do so. The price of waste heat in this case depends on the outdoor temperature, but other options for pricing are also possible.

4.3 Modelling energy systems

Energy systems are complex systems of complete energy supply and demand. The purpose of energy planning is to find a set of sources and conversion devices in such a way that energy requirements or demands are planned in an optimal manner. Energy system models are simplified representations of real systems, built as tools to explain, predict, or control the behaviour of these systems.

Energy planning models have been developed since 1970s'. A brief history of the development of energy planning models is presented in Jebaraj and Iniyan (2006). Nowadays there are many different kinds of energy planning models for different purposes. There are models which concentrate on one specific technology as well as models for planning whole energy systems covering many different conversion technologies. Models can concentrate on, among other things, various environmental issues, economic issues, or the optimisation of different technologies. Energy system models can be classified by the purpose of the model, by the model structure, or by the geographical coverage of the model. Many different classifications of energy system models have been presented in literature while there are only few models that fit into one distinct category. Energy system models can be classified for example by the purpose of the model, by the model structure or by the geographical coverage of the model. Many different classifications of energy system models have been presented in the literature (see van Beck (1999)).

Different energy system models have been studied widely and numerous reviews are found in the literature (Bhattacharyya and Timilsina, 2010; Connolly et al., 2010; Hiremath et al., 2007; Jebaraj and Iniyan, 2006; Manfren et al., 2011; van Beck, 1999). These reviews concentrate on some specific area, such as energy system models suitable for developing countries (Bhattacharyya and Timilsina, 2010) or energy models that can be used to analyse integration of renewable energy (Connolly et al., 2010).

Heating sector can be found in many of the energy simulation tools. CHP is included among others in Balmorel (2014), EnergyPLAN (2014), energyPRO (EMD International A/S, 2013), SIVAEL (2009), Stream (2014), and RETScreen (2014). EnergyPRO, Stream and RETScreen also include district heating simulations. There are also specific models which are designed for district energy applications and for planning district heating and cooling systems, such as the GRADES Heating calculation system developed by Enoro, formerly Process Vision, (Enoro, 2014), Vitec NetSim, Apros (2014), and HEATSPOT (Knutsson et al., 2006).

4.3.1 EnergyPRO

Chapter 7 presents a case study where waste heat is inserted into the district heating and district cooling network. In this study, to calculate the merit order of power plants with given heat demand in an energy system, the energyPRO simulation tool was used. EnergyPRO is an input-output modelling software package used for modelling energy systems (Connolly et al., 2010; EMD International A/S, 2013; Hinojosa et al., 2007). It is used for optimising the operation of plants using technical, financial, and external parameters. With energyPRO, it is possible to model all types of thermal generation (except nuclear), renewable generation, and energy storage systems (Connolly et al., 2010). As a result, energyPRO calculates the merit order of different production plants to minimise the cost of meeting the heat demand.

The energyPRO tool has been applied in several cases published in journal articles presenting case studies; for example, in Denmark, the UK, and Germany. CHP power plants and their investment and operation strategies in Danish energy systems were studied in Lund and Andersen (2005). The study by Nielsen and Möller (2012) concentrates on net zero energy buildings and the possibility of using their excess heat as an energy source. With the energyPRO simulation tool, they model how excess heat production from net zero energy buildings influences different types of DH systems in Denmark. Ostergaard (2012) investigated the system impact of different types of energy storage systems, including district heating storage, biogas storage, and electricity storage in Denmark.

Streckienė et al. simulated a case study with CHP plants and thermal storage in the German spot market where day-ahead prices for electricity show significant variations (Streckienė et al., 2009). A similar approach was taken by Fragaki (Fragaki et al., 2008; Fragaki and Andersen, 2011) to the UK energy market, where only a few CHP plants have thermal storage.

Input values for energyPRO are either heat demand, cooling demand, and/or electricity demand, depending on the optimisation task. Demands can be inserted into the program as rough period estimates or exact hourly distributions (time series). Input values also include information on the environment (such as electricity prices and

Table 5. Working method of the energyPRO tool in this case study

How the energyPRO tool works			
INPUT VALUES			
Environment	**Fuels**	**Producing units**	**Heat storage systems**
Hourly heat demand data	Heat values	Fuel power	Volume
Hourly outdoor temperature data	Fuel prices	Electricity power	Temperature in the top
Hourly electricity price data	Taxes and financial support	Heat power	Temperature in the bottom
		Minimum power	Insulation
		Regulation	
		Taxes and financial support	
		O&M costs	
		Revision times	
↓			
OPTIMISING MERIT ORDER OF PRODUCING UNITS, TARGET: MINIMISING COSTS			
↓			
RESULTS: COSTS AND EMISSIONS			

outdoor temperatures), fuels (such as heat values, possible restrictions, and prices), and production units (such as production figures, minimum power, O&M costs, and taxes).

The input values for the energyPRO model used in this study are presented in Table 5. The user can define whether all producing units can produce heat for heat storage (which was the case in this study).

EnergyPRO calculates the annual production, typically in one-hour steps, allowing the optimisation to take hourly-varying electricity prices into account. EnergyPRO does not calculate the optimal merit order chronologically, but it can find optimal operation strategies in the most favourable periods. The reason for this is that each new production has to be carefully checked to avoid disturbing already-planned future production, in order to avoid problems with, for example, varying electricity prices (Lund and Andersen, 2005).Figure 14 shows the graphical user mode for the energyPRO simulation tool with case examples presented.

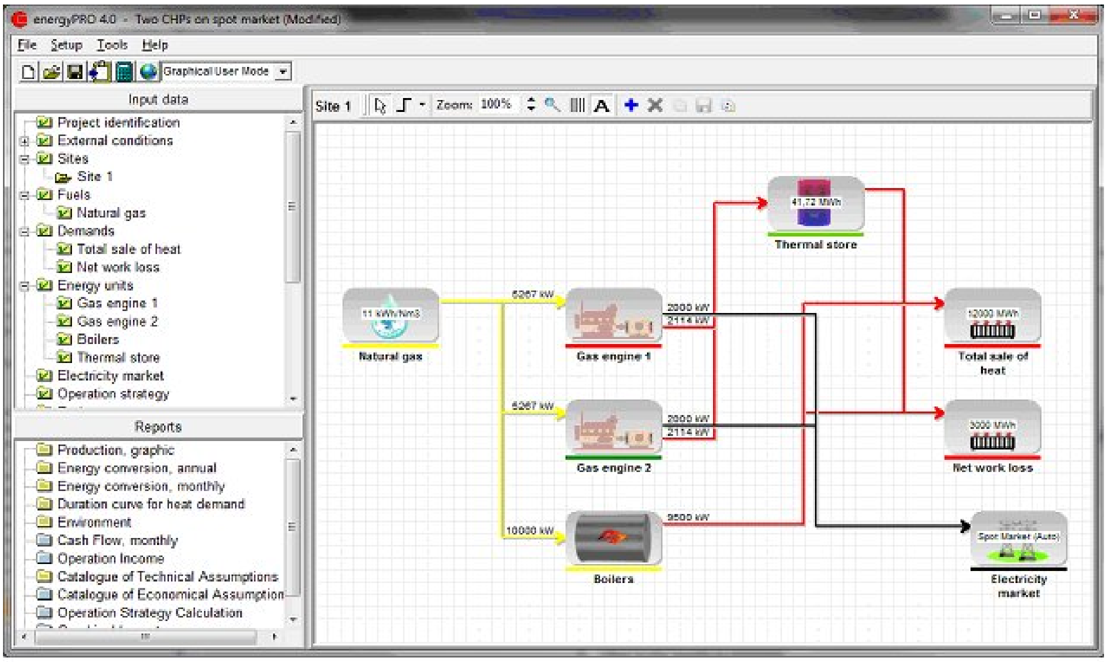

Figure 14. Example of the graphical user mode of the energyPRO simulation tool (EMD International A/S, 2013)

Figure 15 presents how energyPRO gives the hourly results in graphical mode. In this figure, the upper graph shows the electricity tariff up against which production is optimised. The second and third graphs show the optimised heat and electricity production with different production units. The bottom graph shows how the thermal storage is used during particular hours.

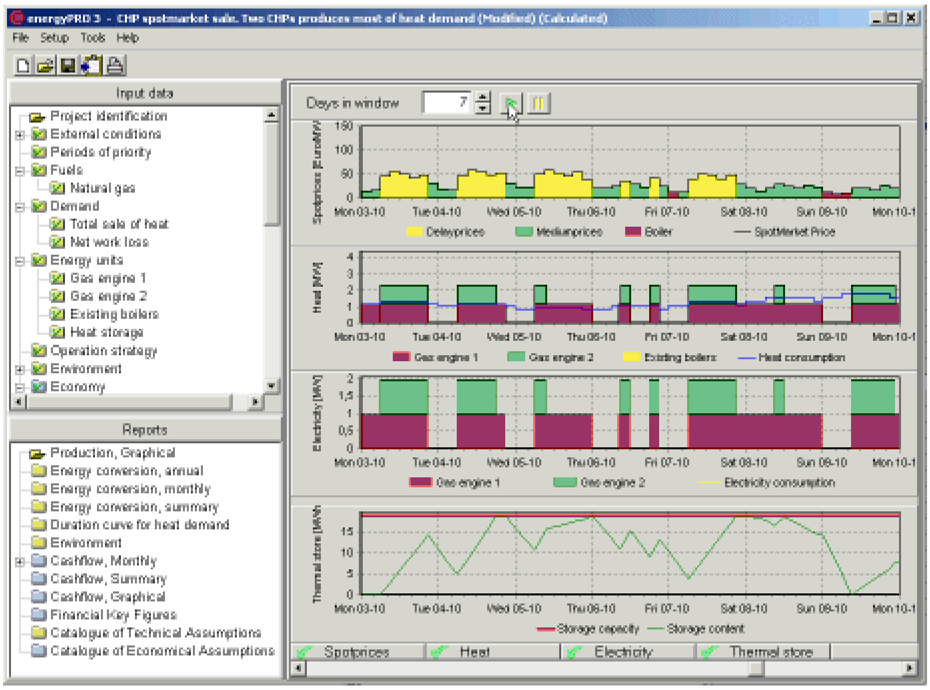

Figure 15. Example of how the results are shown hourly in graphical format in the energyPRO simulation tool (EMD International A/S, 2013)

5 CASE I: Remote customer measurements and forecasting DH consumption

One of the challenges of the DHC systems is better utilisation of the ICT and data available from remote customer measurements. There are many benefits that energy companies can achieve after remote measurements are applied fully, but work is still ongoing. This chapter will focus on remote metering in a DHC network and the utilisation of remote customer measurements. First, possibilities and benefits of remote metering are listed. Secondly, this chapter concentrates on building a forecasting model where hourly remote measurements are utilised.

5.1 Target of the study

The thermal energy consumed in district-heated houses is computed based on three main measurements (see a more detailed description in Chapter 2, section 2.3.3). These measurements are the mass flow of the DH water and the temperatures of the supply and return water. From these measurements, the heat consumption meter calculates the thermal energy consumed.

Traditionally, customers have sent heat meter readings to the energy company once a year. The main problem of this arrangement has been missing data. Many DH companies are moving towards remote meter reading, which means that the data for thermal energy consumed is sent to the energy company automatically. This will allow energy companies to develop their processes, and one possibility is to develop DH forecasting models.

DH forecasting models are described in more detail in Chapter 2, section 2.3.4. A common feature of the earlier forecasting models was that forecasting data is based on DH production data from heat producer for a larger area (city or neighbourhood). In this study, the forecasting models are based on hourly customer measurements. More specific forecasts based on individual customer measurements may benefit both DH producers and single customers. For the heat producer, it allows for better production planning and optimisation. Customer- and area-specific forecasts allow the DH company to determine where and when it should produce heat and how it should use heat storage systems optimally. With heat consumption data from single customers, it is possible to develop customer profiles for different customer types. Forecasts for different existing and planned neighbourhoods may be developed, as well as estimates for the consumption of customers for which measurement data is missing. For single DH customers, specific forecasts allow planning for their own heat consumption and possible local production, using e.g., heat pumps and solar collectors. Such benefits can be expected in the future when smart DH systems are fully available.

The value of this part of the study was the availability of more accurate heat consumption data, directly from customers and almost in real time. The target was to develop a forecasting model of DH consumption based on data from individual customers. The focus was to find out if it is possible to develop more specific forecasting models for DH consumption based on hourly consumption data from individual customers. The forecasting model implemented in this research was formed using linear regression based on outdoor temperature data and the social component of the heat consumption. Information about the precise geographical location of the customers was not available, so it was not possible to take into account more specific weather conditions such as the effects of wind speed, solar radiation, or precipitation on heat consumption.

5.2 Methods and data used

5.2.1 Data used

The data used in this research consisted of hourly-based DH consumption data from single customers of Helsingin Energia, the energy company of Helsinki producing electricity, heat, and cooling for the city dwellers. The hourly consumption data was collected from apartment buildings built in different decades. The data covers the full year 2011. The measurements collected from the customers were cumulative water flow (m^3), supply water temperature (°C), and return water temperature (°C). From these parameters, the following data was calculated automatically and also received directly from customers: cumulative energy used (MWh), hourly consumed energy (MWh), and the utilisation rate of consumed energy for every hour (scale from 0 to 1 as ratio of nominal maximum water flow). Besides these, the hourly outdoor temperature of Helsinki was available for the same period of time as the DH consumption data.

Initially, data was received from 14 customers. To evaluate the quality of the data, each data series was first investigated graphically. Because remote meter reading systems have been installed quite recently (and the work is still ongoing), the data series were more or less incomplete. Data for some days was missing from all customers. In addition, a few customers had even longer periods of data missing. These problems refer to either a centralised data acquisition problem affecting all customers or to a data acquisition problem for a single customer. Besides these, a small number of measurements for randomly-placed individual hours were also missing.

The main part of the missing data was for the summer period, which is why the forecasting model was developed only for the winter period (the middle of September to the middle of May), when DH is mainly used in Finland. However, in the case of three customers, some data was missing for a longer period of time. Customers no. 3, no. 4, and no. 14 were rejected from the study because the amount of data missing was more than 16 percent (16.8 percent–23.8 percent). In addition, two customers (no. 9 and no. 10) were rejected because the precision of the hourly metering values was not sufficient. Due to a scaling problem, these measurements had precision to only one decimal place. In the end, nine customers were included in the study. Even then, some of the data was missing from single hours. These single missing data were replaced by interpolating between measurements from the previous and following hours. Table 6 presents the

Table 6. Data of customers included in the forecasting model

Customer no.	Decade of construction	Max water flow (m3)	Missing data (%)
1	1900	5,6	0,38
2	1900	2,8	0,05
5	1970	1,6	0
6	1970	3,2	0,03
7	1980	5,6	0,41
8	1980	4,8	0,94
11	2000	6,4	0,47
12	2000	4,8	0,62
13	2010	3,4	0,91

included customers and also lists the construction decade of the building, maximum water flow, and the share of the missing data. Compared to earlier forecasting models concerning DH consumption from in previous studies, the amount of missing data is very small (Nielsen and Madsen, 2006, 2000).

5.2.2 Regression analysis

Regression analysis is a statistical analysis method describing how one variable depends on another. Linear regression is used to estimate the linear dependency of variables. The forecasting model aims to explain the behaviour of the unknown quantity *y* in terms of known quantities *x*, parameters *a* and random noise *e*

$$y=\mathrm{f}(x,a)+e \tag{3}$$

Forecasting models can be classified according to the shape of the function f and in this paper the focus is on a linear regression model. The linear regression model can be written as a form of

$$y_t = a_0 + a_1 x_t, \qquad t = 1 \dots T \tag{4}$$

This is a linear equation system with two unknowns a_0 and a_1 and one constraint x_t for each period of time t. Because there are, in general, many more constraints than variables, this is an over-determined equation system and it can be solved in the least squares sense. Each equation has a specific error variable e_t

$$e_t = a_0 + a_1 x_t - y_t, \qquad t = 1 \dots T \tag{5}$$

Parameters a_0 and a_1 are values sought that minimise the square sum of the error variables

$$\mathrm{Min}\; e_1^2 + e_2^2 + \cdots + e_T^2 \tag{6}$$

With matrix notations the problem can be written as

$$\text{Min } \boldsymbol{e}^T\boldsymbol{e} \quad \text{s.t} \tag{7}$$

$$\boldsymbol{e} = \boldsymbol{Xa} - \boldsymbol{y} \tag{8}$$

Substituting **e** into the objective function yields an unconstraint optimisation problem

$$\text{Min } (\boldsymbol{Xa} - \boldsymbol{y})^T(\boldsymbol{Xa} - \boldsymbol{y}) = \boldsymbol{a}^T\boldsymbol{X}^T\boldsymbol{Xa} - 2\boldsymbol{a}^T\boldsymbol{X}^T\boldsymbol{y} + \boldsymbol{y}^T\boldsymbol{y} \tag{9}$$

Forming the derivative and setting it to zero gives the solution

$$2\boldsymbol{X}^T\boldsymbol{Xa} - 2\boldsymbol{X}^T\boldsymbol{y} = 0 \rightarrow \boldsymbol{a} = (\boldsymbol{X}^T\boldsymbol{X})^{-1}\boldsymbol{X}^T\boldsymbol{y} \tag{10}$$

In this study, heat consumption *y* is explained by a linear model based on the outdoor temperature *x*, determining the parameters using history data represented in Chapter 4, section 4.2.1.

It was discovered how much the forecasting model accuracy increases if the social component is included in the forecasting model in addition to the outdoor temperature. This was done by including the weekly pattern of heat consumption in the forecasting model in four different ways. The weekly pattern was added in the regression formula

$$y_t = a_{h(t)} + a_1 x_t \tag{11}$$

where $a_{h(t)}$ is an average of each hours' (depending on the model) error classified hourly. The different models with their names and short descriptions are presented in Table 7.

In the fourth and fifth models, the midweek holidays in the Finnish calendar were taken into account. In the year 2011, there were nine midweek holidays which were considered as Saturdays or Sundays depending on the nature of the holiday. The assumption was that if the shops were partly open on a midweek holiday, it was considered as a Saturday. Other midweek holidays were considered as Sundays.

Table 7. Names and descriptions of the models

Model name	Description
T	Only the outdoor temperature (T_{out}) was considered
T168	The T_{out} together with a 168-hour weekly pattern was used.
T72	The T_{out} together with a 72-hour weekly pattern (working days, Saturdays, Sundays) was used.
T168H	Same as the T168 model, but midweek holidays were classified as Saturdays or Sundays.
T72H	Same as the T72 model, but midweek holidays were classified as Saturdays and Sundays.

Five different forecasting models were estimated for each customer separately, for customer pairs, and for all the customers together. Customer pairs were formed from the sum of customers whose buildings were built in the same decade. The customer pairs were customers no. 1 and no. 2 (built at the beginning of 1900), customers no. 5 and no. 6 (built in the 1970s), customers no. 7 and no. 8 (built in 1980s), and customers no. 11 and no. 12 (built in 2000). Lastly, forecasting models were made for all the customers as a group.

As stated earlier, only winter time was considered in this forecasting model; summer time from mid-May to mid-September was excluded. The period of 15.3.2011 5:00 p.m. to 17.3.2011 7:00 p.m. was excluded because most of the data was missing.

5.2.3 Methods used for estimating forecasting error

The accuracy of different forecasting models was compared with the N-1 method. This means that the forecasting models for each customer separately, for customer pairs, and for the sum of all customers were constructed for the inspected period of time, but week no. 13/2011 was excluded. When the forecasting models were formulated, they were tested for week no. 13/2011 and the accuracy of the models was compared. Week no. 13/2011 was chosen because in the year 2011 it was a week of typical winter weather in Helsinki, with temperatures varying from -9.8 °C to +4.5 °C. The average temperature was -1 °C.

The accuracy of different models was compared using absolute and relative error of the measured and simulated values of the model. The relative error was calculated by dividing standard deviation by the average of measured values.

$$Relative\ error = \frac{SD}{\sum \bar{x}} \quad (12)$$

The standard deviation (SD) is a measure of how widely values are dispersed from the average value, calculated as

$$SD = \sqrt{\frac{\sum_i (x_i - \bar{x})^2}{n}} \quad (13)$$

where x_i is the observation and *n* is the sample size.

5.3 Results and discussion

The first forecasting model (T) was implemented using only outdoor temperature data in the linear regression model. Figure 16 and Figure 17 present two scatter charts of two customers' DH consumption as a function of outdoor temperature. When the outdoor temperature decreases, the heat consumption increases. These two customers were chosen as an example to show the difference between forecast models for different customers. For customer no. 1 (in Figure 16) the consumption points follow the

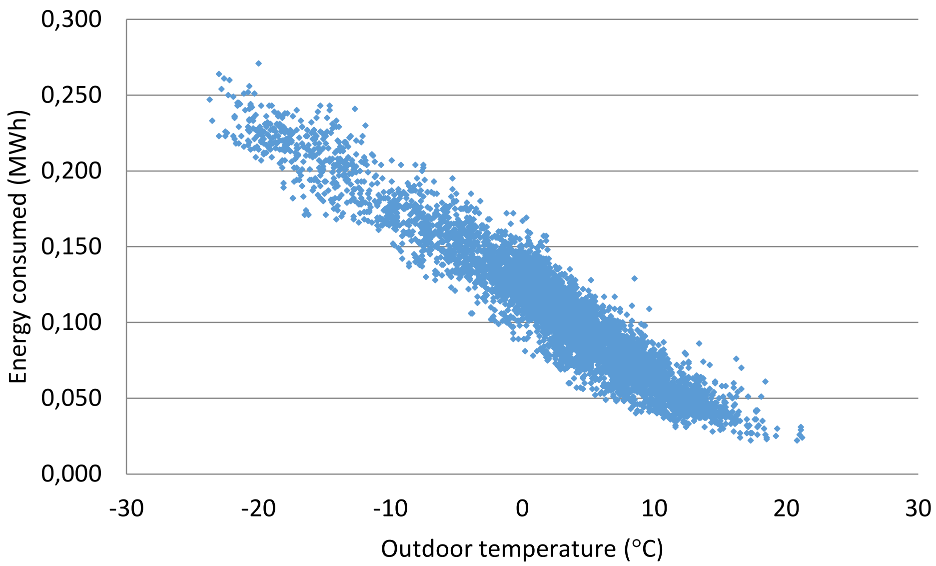

Figure 16. Regression lines for customer no. 1, with good accuracy.

regression line closely and the error for regression is small. For customer no. 6 (Figure 17) the scatter diagram shows that the error for regression is larger and the consumption points do not follow the regression line as well as for customer no. 1.

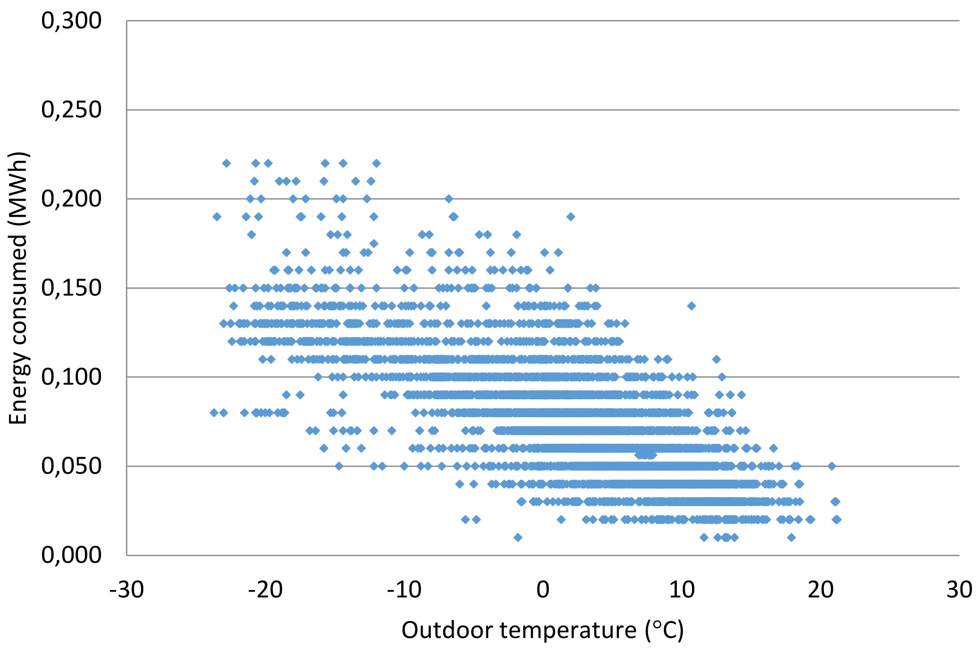

Figure 17. Regression lines for customer no. 6, with poor accuracy.

If the summer period was included in the forecasting models, the temperature function for the whole year would be non-linear because the heat consumption for heating houses in the summer is low, in practice zero at temperatures above 17 °C. However, DH is also needed in the summer to provide domestic hot water. When summer is excluded from the forecasting model, the linear model approximates the relationship between heat consumption and outdoor temperature well.

The social component, i.e., weekly pattern of heat consumption, was then added to the forecasting models. The weekly pattern was taken into account in four different ways as described in Chapter 4, section 4.2.2. Figure 18 shows the measured hourly consumption of customer 1 ('Measured') for week 13/2011. The outdoor temperature of the selected week (secondary axis) demonstrates a typical winter temperature range in Southern Finland, extending from +4.5 °C to -9.8 °C. The measured hourly consumption curve shows the typical consumption pattern for the week with morning and evening peaks.

For this customer, the heat consumption increased at the end of the week, which was explained by decreased outdoor temperature.

Figure 18 presents simulation results of three different forecasting models. The first forecasting model, model T, based on only outdoor temperature data, shows that it estimates the consumption quite well, but most of the consumption peaks are underestimated by the model, whilst for the consumption peaks on Friday and Saturday the forecast gives values that are too high. The relative error for this model was 9.5

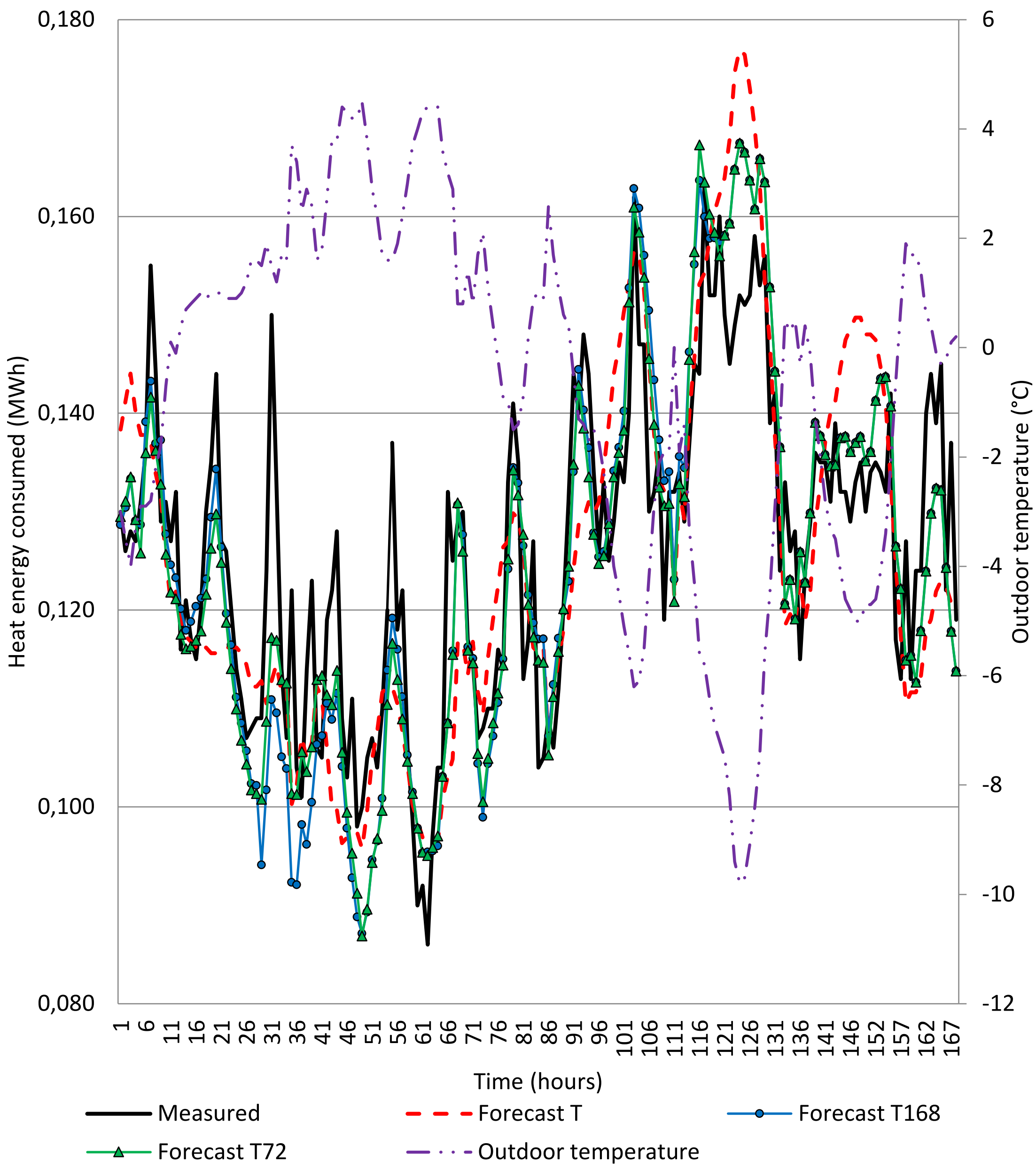

Figure 18. N-1 forecasting models for week 13/2011 for customer no. 1

percent. Consumption peaks can be predicted with better accuracy when the weekly pattern is included in the forecasting model. Model T168, with a weekly pattern of 168 hours, gives a relative error of 7.69 percent. In the third model, model T72, where the weekly pattern is considered as working days, Saturdays and Sundays, consumption peaks are modelled even more accurately, with a relative error of 7.15 percent. The models T168H and T72H, where the midweek holidays were included, gave almost identical results to models without the midweek holidays. For better clarity, these results are omitted from Figure 18, but the results can be seen in Table 6.

Table 8 and Table 9 summarise the relative and absolute errors of all forecasting models for individual customers, pairs of customers, and all customers grouped together. The relative error in the T-models for individual customers varies from 9.50 percent to 26.74 percent. Variation is quite large due to differences among customers. The accuracy of the forecast for small customers with small water flow (no. 5 and no. 6) is worse than for big customers (no. 1, no. 8, and no. 11).

Table 8. Relative errors of different forecasting models

	Relative errors (%)				
Customer	**T**	**T168**	**T72**	**T168H**	**T72H**
1	9,50	7,69	7,15	7,76	7,17
2	10,62	7,53	7,66	7,50	7,63
5	20,81	14,90	15,42	14,99	15,47
6	26,74	24,46	24,32	24,19	24,06
7	14,42	8,09	7,51	8,13	7,53
8	10,40	6,77	6,25	6,74	6,26
11	11,61	7,88	7,58	7,89	7,59
12	12,87	8,45	8,32	8,39	8,24
13	21,65	15,52	15,82	15,51	15,81
Sum of 1 and 2	9,13	6,69	6,43	6,71	6,41
Sum of 5 and 6	19,83	16,04	16,12	15,86	15,94
Sum of 7 and 8	12,05	6,51	5,80	6,52	5,81
Sum of 11 and12	11,29	6,41	6,41	6,37	6,36
Sum of all	10,67	5,34	5,28	5,33	5,25

Including the weekly pattern brings more accuracy to all forecasting models. The results are 2.35–6.91 percentage points better when the weekly pattern is included, depending on the customer and the model type. The accuracy of the models including the weekly pattern varies, because different customers have different user habits. For example, the accuracy of predicting the consumption of customer no. 7 improves almost seven percentage points when the weekly pattern is added to the model. But for customer no. 6, the accuracy improves only about two percentage points and the accuracy of prediction is low in every model. Table 8 and Table 9 also show that the forecasting models for individual customers are worse than for pairs of customers or for all customers grouped together. As the heat consumption for single customers does not typically coincide with one another, the consumption for a larger set of customers is evened out and the relative prediction error is made smaller.

Table 9. Absolute errors of different forecasting models

	Absolute errors (MWh)				
Customer	T	T168	T72	T168H	T72H
1	0,0097	0,0076	0,0073	0,0078	0,0074
2	0,0078	0,0060	0,0061	0,0061	0,0061
5	0,0081	0,0056	0,0057	0,0056	0,0057
6	0,0164	0,0135	0,0135	0,0134	0,0134
7	0,0196	0,0109	0,0102	0,0109	0,0102
8	0,0107	0,0074	0,0071	0,0074	0,0072
11	0,0160	0,0104	0,0102	0,0104	0,0102
12	0,0154	0,0105	0,0105	0,0105	0,0104
13	0,0141	0,0111	0,0112	0,0110	0,0112
Sum of 1 and 2	0,0162	0,0122	0,0119	0,0123	0,0120
Sum of 5 and 6	0,0204	0,0148	0,0148	0,0147	0,0146
Sum of 7 and 8	0,0297	0,0153	0,0143	0,0154	0,0144
Sum of 11 and 12	0,0291	0,0166	0,0167	0,0165	0,0165
Sum of all	0,0872	0,0421	0,0424	0,0420	0,0423

It is difficult to compare the accuracy results with earlier studies, where forecasting was based on DH production data, because the forecasting methods, network size, and examination periods vary (Dotzauer, 2002; Kvarnström et al., 2006). However, it seems that the forecasting models developed in this study, using consumption data from customers, are competitive with earlier studies. For the group of customers, the relative error was even smaller than in earlier studies.

5.4 Conclusions

In this part of the study, forecasting models for DH consumption were developed using hourly heat consumption data from individual customers. The models were constructed based on linear regression, using the outdoor temperature data and the social component of the heat consumption as explanatory factors.

The results show that accuracy of the forecasting model varies depending on the customer. The forecasts tend to be more accurate for bigger customers and aggregated groups of customers. In the best cases, a rather simple model was shown to predict the heat consumption with reasonable accuracy. The forecasting model for the group of nine customers was very accurate and the relative errors were smaller than in earlier studies. This may be due to better-quality source data and the fact that the temporal mismatch between production and consumption does not disturb the model.

6 CASE II: Flexibility and customer participation – Demand-side management

One of the challenges in DHC systems as a part of smart cities is to bring flexibility to the DHC network. DHC systems are already a flexible part of the energy system, with the ability to store energy (heat or cold), but the possibility of using residential buildings as short-term heat storage facilities has not been studied widely. This part of the study focuses on the flexibility of the DH system, and the concentration is on the utilisation of heat storage systems in the short term using customer participation. Here the efficiency of the energy system is increased by cutting the heat for one hour during the morning peak for the customers living in block buildings.

6.1 Target of the study

The target of this part of the study is to examine the possibility of residential block buildings operating as short-term heat storage facilities to reduce the heat load peaks in the DH system. The research question can be divided into two parts. First, the reaction of buildings of differing ages to the temporal heat cut, with varying outdoor temperatures, was ascertained, as well as how this would affect the indoor temperature level of the buildings. This part was mainly done in Jokinen (2013) but the methodology, input data, and results are briefly described here as well. Secondly, using the previous results, the object was to figure out the overall DSM potential of the buildings. The starting point of this study was to keep the DH customers satisfied with the heat delivery. This means that DSM is implemented in such a way that the heat is reduced for one hour every weekday morning. The restriction was that the indoor temperature could not decrease over 1 °C. The heat for the domestic hot water was not reduced; technologically, this is possible because of the connection to the DH (see Figure 4).

As stated before, DSM for DH buildings has been studied earlier but the concentration has been mainly on single buildings and office buildings. However, far too little attention has been paid to the effects of DSM on the residential buildings despite the fact that in Helsinki, for example, approximately 54 percent of the DH customers (measured in space area) are residential buildings (Statistics Finland, 2013). DSM studies on a large scale (for example, city-wide) are lacking.

6.2 Methods and data used

Buildings of different ages respond to heat reduction and thus to the temperature change in diverse ways. This is the reason why an extensive study is needed, where the inside temperature behaviour in residential buildings during a heat reduction is estimated. Structures and technical systems in simulated buildings represented the typical values according to the regulations in effect during each decade (Jokinen, 2013). The buildings were simulated using the IDA-ICE program (Björsell et al., 1999; IDA, 2013; Salvalai, 2012). In this study, it was important to take into account the speed of the inside temperature change when simulating buildings. Dynamic simulation models are based on a detailed thermal model of the building when it is possible to take into consideration the time delays in the buildings. The benefit of the dynamic simulation model is the possibility of using the hourly weather data.

The computations conducted in this study concentrated on analysing the block buildings and the DH system located in Helsinki, Finland, where 47 percent of the residential buildings are block buildings. The building stock consists of buildings of different ages. Table 10 presents the number of block buildings, with floor space, built in different

Table 10. The block buildings in Helsinki (number and floor space) divided by the building year (Statistics Finland, 2013)

Building year	Residential buildings (number)	Floor space (m^2)	The share of floor space (%)
- 1920	698	1 755 460	8,0
1921–1939	1 265	3 494 868	15,9
1940–1959	1 432	2 933 152	13,3
1960–1969	1 630	3 803 396	17,3
1970–1979	1 146	2 671 188	12,2
1980–1989	1 651	2 167 585	9,9
1990–1999	1 297	2 440 596	11,1
2000–2009	778	1 998 797	9,1
2010–2012	245	678 189	3,1
Sum	10 154	21 975 263	

decades. The largest share (over 17 percent) of the block buildings in Helsinki was built in the 1960s as more than over 17 % of the buildings were built in this decade. (Statistics Finland, 2013).

The thermal behaviour of the residential buildings is studied in conditions where the heat is cut for one hour. The starting point of this research is the customer satisfaction with the heat delivery. This means that the heat cut must be implemented in a way which does not cause harm to the customers. In Finland, the optimal inside temperature (affected by air humidity, gender, and age) is 21 °C (Seppänen, 2001) which refers to the temperature level with which most of the people are satisfied and the number of dissatisfied people are in a minority. Beside this, comfort decreases if the inside temperature varies too much too fast. This is the reason why the inside temperature cannot fluctuate more than 1 °C per hour inside the apartment (Seppänen, 2001).

The optimal inside temperature is defined when air humidity is 50 percent, and during the winter time, when air humidity decreases, the optimal inside temperature increases 0.3 °C for every 10 percentage points decrease in air humidity (Seppänen, 2001). Gender and age do not affect the optimal temperature directly, but the differences come from the different clothing habits of men and women as well as the activity levels of people of different ages. In this study, the days where the decrease of the inside temperature does not exceed 1 °C during the heat cut are regarded as theoretical DSM potential. For the simulations, the heat is cut at 7:00 a.m. on weekdays when the heat consumption peak typically occurs. The delivery of the domestic hot water is not cut.

All the simulated buildings are based on the block building built in 1968 which is presented in Figure 19 and simulated with the IDA-ICE tool. The input values for the simulations of the buildings of different ages varied according to the building regulations. Every room in the simulated buildings was modelled separately (Jokinen, 2013).

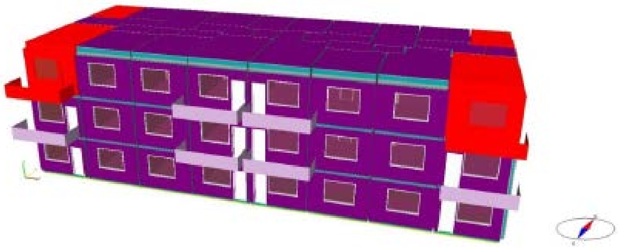

Figure 19. A block building built in the year 1968, simulated with the IDA-ICE tool. The red colour shows the rooms which are critical in the sense of the decrease of the indoor temperature (in this case, upper corner rooms). (Jokinen, 2013)

The structures, heat insulation, and ventilation, as well as the heating systems of the residential buildings, have changed over the years. The structure type has changed from a masonry structure to a mixed structure, and nowadays the most commonly used structural type is concrete elements. The structure of the external wall has changed from a massive two-layer brick uninsulated wall structure to a more energy-efficient sandwich structure. Regulations concerning heat insulation have also evolved since the 1930s to be more energy efficient. The ventilation in the block buildings has traditionally been natural ventilation, but since the 1960s, forced ventilation systems have been installed. Heat recovery systems have become more common since the year 2000. Traditional heating systems in the block buildings were based on stove heating; these have been displaced by central heating systems beginning in the 1910s. The DH systems have a long tradition in Finland from the 1950s. In Helsinki in 2012, 93.7 percent of all block buildings (9513 buildings) were heated with DH (96.8 percent as floor space) (Mäkiö, 1989; Neuvonen, 2006; Statistics Finland, 2013).

The input values for the simulations are presented in Table 11. The thermal load caused by the people (125 MW) inside the building is taken into account in those rooms where activity takes place. The number of the people is 1/28 people/m^2 (The Ministry of the Environment, 2010).

The inside temperature of the buildings does not follow the changes in the heat load immediately but has a time delay, which is due to the large heat load capacity of the buildings. With this time delay, it is possible to gain both benefits and disadvantages. Due to the time delay, the inside temperature stays stable, which simplifies the heat

Table 11. The input values for the simulations of the buildings (Jokinen, 2013)

	1880-1919	1920-1939	1940-1960	1968	1976	1985	2003	2010
U-values of the building elements:								
External wall (W/m^2,K)	0,91	0,91	0,53	0,44	0,4	0,28	0,25	0,17
Roof (W/m^2,K)	0,4	0,2	0,45	0,35	0,35	0,22	0,16	0,09
Base floor (W/m^2,K)	0,48	0,2	0,59	0,41	0,4	0,36	0,25	0,16
Windows (W/m^2,K)	2,1	2,1	2,1	2,1	2,1	2,1	1,4	1,0
Doors (W/m^2,K)	0,7	0,7	0,7	0,7	0,7	0,7	1,4	1,0
Other input values:								
n50-value (l/h)	6	6	6	6	6	6	4	2
Annual efficiency of the ventilation heat recovery (%)	0	0	0	0	0	0	30	45
Flexibility of the thermal loss of buildings' envelope (%)	0	0	0	0	0	0	10	30

control. It does not decrease rapidly even if the heat is stopped suddenly. The disadvantage of the time delay is in the cases where the buildings are used only occasionally, so it is not possible to heat up or cool the building down quickly.

The theoretical potential for DSM (Q_{Teor}) is formed from the average heat load during the heat cut for each building type. From the simulation models, the average heat load for those days when a heat reduction is possible is calculated as a result. For each building type, the theoretical potential for DSM can be calculated by multiplying the average heat load (*P*) during the heat reduction period by the space area for each building type (*A*), which can be derived from Table 11. This is presented in formula (14).

$$Q_{Teor} = \sum P * A \tag{14}$$

Heat load during the heat reduction period is presented in unit W/m^2 and the space area in unit m^2.

6.3 Results and discussion

The heat load varies for block buildings built in different decades. The heat loads during the heat cut for simulated block buildings with relation to the outdoor temperature are presented in Figure 20. The heat loads presented do not include the heat needed for domestic hot water but only the heat required for the space heating. The block buildings built before 1985 follow approximately the same heat load curve. A big change can be seen for the buildings built in 2003 and 2010, for which the heat loads during the heat reduction are much smaller when compared with the older buildings.

There are three important factors affecting this. The first one is the smaller n50-value for buildings built after the year 2003. The n50-value indicates the leakage air flow rate (see Table 11) and it affects the energy consumption significantly: a change in a whole number in the n50-value affects the heat demand of the building by seven percent

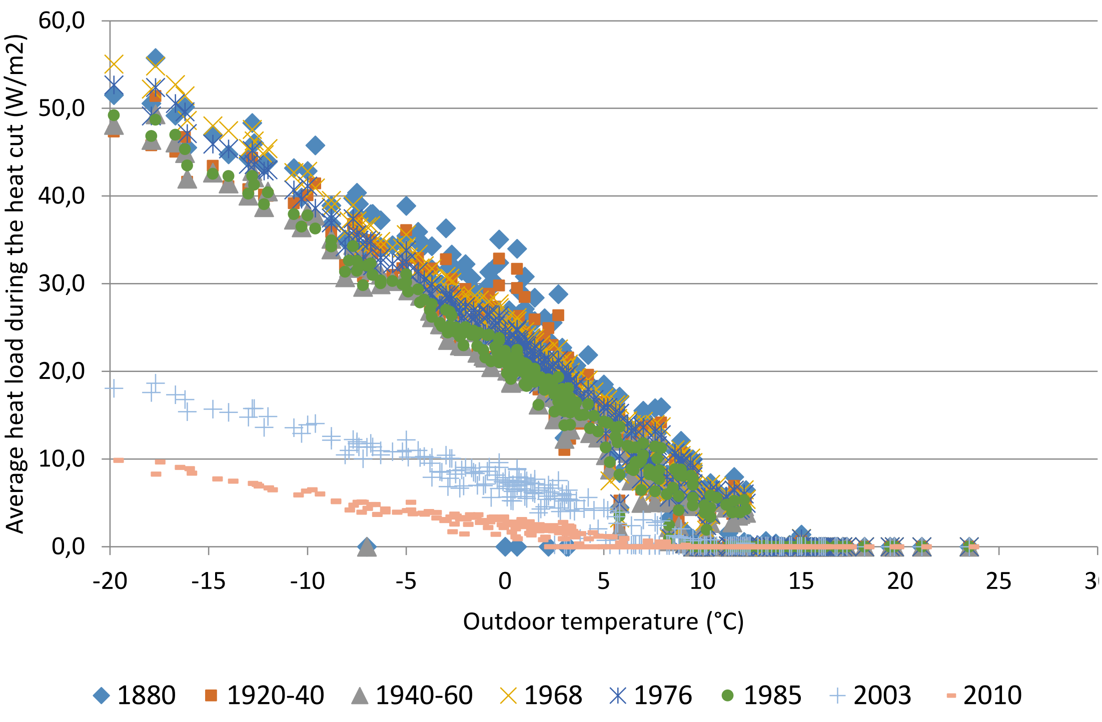

Figure 20. The average heat load (W/m^2) for buildings of different ages during a heat cut with different outdoor temperatures. The heat needed for domestic hot water is not included.

(Rakennustieto Oy, 2010). The second factor affecting the smaller heat loads in buildings built after 2003 is the forced ventilation system, where the air is reheated with an electric heater in the ventilation system. The third factor is heat recovery from exhaust air with an air-to-air heat exchanger, which became more common after the year 2000.

Figure 20 shows that the largest potential to decrease the level of heat load by using DSM is in block buildings built before the year 2000. The heat load is high in these buildings. In newer buildings, the time when heat is not needed for space heating is longer than for the older buildings. For the building built in 2003, heat was not needed for space heating during the days from 1.5.2012 to 16.9.2012 and for the building built in 2010, heat was not needed from 24.4.2012 to 7.10.2012.

The change in the indoor temperature in relation to the outdoor temperature during the heat reduction in block buildings built in different decades is presented in Figure 21. The horizontal red line shows the maximum temperature decrease (1 °C) that was set as a precondition for the residents' comfort. Figure 21 shows that the newer the building is, the better the heat storage capacity it has, which means slower cooling of the building. For example, the indoor temperature of the block building built in 2010 cooled down only 0.6 °C over the course of one hour, even with the coldest outdoor temperatures. The inside temperature for the building built in 2003 did not decrease more than the allowable 1 °C during the heat reduction period. This means that for these block buildings, DSM was implemented for all the days when space heating was needed.

For the older block buildings, there were days when it was not possible to implement the heat reduction because it would have caused too great a change in inside temperature. The critical outdoor temperature causing this was -17 °C for the buildings built in 1976 and 1985. This means that there were fewer than five days when DSM could not be implemented. For the building built in 1968, the critical outdoor temperature was -12.6 °C and the heat reduction could not be implemented for a total of nine days.

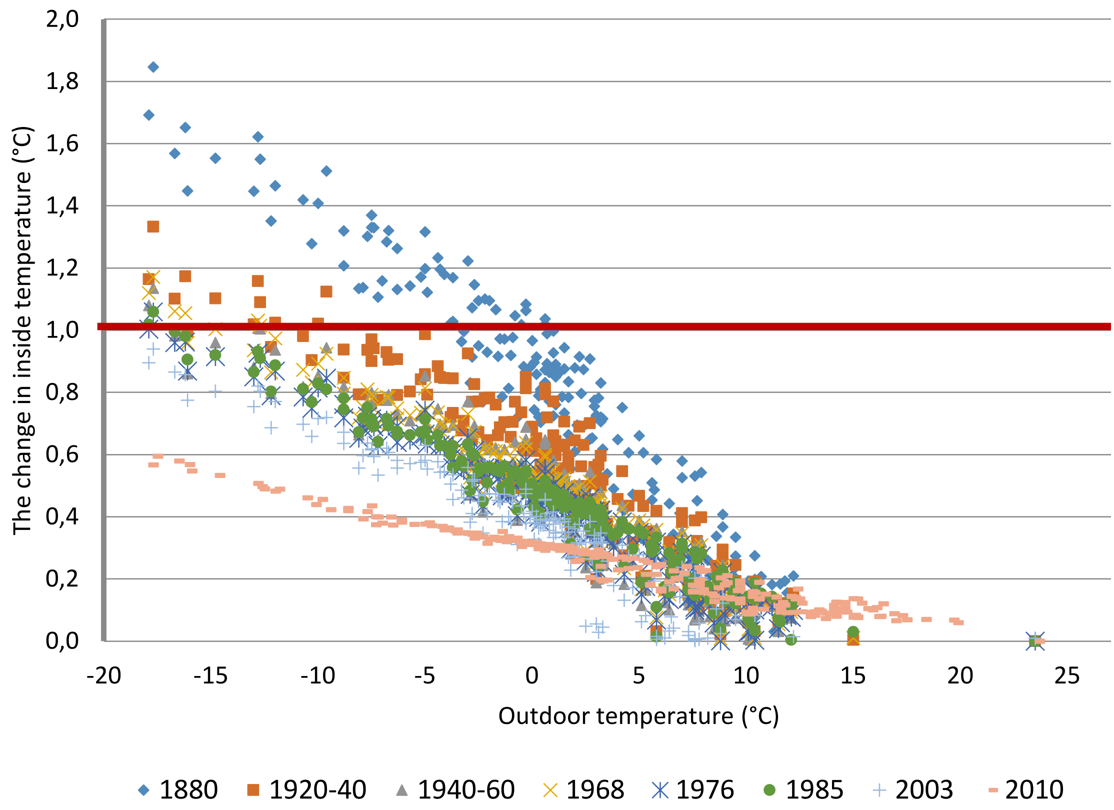

Figure 21. The relationship between the indoor temperature change after the heat reduction and the outdoor temperature. The red horizontal line shows the maximum value of the indoor temperature change, which was set to 1 °C to ensure the comfort of the residents. The points whose value is higher than 1 °C show the number of days when a heat cut was not possible (one point is equal to one day).

The heat behaviour during the winter time of the buildings built in 1940–1959 was exceptional compared to the other simulated buildings. When the winter frosts were thawing, the inside temperature cooled down more than during times when the outdoor temperature was even colder. It was therefore not possible to give a critical temperature for DSM for these buildings. However, during 2012, there were five days when it was not possible to implement the heat reduction.

The DSM potential for the buildings built during the years 1920–1939 is high, because they still need heat energy in June. The critical outdoor temperature for the heat reduction was -10 °C; in 2012, there were 13 days when the heat reduction could not be implemented. The DSM potential was the smallest for the oldest buildings, built in 1880–

1920; in which the heat cut could not be implemented in 59 days due to decrease of inside temperature.

According to the results, the block buildings with the most potential for DSM were the buildings built during the years 1940–2002. The reason for this is the large quantity of buildings of this age, as well as their high heat demands. The cooling of buildings of this age is relatively slow. The results showed that the DSM potential of the oldest buildings (built before the year 1920) was the smallest. Usually the oldest block buildings are built densely in the city centre, however, where the cooling of the buildings can be slower in reality than in the simulations; thus the potential for DSM is higher.

Figure 22 presents the overall theoretical DSM for each day in the year 2012 (columns), produced with formula (13). The different colours show the DSM potential of the buildings built each year. This figure also shows the total DH consumption (grey line) every day at 7:00 a.m. without any realised DSM. This gives an overall view of the

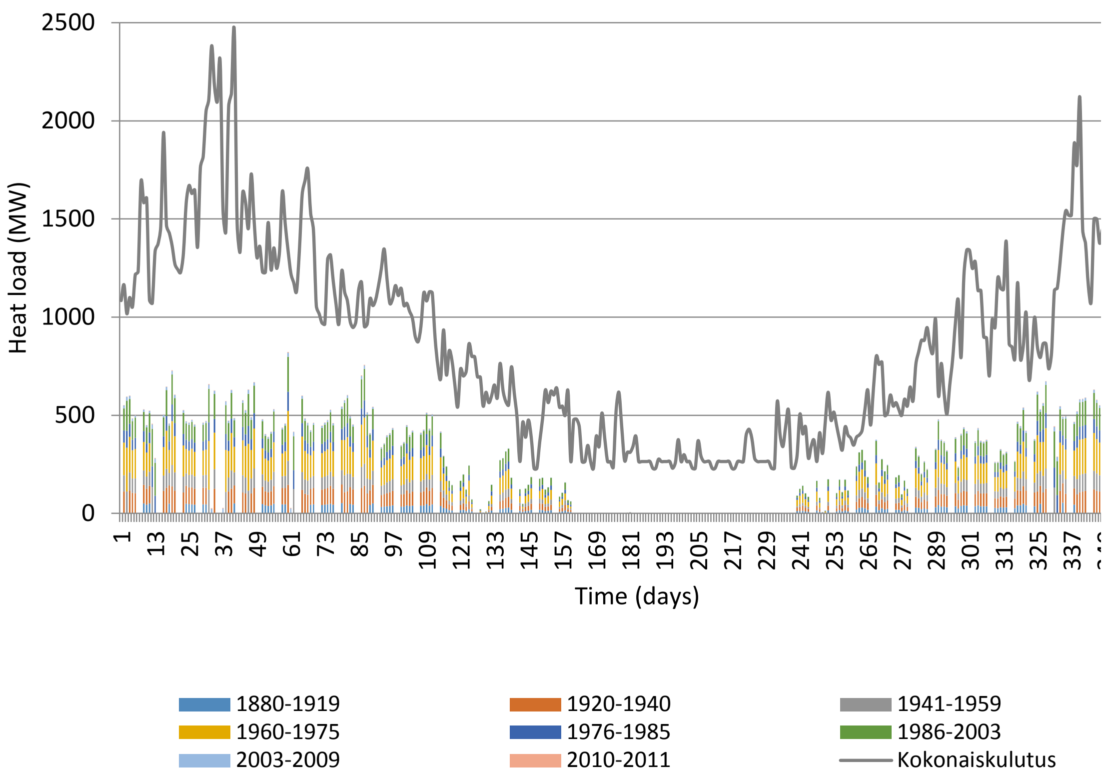

Figure 22. The total potential for DSM during the year 2012. The grey line shows the total demand on the DH and the bars the maximum hourly heat demand decrease achieved by DSM.

potential for DSM for energy savings. Results show that the theoretical potential for DSM of the residential block buildings in Helsinki was approximately one percent of the total district heating energy supply of the company, using the data from 2012. Considering the momentary heat effect, the significance was much larger, approximately 80 percent.

6.4 Conclusions

The purpose of this part of the study was to determine the potential of DSM for DH block buildings in Helsinki, Finland. The thermal behaviour of eight block buildings built in different decades was simulated using outdoor temperature data from the year 2012. The input values for the simulations covered the typical construction values for each building type. DSM was implemented so that the heat was cut every weekday morning at 7:00 a.m., when typically there is a consumption peak in the DH. A one-hour heat reduction was selected to examine how the apartments would. Longer periods of heat cuts would also be possible in the apartments where the indoor temperature did not decrease below the desired level. This would especially include apartments built after the year 2000, and would increase the potential for DSM. The heat reductions were not implemented at the weekends because the largest heat demand peaks occur during the weekdays. The heat for the domestic hot water was not reduced. The starting point for DSM was that the indoor temperature of the buildings could not decrease more than 1 °C.

This case study found that thermal behaviour of the buildings varies by date built. The buildings with the most potential for DSM were the ones built during the years 1940–2002. In these buildings, the indoor temperature did not fall below the maximum acceptable value; but the heat load was high enough that a heat reduction was beneficial as an energy-saving measure. The new buildings were already so energy-efficient that the heat load, even with the coldest outdoor temperatures, was not very high.

The results of this study indicate that DSM has the potential to lower the heat load of block buildings without causing any harm or discomfort to the residents. This leads to higher efficiency for the system, since less peak load capacity is needed. The heat needed for the peak load periods is mainly produced with HOBs, which use fossil fuels, so their energy efficiency from a system point of view is lower than that of CHP plants. Also, part of the start-up costs of separate heating plants could be avoided if DSM could be implemented. For the energy company, the benefits of DSM are lower heat production costs, since the larger part of heat is produced with CHP plants. The energy costs for the DH customer might decrease if the level of consumption falls due to DSM. The lower cost level does not necessarily occur if the reduced heat load is compensated for in the consecutive hours while recovering the cut-off energy. Thus, the peak load may fall as a later peak may take place during the morning hours.

7 CASE III: –Utilisation of waste heat in DH and DC networks

One of the challenges for a DHC system and for the whole energy system is to take more waste heat into the network, which would increase the energy efficiency of the system and decrease the use of primary energy. This chapter presents and evaluates a business model where waste heat is sold to the DHC network at a predetermined price. The business model is called Open DHC and it is implemented in Fortum's network in Stockholm. The whole energy system is modelled to see how the reception of waste heat affects the operations of the system, with special attention to the level of emissions and the question of profitability.

7.1 Target of the study

The purpose of this chapter is to present the Open DHC concept and critically evaluate its opportunities and challenges in terms of increasing the energy efficiency of DH systems and decreasing CO_2 emissions. The pricing model is estimated relative to the waste heat suppliers as well as the energy company. In this study, there are two research questions: first, when is it profitable for a waste heat supplier to sell waste heat to a DH network? and second, how does the reception of waste heat affect the operations of the entire energy system? This chapter presents a case study where relatively low-temperature waste heat was sold to an energy company as prime heat (these terms are explained in the following sections). The temperature of the waste heat was first increased using a heat pump whenever it was profitable for the waste heat supplier to do so, and then sold to the energy company in question. For this, an optimisation tool was implemented. The impacts on the merit order of the energy system and, consequently, the impacts on emissions and profitability, were calculated using the energyPRO simulation tool.

The following terminology has been developed to describe the situation being studied in this paper (see Figure 23). The energy company delivers heating and cooling to the customer. The customer has waste heat available. The temperature of the waste heat (T_{WH}) is too low to be fed into the DH system as it is, so the waste heat supplier increases the temperature level using a heat pump. Primed waste heat refers to the heat product at an acceptable temperature level (T_{PWH}) after the heat pump has been used. Primed waste heat is fed into the DHC system and the energy company compensates the waste heat supplier at market prices.

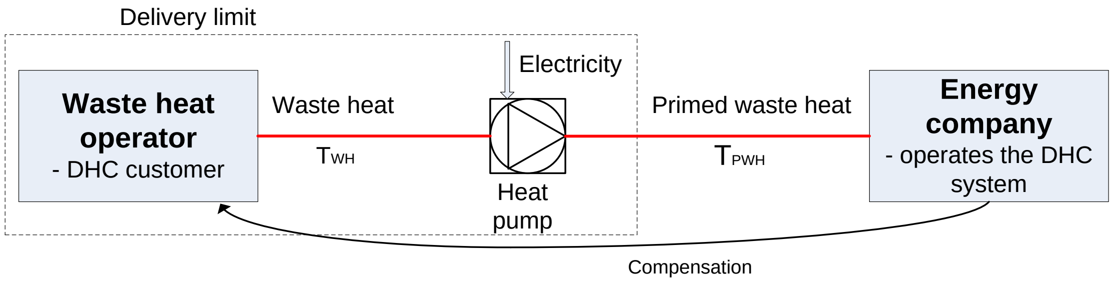

Figure 23. Terminology used in this study. The waste heat supplier is responsible for increasing the waste heat temperature to an acceptable level (delivery limit). After the temperature has been increased, the primed waste heat is fed into the DH network. The energy company then compensates the waste heat operator.

7.1.1 Presentation of Open DHC

The idea behind Open DHC is to create a business model where the customer can sell the waste heat back to the producer at a predetermined price. In the Open DHC system, customers can compete with a producer's own heat production and the producer sets a market price for waste heat based on its own production costs. If the customer can deliver heat at a lower price, the producer will buy it. Four different products are presented in the Open DHC system: prime heat, secondary heat, recycled heat, and heat capacity.

Prime heat is the most valuable product. It is transferred from the customer's building to the producer's heat network through the DH producer's supply pipe. The price is equivalent to or lower than the incremental variable cost of the energy company's own production costs. The target group for selling prime heat is primarily those customers with existing facilities with an excess heat capacity, where the temperature is high enough so that it can be fed to the supply pipe, or customers who have appliances that increase the temperature level. Secondary heat is water for which the temperature level must be at least 55–64 °C. The heat is transferred to the producer's heat network through the DH producer's return pipe. The target group for selling secondary heat is primarily those customers who have waste heat that cannot be recycled locally and who possibly have a heat pump to increase the temperature level of the waste heat.

The lowest delivery temperatures of prime and secondary heat, as well as the prices for them, are presented in Figure 24. The price for prime and secondary heat is set daily by the energy company according to the outdoor temperature; so, the colder the weather, the more valuable the product. The customer must optimise in which category the heat should be sold. This naturally depends on the temperature level of the waste heat, which affects how much the temperature has to be increased before feeding it to the DH network. The higher amount of compensation for prime heat is one factor influencing the optimisation process. The coefficient of performance (COP) of the heat pump decreases if a larger temperature increase is needed. The amount of electricity needed will also increase.

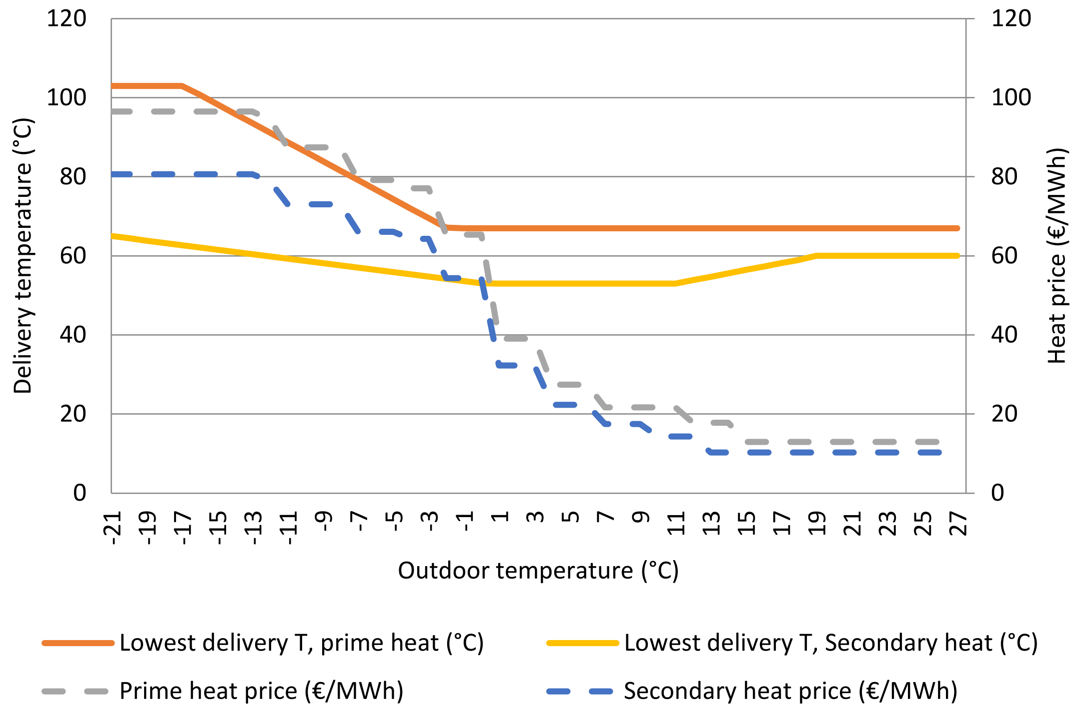

Figure 24. Demanded delivery temperature and compensation of heat with different outdoor temperatures in an Open DHC system in Stockholm (Fortum, 2013a)

The last two heat products in the Open DHC business model, recycled heat and heat capacity, differ from the two previous products. The temperature of recycled heat must be above 15 °C and the price of the product is determined based on the water temperature; thus, higher prices are possible when the water temperature is higher. Recycled heat flows through the district cooling return pipe in order to heat up the district heat in large heat pump systems and it is purchased only in winter time. The product called heat capacity is compensated for or purchased either as heat or cooling energy when customers temporarily reduce their heating or cooling needs (flexible consumption) or lease their existing heating or cooling capacity to an energy company. The price of the heat capacity is fixed via private agreements between the energy company and the customer.

7.2 Methodology and case study presentation

The purpose of this study is to investigate how feeding waste heat into a DH supply pipe (a product called prime heat, see previous section for definition) influences the way in which the energy system operates. The study focuses primarily on merit order, costs, and emission levels. Calculations for this study are based on the energy system operating in Stockholm, Sweden (from now on called the energy system). The reason for this is that the pricing model for waste heat has been developed for this particular energy system, originally based on the marginal production costs of the energy company. In this investigation, the maximum load of the waste heat fed into the DH system is 20 MW. The original temperature of the waste heat varied between 0 and 50 °C at intervals of 5 °C, and different scenarios were calculated (11 scenarios altogether) based on the temperature. The case in which the original temperature of the waste heat is 0 °C represents a situation where ground-source heat is fed into the DH system. The temperature level of the waste heat was primed to the required level using a heat pump. The premise was that waste heat is fed into the DH system during those hours when it is most profitable for the waste heat supplier.

The methodology (calculation order) of this study is divided into four parts. In the first part, a reference case without any primed waste heat was analysed. In the second part, the hours when selling the primed waste heat (at different temperatures, 11 cases) to the DH system was profitable for a waste heat supplier were investigated. In the third part, the ways in which feeding the primed waste heat into the DH system affected the energy company were examined for each different scenario. In the last part, the energy systems calculated in parts one and three were compared. Next, the tools and methods used in this study are presented and validated.

7.2.1 Presentation of the energy system and the calculations

The DH network in the Stockholm region consists of four different parts with approximately 70 heating plants delivering more than 12 TWh of heat annually. The heating plants are owned by five major DH producers in the area. Some of the DH companies co-operate with one another in the heat trade. In the Stockholm region, Fortum produces DH in three main areas using a versatile selection of heat production plants and fuels (Dahlroth, 2009; Djuric Ilic et al., 2012; Svensk Fjärrvärme, 2011). Note that even though the part of Stockholm's DH network operated by Fortum is used as a reference case, it does not exactly represent the real situation. For example, in the calculations, the DH network was modelled as one big network and not as three separate networks with transmission pipes. Also, the heat trades and the co-operation between the different DH companies were not taken into account. The idea was to observe retrospectively how the energy system would have changed if primed waste heat had been fed into the DH network whenever it was profitable for the customer.

The calculations for the studied energy system aim primarily to satisfy the given heat demand (see Figure 25, where a rough illustration of the calculated energy system is presented). The energy system contains a versatile mix of different plants producing heat. For heat production, the system includes CHP plants and heat-only boilers as well as sea-water heat pumps, which partly use electricity as the source of power. The CHP plants, together with the heat pumps, produce the base heat load for the system. Heat production with CHP plants leads to savings in primary energy use and reduced emissions if the production replaces more energy- and emission-intensive marginal electricity in the electricity network (Rinne and Syri, 2013).

With DH production, the smallest variable costs are for the large CHP plants, while the highest costs are for the heat-only boilers (HOBs). This is why the heat for peak load periods was produced using the HOBs. To simplify the calculation, HOBs were considered as a single boiler including both oil-fired HOBs and electricity HOBs. In reality, HOBs are located around the city. Even though the main focus is on producing heat, electricity is still produced in CHP plants and used by heat pumps and the electric boiler in this system. This is why energy system operations need to be optimised hourly: to take into account the changes in the price of electricity. The energy system also contains heat storage units, which is why it is not relevant to do the optimisation process only on an hourly basis; rather, the system must include an optimal strategy for a longer period of time.

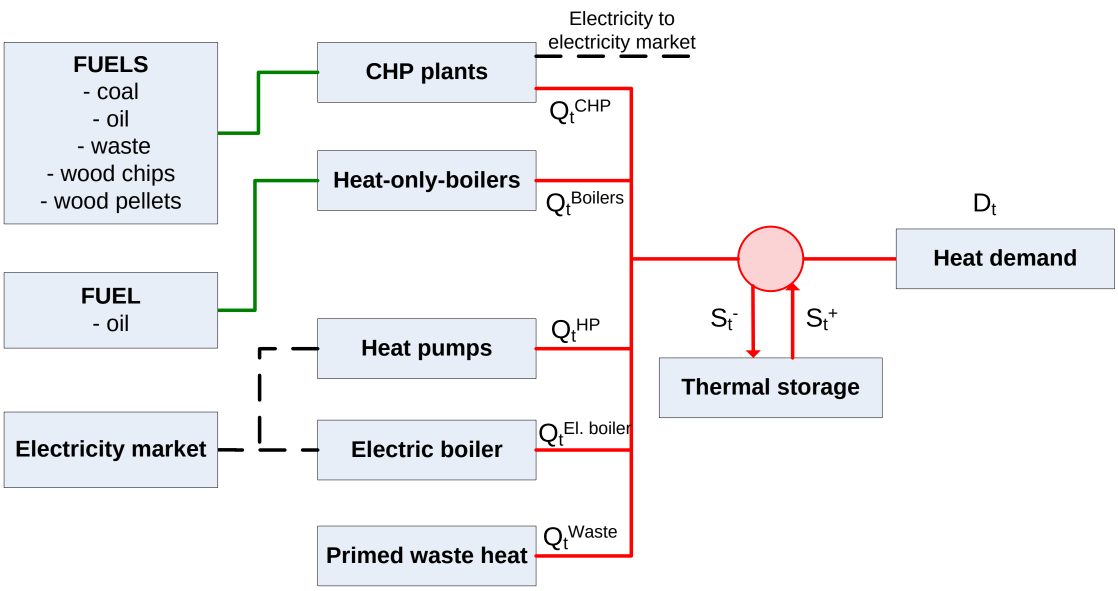

Figure 25. Rough illustration of the calculations used for the energy system. The red solid line represents the heat flows, while the black dashed lines represent the electricity flows and the green solid lines represent the fuel flows. The primary energy used in the industrial plant is not considered in the calculations, thus only the waste heat from it is considered.

To optimise the energy system operations, different input values are needed. The boundary terms for computing the values are the changes in heat demand and the capacity parameters of the production plants. In addition, the use of heat storage is limited by the size of the storage facility as well as the input and output maximum flows. Input values also include information about the surrounding conditions, such as electricity prices, outdoor temperatures, energy taxes, and emission levels. The energy system can be optimised so that the production costs are minimised.

At the hourly level, the heat production from the different production units, the storage capacity, and the heat demand have to be in balance, as illustrated in Equation (15):

$$Q_t^{CHP} + Q_t^{Boilers} + Q_t^{HP} + Q_t^{El.boiler} + Q_t^{Waste} + S_t^- = S_t^+ + D_t \qquad t = 1, \dots, 8760 \qquad (15)$$

where different Q_t represents the heat production from the different production units (CHP plants, fuel-fired boilers, heat pumps (HP), electric boilers, and primed waste heat), S_t^- and S_t^+ represent the heat charging and discharging of heat from storage and D_t represents the heat demand.

The reference case was calculated using hourly data from 2011. The input values for the heat and power plants are presented in Table 12 and Table 13. A heat storage capacity of 60 000 m^3 is included. The heat storage capacity of the DH network (DH pipes) was not taken into account in the calculations.

The calculations are based on actual hourly outdoor temperature data from Stockholm for the year 2011 (Statistics Sweden, 2011), as well as the SPOT prices for electricity (Nord Pool, 2011). The heat needed for domestic hot water was considered as a constant value and the different demand peaks caused by the use of hot water during the mornings and evenings were not taken into account. This gives a sufficient value for the heat demand during the year. The fuel prices (International Energy Agency, 2010b; Vuorinen, 2009) and energy taxes in Sweden (Skatteverket, 2013), as well as the variable O&M costs for the power plants (International Energy Agency, 2010b; Vuorinen, 2009), were derived from several sources. The variable O&M costs are expressed in relation to electric power production for the CHP plants and in relation to heat production for HOBs and heat pumps. All of the CHP plants have start-up and shut-down periods of four hours each. The CHP plants include turn-on costs (International Energy Agency, 2010b; Vuorinen, 2009), which will affect the merit order of the system considerably when production is divided into the different production units.

Table 12. Information on the power plants producing DH for the energy systems (Fortum, 2013b; International Energy Agency, 2010b; Vuorinen, 2009) (the variable O&M costs do not include fuel costs)

Power Plant	Fuel (MW)	Heat (MW)	Elec. Power/Cons (MW)	Variable O&M costs (€/MWh)	Turn-on costs (€/turn on)
Coal CHP	454	250	145	7	7 000
Waste CHP	390	267	71	40	10 000
Wood CHP	135	75	42	5	4 500
Wood pellets CHP	335	215	75	5	16 000
Oil CHP	607	330	210	15	7 000
Heat pump 1		225	65	5	-
Heat pump 2		256	88	5	-
Heat pump 3		50	18	5	-
Heat only boiler, oil	1 425	1 300		10	-
Electric boiler		180	180	1	-
Heat storage	60 000 m^3				

Table 13. Heat values, fuel prices, and CO_2 emission factors used in the calculations (Rinne and Syri, 2013; Statistics Finland, 2011)

		Coal	Waste	Wood	Wood pellets	Oil	Marginal electricity
Heat value	**MJ/kg**	27	20	12	18	42	
Fuel price	**€/kg**	0,071	0	0,07	0,165	0,57	
CO_2-emission factor		94 g/MJ	-	-	-	77 g/MJ	0.68 t/MWh

To calculate the merit order of the power plants based on the given heat demand in the energy system, the energyPRO simulation tool was used. EnergyPRO (Connolly et al., 2010; EMD International A/S, 2013; Hinojosa et al., 2007) is an input-output software package used for modelling energy systems. It is used to optimise the operation of plants using technical, financial, and external parameters. As a result, energyPRO can calculate the merit order of different production plants that minimise the cost of production to meet the heat demand. The energyPRO simulation tool has been used in various cases; for example, in Denmark (Lund and Andersen, 2005; Nielsen and Möller, 2012; Østergaard, 2012)), the UK (Fragaki et al., 2008; Fragaki and Andersen, 2011) and Germany (Streckienė et al., 2009). EnergyPRO also calculates annual production rates, typically in one-hour steps. In this way, the optimisation process takes hourly varying electricity prices into account. The energyPRO simulation tool does not calculate the optimal merit order chronologically, but it locates an optimal operation strategy for the most favourable periods. The reason for this is that each time new energy is produced, it has to be carefully checked to avoid disturbing the already planned future production rates and to avoid encountering any problems, for example, with varying electricity prices (Lund and Andersen, 2005).

7.2.2 Calculation methods for profitability

The original temperature of the waste heat in this case study was so low that it had to be increased using heat pumps before being fed into the DH system. This study concentrates only on cases where waste heat is fed into the DH supply pipe (prime heat, details in Chapter 6, section 6.1.1). The principle of connecting the waste heat source to the DH network is shown in Figure 26. The temperature levels shown in the figure are only estimates. In Figure 26, waste heat is used to heat up the DH water from the return pipe using the heat pump so that the temperature level is high enough for the DH supply pipe. Investment costs for the heat pump facilities are not included in the calculations.

The calculations are based on the idea that waste heat is sold to the energy company during those hours when it is profitable for the waste heat seller. For this, hourly calculations are carried out that take into account hourly electricity prices. Electricity is used to power the heat pump.

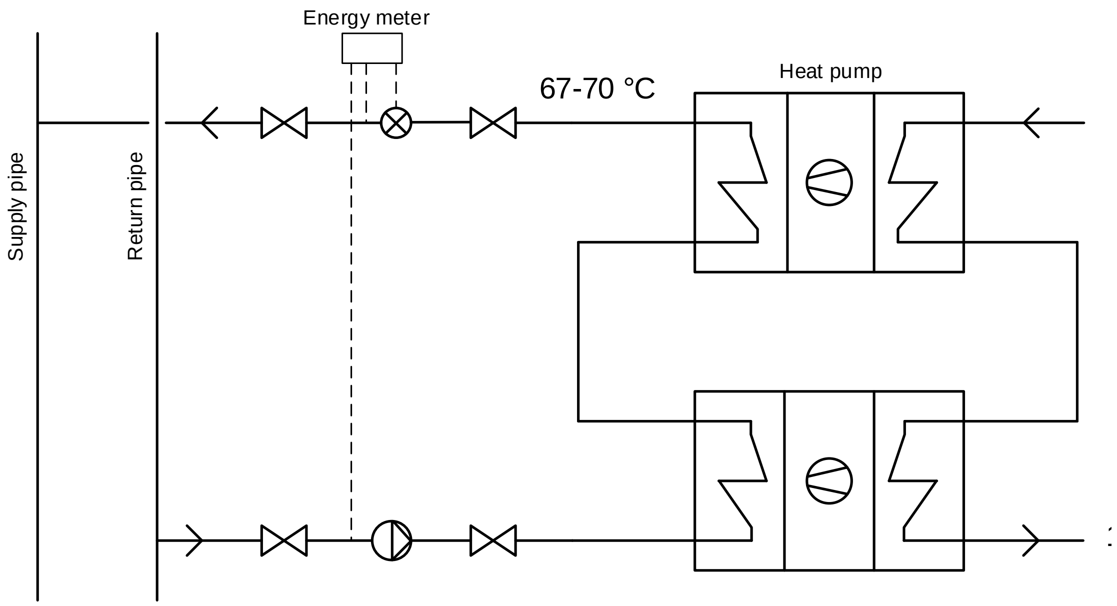

Figure 26. Sample case of a data centre with the heat pump connected to the DH network (prime heat). The temperatures in the figure are examples only; higher temperatures from the cold side are also possible.

It was calculated whether or not it is profitable to the waste heat seller to sell the heat at each particular hour. If the criterion for equation (16)

$$\frac{r_{el} + r_{elec.tax} + r_{trans}}{COP} < r_{PH} \tag{16}$$

is fulfilled, then the heat load (kW) from the waste heat is fed into the DH networks for that particular hour. If Equation (15) is not fulfilled, then it will not be profitable to sell the waste heat at that particular hour. The examination is done hourly. In Equation (15), r_{el} is the Nordpool spot electricity price each hour, $r_{elec.tax}$ stands for the electricity taxes, and r_{trans} is the electricity transmission costs, while $r_{PH}$is the price that the energy company pays for the waste heat each hour (depending on the outdoor temperature) and COP is the coefficient of performance for the heat pump. The COP value used here is based on rather small ground-source heat pumps operating at about 10 kW of output. It is roughly the same, within a sufficient degree of accuracy, for larger units using the same type of technology.

7.3 Results and discussion

7.3.1 Results of the reference case

First, calculations of the reference case without any primed waste heat being fed into the energy system were made. The idea was to find out the merit order of the power plants with the given heat demand and electricity prices. With this information, it was possible to determine the costs and emission levels caused by producing the necessary heat.

Most energy systems contain a versatile mix of power plants with different marginal costs for production. In an optimal energy system, the heat production plant with the lowest production costs produces the base heat. When the heat demand increases, the heat plant with the second lowest production costs is added to the production mix. In an energy system with CHP plants (or plants that use electricity), the electricity price affects the marginal cost of production, and thus, the merit order of the power plants. The electricity price fluctuates a great deal during the year.

Figure 27, Table 14, and Table 15 show the results of the reference case for the year 2011. With the given input values, the base load of the heating system was produced

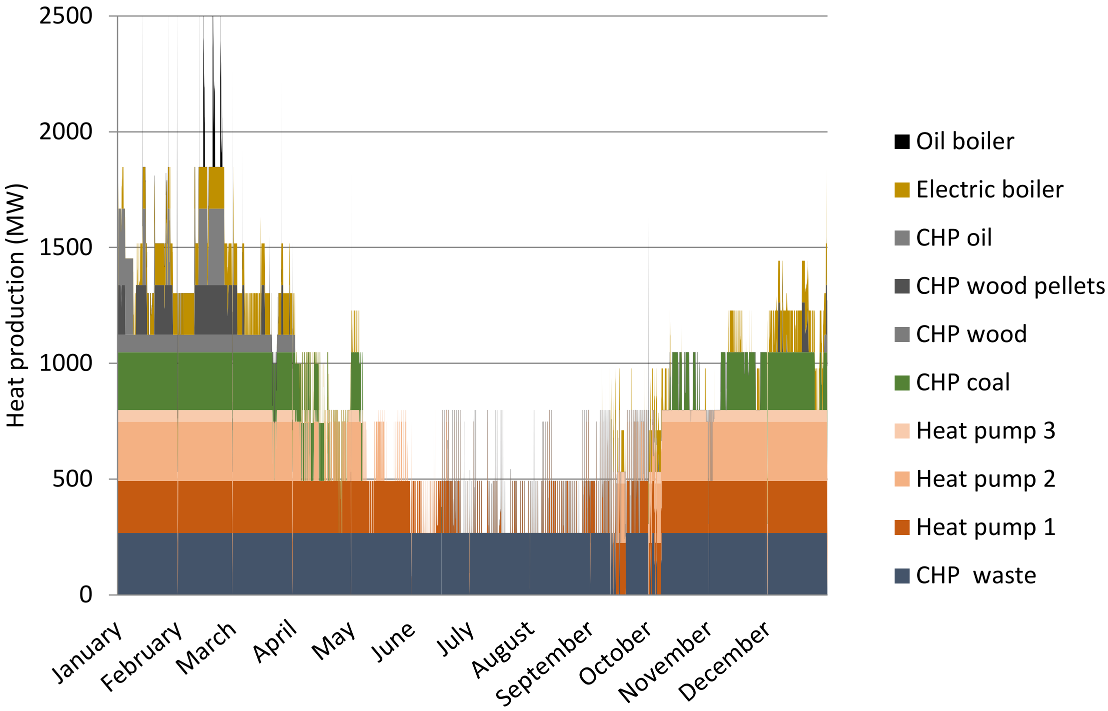

Figure 27. Heat production for the reference case, 2011

using the CHP plant, which is fuelled with waste. The reason for this has to do with the nature of the fuel, which is continuously produced by the inhabitants of the municipality. Additionally, the heat pumps assist in producing the base load. In September, there are two periods of time during which the heat demand is covered using only the heat pumps. The reason for this is the low electricity price during those periods of time, making it unprofitable to produce CHP. The peak loads are mainly handled using oil boilers. The turn-on costs for the CHP plants affect the merit order significantly. Table 14 shows the heat production figures (in GWh and as a percentage of the overall production) for the different heat production types. Table 15 shows an overall picture of the energy system during the year 2011.

Table 14. Plant-specific results for the reference case

		Heat pumps	**CHP waste**	**CHP coal**	**CHP wood**	**CHP wood pellets**	**CHP oil**	**Electric boiler**	**Oil boiler**
Heat production	GWh	3 264	2 262	1 018	163	252	198	521	51
Heat production	%	42,2	29,3	13,2	2,1	3,3	2,6	6,7	0,7

Table 15. Overall production results for the reference case

Heat demand	GWh	7 729
Fuel consumption (at CHP plants and with HOBs)	GWh	6 261
Electricity consumption (HPs and electric boiler)	GWh	1 559
Electricity production (CHP plants)	GWh	1 497
CO_2 emissions	t_{CO2}/a	784 735

7.3.2 Results with the waste heat included

The aim of the study was to investigate how feeding waste heat into an energy system affects its operations, including merit order, the CO_2 emissions of the entire energy system, and profitability. The profitable sale of waste heat is affected by many factors, such as the hourly price of electricity, the price paid for the waste heat by the energy company, and the demanded temperature level for the waste heat.

Figure 28 shows the level of primed waste heat fed into the DH supply pipe on four sample days when operations were guided by the profitability to the waste heat supplier. The figure also shows the outdoor temperature (varying from -11,7 °C to 3,8 °C) and the electricity price (varying from 33.6 €/MWh to 63.8 €/MWh) on the same days. The figure illustrates how the temperature of the primed waste heat is dependent upon the outdoor temperature. For example, for those hours when the outdoor temperature falls to its lowest level, feeding the primed waste heat into the system is not very profitable for the supplier. Also, the lower the level of the waste heat's original temperature, the less profitable it is to the supplier to sell the waste heat. This is due to

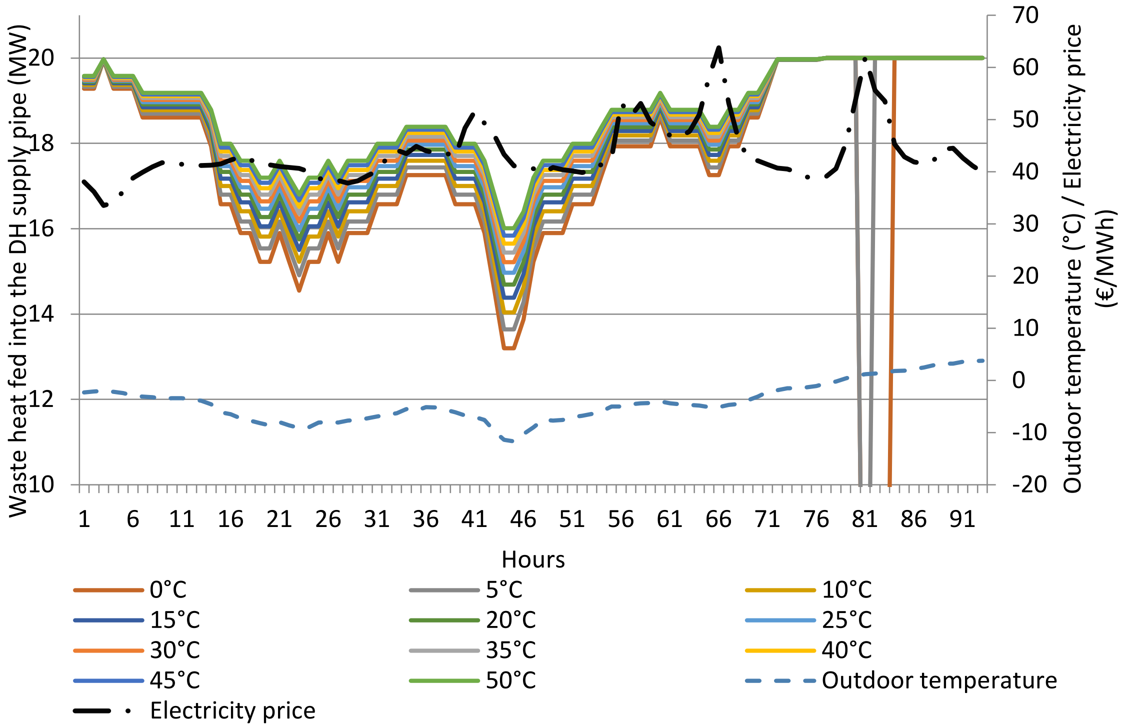

Figure 28. The primed waste heat (MW) fed into the supply pipe with different original temperatures (0–50 °C) on four sample days (maximum load 20 MW). The outdoor temperature and the electricity price on those days are also represented. The decrease in the waste heat output, e.g., by 44 hours, is due to the cold weather and the higher output water temperature needed from the heat pump. This leads to a decrease in the maximum output heat effect from the pump. When the heat source temperature is higher, this phenomenon is not that strong. The non-profitable operation, rounded to 81 hours, is due to the high electricity price compared to the heat sales price, which is low during the mild weather conditions at that particular time.

the fact that the temperature of the waste heat has to be increased using heat pumps and the maximum output of the pump decreases when the temperature difference between the heat source and the heat output increases. The same applies to the COP of the heat pump: it also decreases when the temperature difference increases. Similarly, the electricity price affects the profitability of selling waste heat, and this can also be seen in the figure at hours 81–83.

Table 16 shows the amounts of waste heat energy that were profitable for the supplier to sell to the energy company at different waste heat temperatures (the maximum waste heat load was 20 MW) during the year 2011. From the table, we can see that the higher the waste heat temperature, the more profitable it is to sell the waste heat to the DH system. This is due to the higher maximum output and the COP of the heat pump when the temperature increase is smaller. The table also shows the electricity consumption and the CO_2 emissions related to use of the heat pump. Finally, the costs

Table 16. The amounts of primed waste heat that were profitable for the supplier to sell to the energy company at different waste heat temperatures during the year 2011. The maximum waste heat load was 20 MW.

Waste heat original temperature	Energy from waste heat (MWh/a)	Share of hours (%) when waste heat feeding is profitable	Electricity used for HP (waste heat) (MWh/a)	CO_2 emissions related to HP use (t/a)	Costs for the energy company (€/a) receiving the waste heat
0	53 880	32,2	146 558	99 660	3 390 320
5	55 813	33,3	121 738	82 782	3 467 741
10	67 244	39,7	101 560	69 061	3 809 691
15	79 077	46,4	85 051	57 835	4 147 171
20	96 576	56,3	71 467	48 598	4 559 027
25	113 323	65,8	60 235	40 960	4 937 645
30	125 859	72,9	50 906	34 616	5 184 504
35	130 785	75,7	43 128	29 327	5 278 555
40	139 684	80,7	36 619	24 901	5 410 157
45	165 997	95,7	31 156	21 186	5 779 671
50	172 883	99,6	26 557	18 059	5 882 106

for the energy company due to the waste heat being fed into the DH system under different scenarios (temperature level of waste heat) are shown.

Figure 29 compares the operational income and CO_2 emissions of the DH system receiving the waste heat with the reference case. A value of one in the figure indicates that either the CO_2 emissions or the operational income is at the same level as in the reference case. The extent to which the CO_2 emissions of the heat pump increase the temperature level of the waste heat is taken into account when calculating the emissions of the entire energy system.

The results show that the energy company has made a pricing model in such a way that the profitability stays fairly constant in all cases and the changes in profitability are only minor. However, it must be noted that in this study, the emphasis was only on one method of feeding waste heat into the DH system and the amount of waste heat was small. The effects on the energy system if, for example, waste heat were to be fed into the DH return pipe, were not considered in this study. The comparison of the CO_2 emissions of the DH system where waste heat was recovered with the reference case was made. Here, the CLCA method (Rinne and Syri, 2013) yielded an emission factor of 0.68 t/MWh for marginal electricity (heat pump). The results show that the CO_2 emission levels for the entire energy system increased in most cases. Only in the cases where the original temperature of the waste heat was 45 °C or above did the CO_2 emission levels

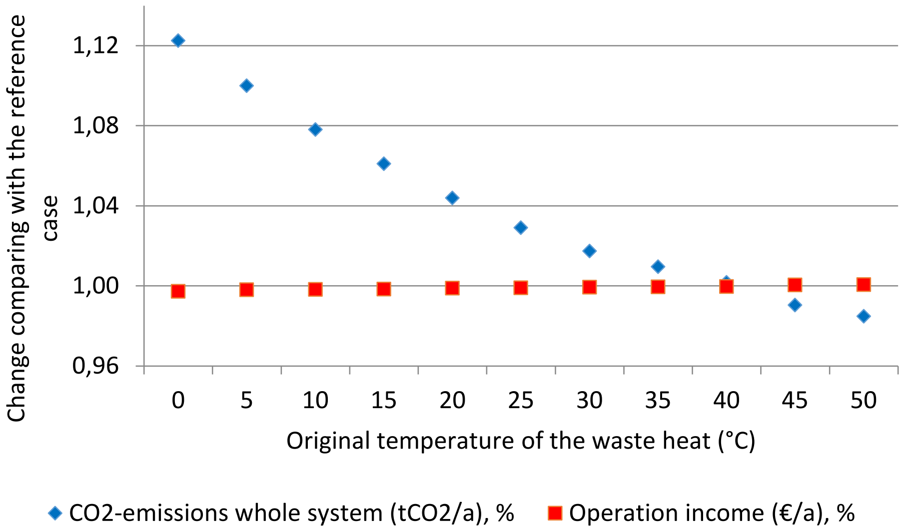

Figure 29. Comparison to the reference case. Values lower than one mean that the figure is smaller when compared to the reference case.

decrease. This was due to the fact that the lower the original temperature level of the waste heat, the more heat pump energy (electricity) must be used before the waste heat can be fed into the DH network.

7.4 Conclusions

The current study presented the concept of a new DHC business model, called Open DHC, and used a case study to evaluate its profitability and benefits for both heat customers and energy companies. It has to be emphasised that this analysis concentrated only on a single heat product (prime heat) in the Open DHC system, which was the most valuable product that we identified and which was fed into the DH supply pipe. The acceptable temperature level and the paid price for the prime heat were set by the energy company according to the outdoor temperature level. The analysis presented the generally known fact that optimising the energy system is a complicated task where different aspects are affected, such as the price of the electricity and the existing power plants. This is why the optimisation process has to be done hourly. The findings suggest that, in general, it is profitable for heat customers to sell their waste heat in situations where the price of electricity is low. In such situations, priming the temperature of the waste heat using the heat pump is affordable for the customer. The selling of the waste heat is also influenced by the outside temperature, which the energy company uses to determine the temperature of the waste heat.

Earlier studies in the existing literature give positive results for feeding industrial waste heat into DH systems when considered from both economic and environmental perspectives. However, in this study, when priming the waste heat with a heat pump was included in the emissions calculations, the emissions level of the whole system did not necessarily decrease. This was the case when the original temperature of the waste heat was under 45 °C. These results emphasise the fact that the system boundaries must be set widely for the analysis and that partial optimisation of the systems should be avoided. If the emissions level of the system were to be considered only with respect to the energy company, the level would naturally decrease with the amount of waste heat fed into the DH system because the company's own production would decrease. However, to obtain the correct results, the emissions caused by the use of a heat pump to prime the waste heat must be included in the analysis. In a low-temperature DH network, the concept of Open DHC would be more profitable, where waste heat at lower temperatures would be suitable and some of the waste heat could be fed into the DH system as such.

Despite the results from the case study, Open DHC is an interesting approach for the energy and heat markets, where increasing energy efficiency is necessary in order to meet climate policy targets. In the case of DH systems, one of the objectives in the future will be to utilise all available surplus thermal energy; the Open DHC business model is an excellent starting point for doing this because of its novel pricing method. An Open DHC system can be also considered as a flexible part of energy and DH systems where flexibility is introduced by the use of heat pumps. Such flexibility requires maintaining smart control of the heat pumps. An Open DHC system can be applied in different DH systems, but the pricing of the waste heat must be specific to every system because the price is based on the variable cost of the energy company’s own production costs.

8 Conclusions

Energy systems are evolving, and pressure to increase energy efficiency as well as the levels of renewable energy use is increasing. DH and DC businesses are expected to respond to the changing market. Beside this, they should develop and bring new ideas to the heating market to help energy systems to cope with the challenges that they are facing. The main objective of this study was to examine the special characteristics of smart energy systems and to discover how DHC systems are adapting to them. This research highlights three challenges for DHC systems, which are presented as case studies where the concentration was to study how different energy efficiency measures on the consumer side are affecting the energy-efficiency level of the DHC system and, in the end, the whole energy system. The case studies covered the areas of DH forecasting models based on remote measurements (Chapter 4), the DSM potential of district-heated residential buildings (Chapter 5), and energy-system level calculations of a case study where waste heat is utilised in the DHC network (Chapter 6). The conclusions of the case studies can be found at the ends of each respective chapter.

From the definitions of smart cities and smart energy grids, this study finds important factors for smart thermal grids. These factors reveal the challenges for DHC systems on which they especially must concentrate to stay in the forefront of energy systems development. Many of the studies concerning smart cities and smart energy systems repeat the importance of intelligence and utilisation of ICT systems. In a DHC system, this means, for example, the more efficient utilisation of consumer measurements measured and transmitted to the energy company on an hourly basis. In this area, many benefits are still not utilised such as monitoring the network’s state and correcting certain measurement errors automatically. It is also possible to develop new dynamic pricing models as well as consumption forecasting models. These possibilities are still mainly untapped since proper calculation methods and data systems are lacking. In Chapter 4, new forecasting models for DH consumption were developed, based on hourly consumption measurements from individual customers. The conclusion of this part was that the accuracy of the forecasting models varies depending on the customer but it is possible to construct more accurate forecasting models if they are based on single customers, compared to earlier studies where models were constructed based on production data from heat producers for larger areas.

Other factors highlighted in the studies of smart energy systems are their greater efficiency in both production and consumption as well as their flexibility. In DHC systems, these factors mean versatile production plants utilising local resources and heat and cold storage systems, bringing flexibility to the whole energy system. The efficiency of the energy system must be verified by simulating the system with wide system boundaries as is shown in Chapter 6. New heat and cold sources have to be explored; for example, industrial waste heat could be put to greater use. Chapter 6 presents an interesting business model called Open DHC, where customers are offered an opportunity to sell their waste heat to the thermal network. One of the initial benefits of DH and DC systems is their ability to store heat and cold. Chapter 5 discussed the possibility of residential block buildings for operating as short-term heat storage facilities to reduce the heat load peaks in the DH system without jeopardising the reliability of the heat delivery and customer satisfaction. The results showed that theoretically DSM has potential to decrease energy consumption and the momentary heat effect city-wide, but the thermal behaviour and thus the potential for DSM varies between buildings of differing ages.

8.1 Future research

Future research is needed in this area, since energy systems are evolving and DHC systems need to take advantage of such development. Research of smart energy systems has concentrated on smart electricity grids, and only a few studies can be found in the area of smart thermal grids. There is very little research in the area of DC systems, and more is needed. The reason for this is that DC systems have a relatively short history in wide scale. Studies concerning DH and DC in cities in which they are still not available are needed. These types of studies should include energy-system-wide modelling so that decision makers could see the benefits of these systems.

In forecasting energy consumption, especially DH consumption, research should continue in the area of developing DH consumption forecasts for single-family houses as well as other types of buildings. This would allow the development of different kinds of consumption profiles. Such profiles can then be aggregated into forecast models for existing and planned neighbourhoods. Consumption profiles would also allow for estimating consumption for customers with missing measurement data.

In heat storage and DSM management, future research should investigate the exact effects of DSM for the energy system using case studies. It will be necessary to study how large a share of DSM potential can be implemented in reality and how DSM will affect the operation of the energy system. This question is not unambiguous, since the optimisation of the energy system is affected by many considerations such as the structure of the system, timing of the consumption, and the electricity price at different times. The other essential future research area should cover practical implementation of heat cut. The simplest way would be to cut the heat at the heat exchanger. With this connection, the cooling will involve the whole building and the control of the system has to be done according to the rooms in which the temperature changes the most (in most cases the corner rooms). The other possibility would be to build an automated system, where every room would have a control system also in block buildings. The problem here would be higher investment costs as well as possible failure of the adjusting devices. The benefit would be longer heat reduction times.

Future research in the area of supplying waste heat to the DHC network, especially in the case of an Open DHC system, should include case-specific studies of different energy systems receiving waste heat. This study emphasises the importance of system-wide modelling, and it also reveals that it is necessary to evaluate the effects of changes in energy systems on a wide scale, including system-level optimisation with wide boundary levels. The case study presented in this paper did not answer the question of how the operation of the energy system would change if all heat trade products in the Open DHC system were in use. For example, for the waste heat operator it might be more profitable to sell the waste heat as a product called secondary heat in instances when the original temperature is not that high. Future research in this field should examine the benefits of this heat trade. It would also be interesting to assess from a technical standpoint how large amounts and varying qualities of waste heat would affect DH networks.

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