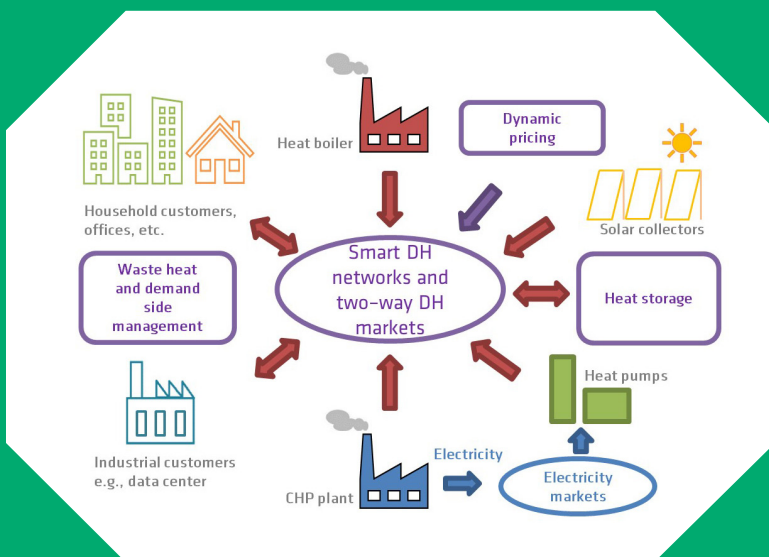


Smart low-carbon district heating networks supporting the energy system transition

Mikko Wahlroos



Smart low-carbon district heating networks supporting the energy system transition

Mikko Wahlroos

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Abstract

Heating and cooling sector represents approximately 50% of the total energy consumption in the EU. The European Commission has begun to put more emphasis on the heating and cooling sector by publishing the EU strategy on heating and cooling. District heating (DH) is one of the most efficient heating solutions, especially in the colder regions with high population density. The amount of DH based heat production has remained on a rather stable level during the past decade. Furthermore, DH has been mainly produced with fossil fuels nowadays, and in order to tackle the emissions of heat production, current DH systems are facing a transition towards cleaner and more cost-efficient production.

This dissertation investigates increasing smartness in DH networks and assesses the introduction of new heat sources to DH networks. In this context, smart DH networks stand for cost-efficient, low-carbon networks that allow prosumers to gain market access to sell their heat to DH networks. This dissertation models increasing the amount of additional heat supply by heat pumps (HPs), solar thermal production, and data center (DC) waste heat in existing DH networks in Finland. Furthermore, the potential for low-temperature DH networks and dynamic pricing of DH production is studied, as well as the future for biomass based combined heat and power (CHP) production in the EU-27.

The results of this thesis indicate that increasing the amount low-carbon DH production technologies decreases utilization of existing units, mainly CHP based heat production and heat-only boilers. Decreasing operational hours of CHP units may decrease the profitability of these units, and the future of CHP is at risk. The current investment environment in the EU does not suggest that biomass CHP would contribute significantly to overall energy efficiency. The results suggest that HPs and DC waste heat would be a suitable alternative for low-carbon DH production, and they could supply heat with high operational hours. DCs can supply heat on a stable level but there are still many barriers slowing down DC waste heat utilization, mainly related to business models between different parties. However, if alternative heat production capacity is not owned by the DH companies, the pricing structure of district heat production should be assessed. Pricing for third-party heat should be transparent so that the utilities can easily assess whether the investment is profitable. Solar thermal production is not feasible for a large-scale DH network in Finland with the current price level, but they could benefit from lower distribution temperatures. Additionally, lower distribution temperatures would increase profitability of HPs and potential for additional low-temperature waste heat supply.

Keywords District heating, Heat production, Energy efficiency, Data center, Heat pumps, Combined heat and power production, Flexibility, Two-way heat markets

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Tiivistelmä

Lämmitys ja jäähdytys vastaavat noin 50% EU:n kokonaisenergiankulutuksesta. Euroopan komissio on alkanut korostaa lämmitys- ja jäähdytyssektoria julkaisemalla lämmitystä ja jäähdytystä koskevan EU:n strategian. Kaukolämpö (KL) on eräs tehokkaimmista lämmitys- ja jäähdytysmenetelmistä erityisesti kylmemmillä ja tiivistä asutetuilla alueilla. KL:llä tuotetun lämmityksen määrä on pysynyt melko vakaalla tasolla viimeisen vuosikymmenen. Nykyään KL tuotetaan pääasiassa fossiililla polttoaineella ja KL-tuotannon päästöjen vähentämiseksi nykyiset KL-järjestelmät kohtaavat murroksen kohti vähähiilisiä sekä kustannustehokkaampia järjestelmiä.

Tässä väitöskirjassa tutkitaan älykkyyden lisäämistä kaukolämmityksessä sekä arvioidaan uusien tuotantomuotojen käyttöönottoa KL-verkoissa. Tässä kontekstissa älykkäillä KL-verkoilla tarkoitetaan kustannustehokkaita, vähäpäästöisiä verkkoja, joissa mahdollistetaan kuluttajien oman lämmöntuotannon myyminen KL-verkkoihin. Tässä väitöskirjassa mallinnetaan lämpöpumppujen, aurinkolämmön, sekä datakeskusten hukkalämmön lisäämistä olemassa oleviin KL-verkkoihin Suomessa. Tämän lisäksi työssä tutkitaan mahdollisuuksia matalammille lämpötiloille KL:n lämmönjakelussa ja KL-tuotannon dynaamiselle hinnoittelulle, sekä arvioidaan biomassaan pohjautuvan yhteistuotannon (CHP) tulevaisuutta Euroopassa.

Tämän väitöskirjan tulokset osoittavat, että vähäpäästöisempien lämmöntuotantomenetelmien lisääminen KL-verkkoihin vähentää erityisesti CHP-laitosten sekä lämpökattiloiden lämmöntuotantoa. Matalammat käyttötunnit CHP-laitoksilla heikentävät laitojen kannattavuutta, minkä vuoksi CHP-tuotannon tulevaisuus on epävarmalla pohjalla. Tällä hetkellä vaikuttaa, että biomassan CHP:n osuus ei tule kasvamaan merkittävästi EU:ssa ja biomassaa tullaan käyttämään vähemmän energiatehokkaasti. Tulosten perusteella lämpöpumput sekä datakeskusten hukkalämpö soveltuvat hyvin vähäpäästöisen tuotannon lisäämiseen ja molempien tuotantomuotojen käyttötunnit voisivat olla korkealla tasolla nykyisissä järjestelmissä. Datakeskukset pystyvät toimimaan tasaisina lämmöntuottajina, mutta hukkalämmön hyödyntämiselle on yhä useita, pääasiallisesti liiketoimintamalleihin liittyviä esteitä. Mikäli vaihtoehtoinen tuotantokapasiteetti ei ole KL-verkon haltijan omistuksessa, KL-tuotannon hinnoittelu vaatii uudelleenarviointia. Kolmannen osapuolen tuottaman lämmön myynti KL-verkkoon tulisi olla läpinäkyvää sekä ennustettavaa, jotta kolmansien osapuolien on helpompi arvioida investointien kannattavuus. Aurinkolämmön hyödyntäminen nykyisissä suuren kokoluokan KL-verkoissa ei vaikuta erityisen kannattavalta Suomessa nykyisillä hinnoilla. Matalammat lämmönjakelun lämpötilat parantaisivat lämpöpumppujen kannattavuutta ja lisäksi sekä aurinkolämmön että hukkalämmön hyödyntämispotentialia.

Avainsanat Kaukolämpö, Lämmöntuotanto, Energiatehokkuus, Datakeskus, Lämpöpumppu, Yhdistetty sähkön- ja lämmöntuotanto, Joustavuus, Kaksisuuntaiset lämpömarkkinat

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to be satisfied with my research, as well as to continue learning new tricks and methods, even in the final steps of finalizing my dissertation.

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Helsinki, February 20th, 2019
Mikko Tapio Wahlroos

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List of Abbreviations and Symbols

ALCA	attributional life-cycle assessment
BAT	best available technology
BAU	business as usual
CHP	combined heat and power
CLCA	consequential life-cycle assessment
CO ₂	carbon dioxide
COP	coefficient of performance
CRAC	computer room air conditioning
DC	data center
DH	district heating
DSM	demand-side management
EC	European Commission
ERE	energy reuse efficiency
EU	European Union
FLH	full-load hour
HOB	heat-only boiler
HP	heat pump
HVAC	heating, ventilation, and air conditioning
IPCC	Intergovernmental Panel on Climate Change
LCA	life-cycle assessment
LTDH	low-temperature district heating
NREAP	national renewable energy action plan
PUE	power usage effectiveness
RES	renewable energy source

SC	solar collector
TES	thermal energy storage
TPA	third-party access
4GDH	fourth generation district heating

List of Publications

This doctoral dissertation consists of a summary and of the following publications, which are referred to in the text by their numerals:

- I.** Wahlroos, Mikko; Cross, Sam; Syri, Sanna. 2014. Prospects for biomass use in large power plants in the EU-27 and the role of Combined Heat and Power production. IEEE 11th International Conference on the European Energy Markets (EEM), Krakow, Poland, 28–30 May, 2014. Pages 1–5. DOI: 10.1109/EEM.2014.6861250
- II.** Wahlroos, Mikko; Pärssinen, Matti; Rinne, Samuli; Syri, Sanna; Manner, Jukka. 2017. Utilizing data center waste heat in district heating – Impacts on energy efficiency and prospects for low-temperature district heating networks. Elsevier. Energy, volume 140, issue 1, pages 1228–1238. ISSN: 0360-5442. DOI:10.1016/j.energy.2017.08.078.
- III.** Wahlroos, Mikko; Pärssinen, Matti; Rinne, Samuli; Syri, Sanna; Manner, Jukka. 2018. Future views on waste heat utilization – case of data centers in Northern Europe. Elsevier. Renewable and Sustainable Energy Reviews, volume 82, issue 2, pages 1749–1764. ISSN: 1364-0321. DOI:10.1016/j.rser.2017.10.058.
- IV.** Rämä, Miika; Wahlroos, Mikko. 2018. Introduction of new decentralised renewable heat supply in an existing district heating system. Elsevier. Energy, volume 154, pages 68–79, ISSN: 0360-5442. DOI: 10.1016/j.energy.2018.03.105.
- V.** Dominković, Dominik Franjo; Wahlroos, Mikko; Syri, Sanna; Pedersen, Allan Schrøder. 2018. Influence of different technologies on dynamic pricing in district heating systems: comparative case studies. Elsevier. Energy, volume 153, pages 136–148. ISSN: 0360-5442. DOI: 10.1016/j.energy.2018.04.028

The Author's Contribution

Publication I: Prospects for biomass use in large power plants in the EU-27 and the role of Combined Heat and Power production

Wahlroos is the main author. Wahlroos and Cross planned the structure of the paper. Wahlroos collected information on plant projects and data from National Renewable Energy Action Plans (NREAPs). Scenarios were developed together by Wahlroos and Cross. Wahlroos wrote the paper, while Cross and Syri provided comments and checked the language.

Publication II: Utilizing data center waste heat in district heating – Impacts on energy efficiency and prospects for low-temperature district heating networks

Wahlroos and Pärssinen are the main authors. The concept was planned with Wahlroos, Pärssinen, and Syri. Wahlroos conducted simulations with EnergyPRO and analyzed the results. Pärssinen did statistical analysis on waste heat availability. Wahlroos and Pärssinen wrote the paper, while Syri and Manner provided comments.

Publication III: Future views on waste heat utilization – case of data centers in Northern Europe

Wahlroos and Pärssinen are the main authors. Wahlroos, Pärssinen, and Syri planned the concept of the paper. Wahlroos carried out the literature review and studied current projects for data centers. Pärssinen provided analysis for business cases for data center operators. Rinne provided lifecycle assessment calculations in the paper. Wahlroos and Pärssinen did the majority of the writing, while Rinne wrote the lifecycle assessment part. Syri and Manner provided comments on the paper.

Publication IV: Introduction of new decentralised renewable heat supply in an existing district heating system

Rämä is the main author. The concept of the paper was structured by both authors. Rämä wrote the majority of the paper and analyzed most of the results. Wahlroos conducted the simulations in energyPRO and participated in the writing process and analyzing results. Data collection was done by both authors.

Publication V: Influence of different technologies on dynamic pricing in district heating systems: comparative case studies

Dominković is the main author. The concept of the paper was planned by Dominković and Wahlroos. Dominković developed and analyzed the Sønderborg case study, and Wahlroos developed and analyzed the Espoo case study. Dominković and Wahlroos collected data for their respective case studies. Dominković provided a detailed literature review and the majority of the writing in the results, while Wahlroos participated in the writing process. Syri and Pedersen provided comments on the paper.

1. Introduction

1.1 Background

Heating and cooling consume 50% of the total energy consumption in the European Union (EU). Fossil fuels are the most common sources for heating and cooling (84% of the total heating and cooling generation), and 90% of the gas consumption in the EU goes to heating buildings [1]. Heating costs represent, on average, 16% of the total spending of households in the EU.

District heating (DH) is one of the most common methods of heating in Europe, and DH has supplied approximately 2.5 EJ of heat annually in Europe since 1990 [2]. DH provides significant amounts of energy, for example in Northern and Eastern Europe, with utilization levels reaching over 50%. However, the amount of supplied heat has remained at a somewhat stable level, and therefore DH cannot be considered a growing market. In DH, heat is typically produced in centralized production units and heat is distributed to consumers via pipelines. As DH is already a mature technology and well developed in several countries, most of the development of DH would focus on existing networks rather than new-built networks. Therefore, the critical issue of DH is how existing DH networks react to an energy system transition.

Energy systems are aiming towards carbon neutrality with a growing share of variable renewable electricity generation as well as a growing share of renewable heat. While the primary focus has been on electricity markets, the heating sector requires attention. Due to high fossil fuel consumption, the heating sector is the primary source of greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC) published a special report in October 2018 in which they stated that rapid changes are needed in order to limit global warming to rising 1.5°C above pre-industrial levels [3]. The IPCC considers heating as one of the most important sectors in which to decrease CO₂ emissions. The IPCC has suggested that DH networks should become more intelligent through tri-generation and introducing heat storage, as well as through increasing the utilization of waste heat¹ [4]. Over 50% of heat is wasted, and it has been estimated that waste heat could cover the whole heat demand of buildings [1].

¹ In this thesis, *waste heat* refers to a by-product or excess heat from the industry, infrastructure, or service sectors. *Waste heat* should not be confused with heat from waste incineration plants.

Most of this waste heat is not utilized due to the lack of distribution networks, such as DH networks.

One of the most significant problems on the building side is insulation, and therefore energy efficiency is highly essential on the EU level. The European Commission (EC) has suggested that 70% of heat consumption could be cut with the better insulation of buildings. However, many households lack the money to invest in better insulation. Moreover, it has been suggested that merely replacing building- or apartment-specific boilers that burn coal, oil, or natural gas and increasing DH system based on combined heat and power (CHP) can decrease primary energy consumption by 3.7% or 7.0% with DH market shares of 30% or 50% respectively [5].

How to implement the ambitious targets proposed in the EU Strategy on Heating and Cooling is a challenge and the transition to entirely carbon-neutral DH systems requires a clear pathway through a transition period of the existing DH networks. Multiple solutions have been proposed for how to develop DH in order to reach the emission targets and increase both energy and cost effectiveness. These solutions include the higher utilization of renewable energy sources² (RESs), developing heat transmission, increasing sectoral integration with electricity, increasing customer interaction in the markets, and providing new flexibility solutions, such as demand side management and storage [1], [6]. Also, increasing the amount of district cooling is prominently envisioned, which would increase the efficiency of district energy networks.

Many studies have presented frameworks for the future DH systems and have discussed the new technologies required to decarbonize DH [5], [7]–[11]. Most of these studies suggest piloting new technologies and implementing case studies. Different technologies have been compared to each other but introducing new technologies into existing networks often lacks detailed cost and emission comparison. Since DH development will mainly occur in existing networks [2], the transition period between existing heat production portfolio and future carbon-neutral DH networks must be studied in detail in existing DH networks.

Due to the reasons presented above, DH systems are facing a transition towards less carbon-intensive systems and towards smarter systems. A market opening is required in DH in order to be able to compete with alternative heating options. The scope of this research and the structure of this thesis are presented in the following chapter.

² According to the EC, renewable energy sources include wind, solar, hydro, tidal, geothermal, and biomass sources.

1.2 Research Scope and Structure

This thesis is a result of several research projects, which addressed bioenergy (BEST project), future European energy markets and sustainable transitions of the heating sector (STEEM project) and developing more intelligent control of energy use in buildings (REINO project). The aim of the BEST project was to build up understanding on future business potentials related to bioenergy for both energy and forestry sectors, while the purpose of the STEEM project was to provide a better understanding on the interaction between electricity and heating systems as well as to model European energy markets and transmission network. REINO project focused on developing intelligent control of energy use in residential and office buildings together with Finnish companies. The following research questions are based on the aims of abovementioned projects. In addition, studies on sustainable solutions for data centers were one of the focal points of research conducted with the help of Fortum Foundation scholarships.

The contribution of this thesis can thus be formulated as answering the following research questions:

Q1. What is the impact of different DH production technologies on cost efficiency and carbon dioxide (CO₂) emissions in future DH systems?

Q2. What are the prospects for biomass CHP to increase energy efficiency in the EU-27 according to the NREAPs?

Q3. What are the prospects for data center (DC) waste heat utilization in cold climate DH systems and what are the benefits for both DH network operators and DC operators?

Q4. How could the dynamic pricing of heat production help the current DH production system and what would be the impacts on a system level?

Q5. What benefits could low-temperature district heating (LTDH) networks bring on a system level?

This thesis investigates the impacts of different low-carbon production technologies on DH systems in the future. The analysis is based on the following criteria: cost and energy efficiency, flexibility, and decreasing CO₂ emissions. Also, the pricing of heat production is studied in order to analyze how heat production pricing could increase third-party access (TPA) and how it would affect energy and the cost-efficiency of the network. Furthermore, the effects of a lower distribution temperature on further increasing energy efficiency are studied.

Cost effectiveness is essential in DH systems. Typically, DH competes with alternative heating solutions, for example, direct electric heating, heat pumps

(HPs), and individual boilers. DH needs to remain competitive against other solutions. In recent years, the price of DH has increased, and it may not be such an efficient solution as it was a few decades ago. This is also partly due to the requirements for connecting to the DH network, if this is possible. Fossil fuels have commonly been the most cost-efficient solution for producing district heat, but due to increasing fuel costs (partly due to the increase in CO₂ emission costs), alternative solutions could become more attractive. Cost efficiency is strongly linked to the price of electricity in most cases.

Flexibility solutions are further needed in order to tackle the issue of the variation between demand and supply. Flexibility can be obtained, for example, by heat storage or demand-side management (DSM). Introducing a two-way heat market – in other words, consumers can produce heat and sell it to a DH network – would make it easier for decentralized heat producers to enter the heat markets and thus increase the flexibility of the DH network system. This would also lead to increased end-consumer participation in the heat markets.

As targets have been set in the global climate policy for the development of RESs, the DH networks need to seek the most efficient solutions. DH production is still market driven, and thus the solutions must be both energy efficient and cost-efficient. Renewable heat can be produced using various RESs (including biomass, solar heat, geothermal, or electricity sources) with a low CO₂ emission factor.

Figure 1 shows the connections between different publications regarding the individual viewpoints of the study. The color of the arrows indicates whether the publication focuses on building a framework for future studies (blue) or if the publication presents the results of a viewpoint (red).

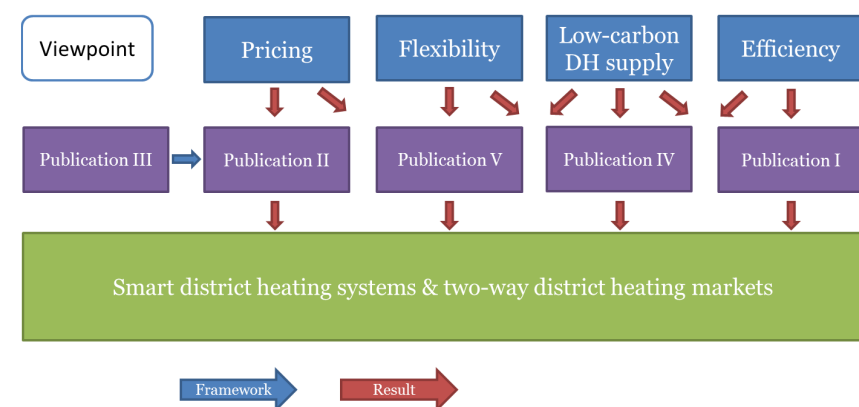


Figure 1. The studied viewpoints and the contribution of individual publications.

1.3 The scope of the thesis

This thesis summarizes the outcomes, methods, and analysis in the following publications. The individual research questions of each publication are presented in Table 1.

The focal point of this thesis is modeling and simulating DH with new production capacity and considering how to utilize resources best. Modeling is required in order to study the benefits of different options for the network and production levels. This thesis aims at modeling the introduction of different low-carbon alternatives to existing DH networks in Finland in order to evaluate the system-level impacts of new low-carbon heat production capacity.

Table 1. The research questions of the individual publications.

Publication I	<p>What are the aims of the EU-27 Member States regarding biomass utilization? Is the focus more on heat or electricity?</p> <p>How does the future look like for biomass-based CHP in Europe on a larger scale?</p> <p>What is the role of biomass CHP in decreasing primary biomass demand among the EU-27?</p>
Publication II	<p>Is the DC load reliable and stable for DH?</p> <p>How would DC waste heat utilization affect other production in an existing large-scale DH system?</p>
Publication III	<p>Can waste heat from DCs be efficiently used in DH?</p> <p>What do business models look like for selling the waste heat from DCs from the perspectives of both DCs and DH?</p> <p>What is the current situation with DCs as a waste heat source?</p>
Publication IV	<p>Is it profitable to replace existing fossil fuel capacity with HPs or solar thermal production regarding cost and emissions?</p> <p>What are the system-level implications of heat production based on new low-carbon investments?</p> <p>How would a lower DH temperature benefit HP or solar thermal production and what are the overall implications on a system level?</p>
Publication V	<p>What is the potential effect of dynamic pricing based on the marginal costs of DH systems?</p> <p>What would be the impact of introducing low marginal cost heat production on CO₂ emissions?</p> <p>How would individual heat storage contribute to the network with dynamic pricing?</p>

Since DH network development mostly focuses on existing networks, our case studies focused on existing, well-developed networks in Finland. The focus was on medium- to large-scale systems.³ Long-term planning is essential in DH

³ Annual DH consumption of over 2000 GWh.

networks, and due to the current political and economic environment, investments in new capacity contain high risks.

In the publications, energy systems are simulated on a city-level, mainly by employing publicly available data, gathered from different utilities. The structure of this thesis is as follows. Chapter 2 discusses the current challenges with DH networks, the concept of smart DH networks, and the studied solutions to help the transition of DH towards having smarter energy systems. The methods and tools used in this dissertation and the publications are presented in Chapter 3. Chapter 4 summarizes the results of the individual publications in the context of smart DH systems. The results are set against the viewpoints presented in Section 1.2. The main findings of the work presented in this dissertation are discussed and summarized in Chapter 5.

2. The literature review and contribution of this dissertation

This section presents a literature review of individual issues, technologies, and the current situation with DH in Finland. Challenges are put into the perspectives of the main viewpoints, and most importantly, the concept of smart systems is presented in Section 2.2.

2.1 The role of DH in Finland and other Nordic countries

DH has traditionally supplied most of the heat in the Nordic countries, except for Norway. Finland and Sweden use more process heat than Denmark, but space heating still represents over 50% of the total heat consumption in Finland [12].

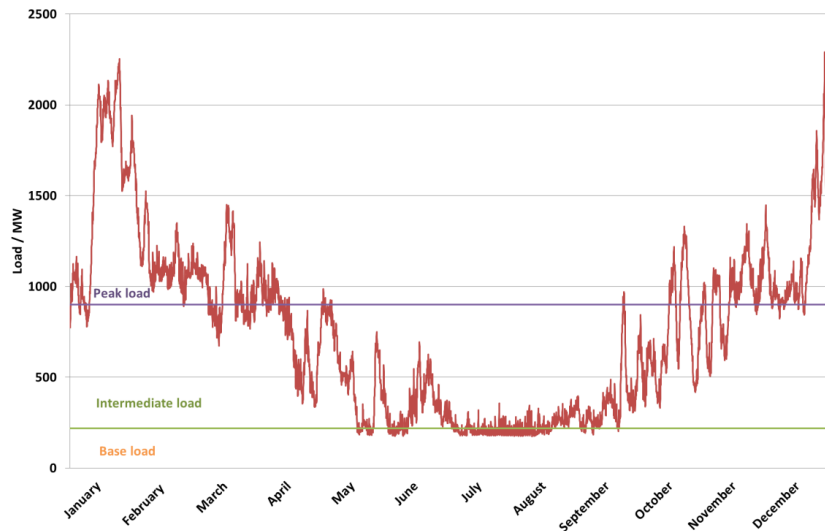


Figure 2. The annual hourly DH load in a simulated large-scale DH network. The red curve represents hourly DH load. The horizontal lines represent different categories of heat load, e.g., base load, intermediate load, and peak load.

Figure 2 presents the annual hourly DH demand in a typical DH network in Finland. Compared to electricity demand, DH demand has more seasonal fluctuation. In the summertime, base load can be easily supplied with low

marginal production cost plants, such as large-scale CHP plants and HPs. Covering the peak load is typically the critical issue in DH profitability. Peak load is often produced by heat-only boilers (HOB) that have a low-investment cost but high marginal cost and are often based on fossil fuels. Peak production is both expensive and often emission intensive, and thus cutting peak production is one of the main challenges for DH network operators.

In many countries, DH is heavily regulated. For example in Finland, DH networks are natural monopolies inside the network. Networks have commonly been operated by local municipal companies, which have made the investments in both DH infrastructure and heat production units. Only the largest external producers who produce high-quality heat⁴ gained access to the network via bilateral contracts. However, in Finland, it is often not mandatory to connect to a DH network. In 2018 the Finnish government proposed that the mandatory requirement to connect to a DH network should be revoked in all networks in the near future.

For the last ten years, the prices of DH have increased for the customers in both Finland and Sweden [13], [14]. DH prices have increased due to the increase in fuel costs and changes in taxation, as well as due to investments in new grid infrastructure. Therefore, other heating solutions have gained momentum, mainly due to the emergence of new, more efficient HP solutions. Consumer-level HP solutions have become more attractive for individual customers on both detached housing and block apartment levels. For example, the Finnish energy utility ST1 offers households and block apartments an alternative where the customer does not need to invest in HPs themselves, but they pay for the company a transparent and stable price for the heat, quite like in DH [15]. Current challenges related to DH are further discussed in Section 2.2.

2.2 DH markets and smart DH networks

The EU started to push for energy market liberalization at the end of the 20th century, but the focus has been more on electricity and gas markets rather than on the heating sector. DH was left out of the immediate scope at the beginning. One crucial goal of the transition was to oblige the operators of transmission and distribution systems to grant equal access to the infrastructure to all the interested parties.

2.2.1 CHP and the connection of DH markets to electricity markets

CHP production has been a pivotal part of DH in many countries. For instance, back-pressure CHP plants supplied 73.4% of the total DH produced in 2015 [16]. In Finland and Sweden, there are many large-scale CHP units (>50 MW), while in Denmark, CHP plants are commonly small biogas-based units. CHP is highly

⁴ In this thesis, *quality of heat* refers to the timing, temperature, and quantity of heat.

efficient and supplies both electricity and heat, but still, most of the CHP units run on fossil fuels. In October 2018 Finnish Energy and Environmental Policy outlined that producing electricity or heat with coal will be banned from May 1st, 2029 [17], which especially affects larger DH networks in Finland.

Due to electricity production from CHP units, DH is closely linked to electricity markets as production profitability often relies on electricity prices. In the current situation, electricity is cheap in Finland and CHP plants are struggling with profitability. Low spot market electricity prices have also been reflected in the overall production costs of DH network operators, which has led to an increase in consumer prices. Furthermore, the current, large CHP plants cannot be ramped up or down according to very short-term changes in, for example, the market prices. Helin et al. proposed that a significant increase of HPs connected to CHP plants could also increase the profitability of CHP when electricity prices are low [18].

2.2.2 Smart DH systems

In this thesis, *smart DH systems* are defined as follows: a cost-efficient, two-way market, which utilizes waste heat sources and renewable energy on an efficient basis. The pricing of heat production in DH should be transparent so that TPA is possible for external producers. Smart district systems aim at carbon neutrality and empowering customers to produce heat and sell excess heat to DH markets. Smart systems require both technical and economic reconstruction compared to existing, typically rigid, DH networks.

Smart energy systems have been widely discussed in recent years across all energy sectors. Sectoral integration between different energy systems (e.g., electricity, heat, and gas markets) has been one of the key elements in the discussion. The concept of smart DH is integral in developing existing DH systems so that they are more cost efficient and environmentally friendly. Fourth generation district heating (4GDH) is a concept first proposed in [14]. The focus of 4GDH is on integrating DH and cooling with the surrounding systems, LTDH networks, promoting low-carbon sources, and increasing customer interaction in DH. DH networks should be used to balance electricity production by utilizing electricity-based production through RESs. A low distribution temperature (e.g., 40–65 °C) is at the core of the concept as it enables low heat losses in distribution and, more significantly, the efficient integration of renewable and excess heat sources [8], [9], [19]. Combining energy supply design with long-term infrastructure planning processes, such as city planning, is also a part of the concept. The following subsection discusses the concept of two-way DH markets and TPA.

2.2.3 The pricing of DH production and two-way DH markets

As was stated in Section 2.1, DH consumer prices have increased in Finland, which has decreased the competitiveness of DH compared to other heat

production technologies. The pricing of district heat for consumers has typically relied on rigid pricing mechanisms, typically agreed one year in advance, which does not reflect the actual momentary production costs of the heat production. DH prices for customers consist of connection, capacity, and energy fees. There has been some development in DH pricing in recent years, and some DH companies offer a seasonal pricing option in which energy fees are lower in summer and higher in winter, alongside the classical rigid pricing structure. However, seasonal pricing does not reflect hourly production costs at all. In this thesis, the pricing of DH for consumers was not studied in detail, but the focus is on pricing on the production side and how it could be better reflected for consumer prices.

Sweden already started deregulating DH markets in 1996, and they have gone the furthest in liberalizing heat markets. However, the cost-based approach is still dominating heat markets, and liberalized markets have not evolved as was hoped [20]. The pricing of DH and the allocation of costs in CHP plants have been studied in [21], and the authors suggested that marginal cost-based pricing would bring various benefits to the system. These benefits include the better representation of production costs, reflecting heat markets to the customers, and motivating heat suppliers to reduce the costs of heat production as they need to compete in the market. Sun et al. proposed two methods for marginal pricing, namely setting the electricity price and entropy drop, but their methods could not reflect the changes in different heat production technologies [22].

The concept of prosumers has emerged in both the electricity and heat sectors in recent years. As prosumers, industrial and individual consumers can both produce their heat and sell excess heat to the grid. Several studies have suggested that prosumers could have a notable impact on increasing the efficiency of the DH network [23], [24]. Paiho et al. identified opening DH markets for prosumers as one of the most influential aspects of tackling the challenges affecting energy production and energy efficiency that were presented in the EC's communications [17]. Some market openings on the production side have happened in recent years in the Nordic countries. For example, the large energy utility Fortum openly publishes DH procurement prices on their websites for three networks in Finland, and in Stockholm, Sweden, Stockholm Exergi (previously Fortum Värme) publishes prices.⁵ Also, DH networks in Aarhus and Copenhagen in Denmark have somewhat dynamic pricing in their networks [25].

In two-way DH markets, heat can be both bought from the market and sold to the market. In many cases, it is not possible to sell heat to the network nowadays. In Finland, the forestry sector has been widely using their process

⁵ For more information on the prices in Finland, see Fortum's webpage (in Finnish) <https://www.fortum.fi/yrityksille-ja-yhteisoille/lammitys/kaukolampo-o/avoin-kaukolampo/avoin-kaukolampo-ostohinnat>
For more information for prices in Sweden, see Stockholm Exergi's webpage <https://www.opendistrictheating.com/>

residues for energy production. Process heat has been used for personal consumption and excess has been sold to DH networks. TPA in DH has typically relied on bilateral agreements between the DH network operator and heat producer. Thus, transparency in DH markets has been missing, and it has been hard for lower quality heat producers to assess the profitability of selling heat to the network. One of the critical questions in two-way markets is also the security of supply. It is essential that the security of supply remains and the capacity must remain there during the coldest periods.

There are multiple market models for two-way DH markets, for example, three different models have been proposed in [26]. Open DH markets, where the network is separated from the heat sales, have been proposed, but the profitability has been questioned [26]. Two-way district markets may be hard to utilize in smaller networks, where there are only one or few production units, as it may many times more beneficial to operate the existing units to their full capacity.

2.3 Biomass use in heat production

Biomass has been a common source for DH in several countries in the EU, and residual wood has been used to produce heat for decades, both in the forest industry and in both DH and individual heating. The EU-27 Member States submitted their NREAPs in 2010 to help the EU reach its target of generating 20% of its energy consumption with RESs by 2020. Many countries plan to increase the share of biomass in electricity, heating, and transport sectors. The targets set by each Member State have raised a question related to the availability of primary biomass in Europe. If the Member States reach their ambitious goals, importing biomass to EU would drastically increase [27]. Therefore, biomass should be used as efficiently as possible.

Even though it has been proposed that biomass could be a useful policy tool to decrease emissions and increase GDP per capita [28], sustainability issues have been a significant concern for efficient biomass utilization [29]. The EC published a working paper on sustainable biomass use, in which they promote the efficient use of biomass, increasing the amount of CHP, and expanding DH networks [30]. The use of primary biomass should be questioned in electricity- or heat-only production. If the sustainability issues come to have even more attention, biomass should be utilized as efficiently as possible. Improving the efficiency of biomass utilization saves primary energy and the demand for biomass decreases.

2.4 Low-carbon DH production technologies and flexibility solutions

A brief outlook of the low carbon technologies for smart DH systems studied in this thesis is presented in the subsections below. The implementation of the

technologies below requires a detailed examination of the existing system. Decreasing the carbon emissions of the energy system is the ultimate goal, but achieving that target requires techno-economic analysis of the system-level implications. System-level assessment is required not only for selecting the most reasonable option for developing the system, but also for sharing the benefits of increased efficiency and creating transparency in a system with, for example, multiple suppliers of heat.

The system-level effects of flexibility in DH need to be addressed. The two most promising solutions (excluding sector coupling) for flexibility in DH are heat storage and DSM. DSM for DH has been proposed as one potential flexibility provider for the system [31], [32], but it was not studied in this thesis. Subsection 2.5.2 discusses the role of storage.

Large-scale HPs are one of the leading technologies planned for decarbonizing DH. HPs have already been implemented in many countries, and different heat sources have been studied. In [33], Lund et al. discussed the socioeconomic potential of large-scale HPs in the context of the power-to-heat concept in Denmark, evaluating the potential for large-scale HPs to be 2–4 GW_{heat}. Lund and Persson [34] introduced the mapping and quantification of heat sources for HPs, stating that heat sources are widely available, larger heat sources are typically found in larger cities, and concluded by saying that seawater will have a substantial role as a heat source in the future Danish energy system. Back et al. analyzed HP competitiveness in the Greater Copenhagen area [35], concluding that HPs reached 3500 full-load hours (FLHs) in a distribution network with a lower temperature level, which suggests that heat pumps would be profitable. Levihn studied a combination of CHPs and HPs in order to balance renewable electricity production within the Stockholm DH system based on empirical data of a real, existing system [36]. Vesterlund et al. investigated the DH system in Kiruna with multiple sources of heat by running an optimization of a model that included the distribution network and the location of the supply units [37]. The study concluded that while the most efficient units were used regardless of the location, they could help in maintaining the lowest possible temperature level within the network needed by the consumers. Helin et al. showed that the addition of HP capacity (0–2000 MW) decreased the operational costs of DH by 8–12%, and consequently market electricity prices increased by 0–40% in the Nordic markets in that model [18].

Solar collectors (SCs) represent another widely studied source of renewable heat. SCs can be used as large-scale, centralized installations or as distributed units in DH, and in combination with thermal energy storage (TES). Winterscheid et al. [38] considered a solar-assisted DH system where a fossil-based CHP unit was used as the primary source of heat, providing a methodology to avoid the overdimensioning of solar systems and storage. They have also proposed that solar thermal systems work well with CHP-based

production in future energy systems with electricity price variations due increased production of electricity by solar panels. Soloha et al. [39] have presented a case study in Latvia with SCs and suggesting that TES could reach a solar fraction of up to 78%. With additional energy efficiency measures included, a fraction of 95% could be reached in the studied case. Both of the aforementioned studies show that SCs paired with TES are a viable solution for reducing emissions in DH systems with a fossil fuel-based heat supply. Rämä and Mohammadi [40] compared distributed and centralized SCs with the same total investment in a small-scale DH system, concluding that a centralized SC plant connected to DH outperforms the distributed systems.

The EC has also proposed large-scale geothermal solutions as one of the technologies for DH. Iceland is one of the forerunners of utilizing geothermal heat, with 89% of the space heating being supplied with geothermal energy in 2013 [41]. Such an efficient system as in Iceland, however, may not be as profitable in most other countries since there the heat needs to be recovered from deeper underground. Drilling technologies have developed in recent times, and deep geothermal solutions have been studied, for example, in Finland [31]. The costs of drilling up to seven or eight kilometers are poorly known, and therefore the economic potential is as yet unclear. It must be noted that deep heat solutions may provide large capacities, and even excessive capacity, for smaller networks.

The sources for low- or high-quality waste heat are many, and most of the high-quality solutions are already utilized. Heat can be recovered from industrial processes, wastewater, and exhaust air. Although heat recovery from excess heat sources is more of an energy efficiency measure, it is often also categorized as *renewable*. HPs can be used to improve the temperature of the heat source. In this thesis, the focus was on DC waste heat. DC waste heat could provide waste heat in large volumes, even though the waste heat may not seem to be of high enough quality. However, there are options for boosting the temperature.

2.4.1 Waste heat utilization from DCs

The amount of DCs is rapidly growing due to the constant increase in data processing. It is estimated that DCs already accounted for 1.1–1.5% of the world's total electricity consumption in 2010 [42]. Almost all of the electricity converts to excess heat; Lu et al. have suggested that 97% of the waste heat could be captured from an air-cooled DC [43]. The biggest challenge that waste heat utilization faces is that heat is a byproduct, which needs to be removed, but selling the waste heat is not the primary business. DCs lack the know-how and the opportunities to utilize excess heat.

Different methods for the utilization of waste heat from DCs have been studied, mainly in Nordic countries, the Netherlands, and Spain. DC waste heat could be used to preheat feeding water in power plants, which would increase

the energy efficiency of the power plant and save CO₂ in the process [44]. Ebrahimi has proposed a payback time of 4–5 years for retrofitting an absorption cooling machine in a DC in order to capture waste heat in a 10 MW DC. Davies et al. studied the integration of DC waste heat in London, suggesting that waste heat utilization would be beneficial, regarding cost savings, in replacing natural gas-based heat production [45].

Location is highly essential for DCs. Electricity costs account for most of the operational costs, but location also limits the availability of cooling solutions and the rent of the DC facility. Furthermore, DCs require a stable political environment in order to analyze long-term investments. Nordic countries provide a suitable environment for DCs in many aspects, and therefore the profitability of waste heat utilization merits assessment.

2.4.2 Heat storage

A need for energy storage has been identified as one of the major components in future energy systems [46]. TES is already a mature technology that can provide a cost-efficient solution for addressing the need for flexibility due to variable renewable energy used in electricity generation, such as solar and wind power. In 2012, the price for TES was 50 times lower than when Li-ion batteries are used to store electricity [47]. TES is already widely used in Denmark in combination with solar thermal plants. TES is cost-efficient, and the current technologies allow scaling the solutions for large-scale solutions. Heat storage is typically located next to a particular power plant and operated by the DH network operator. Novel technologies, such as phase change materials, are studied, but these have not yet proved to be cost-optimal solutions for commercial purposes [48].

Studying different applications for storage is essential. Heat storage can operate both for the short term and the long term, depending on the storage solution and technology. In short-term operation, the perspective is balancing heat production, for example, on a daily level and avoiding the most expensive peak production. Seasonal storage can be used to store heat during summertime and heat can be used in a DH network during wintertime, when the demand is higher. Hast et al. found that HPs are attractive for DH networks, especially when there are HPs in the system, and large-scale storage of 1% of DH demand would be profitable [49]. Rinne and Syri suggested that TES would significantly enhance the operation of CHP units and TES in a future energy system of Finland with high shares of wind power [50].

2.5 Lowering the distribution temperatures of DH

The temperature levels of supply and return water are critical in the efficiency of heat distribution in DH networks. Temperature levels vary in different countries. Supply temperatures vary on average from 70 °C to 95 °C, while return temperatures are on average 40–75 °C [51]. However, in Finland, supply

temperatures typically vary between 75°C and up to 115°C. The higher temperature is required during wintertime in order to meet the requirements of the most demanding customers and to avoid decreasing living quality.

Decreasing the temperature level of DH networks could improve the energy efficiency of DH, and therefore LTDH networks have been studied recently. Li and Svendsen [52] have carried out an exergy and energy analysis of a Danish case system with low distribution temperatures, providing some design principles for reducing energy and exergy losses. Schmidt et al. [53] presented options for implementing LTDH, demonstrating the benefits of the concept. Dalla Rosa and Christensen [54] investigated low-temperature DH, taking into account the effect of human behavior on load patterns, and they compared DH and geothermal building-specific HPs for a low heat density area while concluding that LTDH could be competitive with HPs. Yang and Svendsen [55] analyzed different substation designs for domestic hot water supply with LTDH and evaluated their impact on the return temperatures for a DH network.

Improving waste heat temperature from very low-quality sources may be expensive and utilizing heat might not cover the cost of investment in HPs. HPs would benefit from the low-temperature levels by increasing coefficient of performance (COP) value or waste heat could be fed directly to the supply side of the network, where heat has more value.

The implementation of low-temperature DH networks cannot be done without considering the building side of the DH network. Practical steps for implementing lower temperature levels include the identification of critical radiators and thermal comfort should not be compromised [56]. In wintertime, the high temperature is primarily required for old buildings with poor insulation.

2.6 A summary of the literature review and the contribution of the dissertation

As the literature review suggests, there are multiple alternatives for low-carbon DH and transforming current DH networks into smarter energy systems. As the challenges lie ahead regarding DH competitiveness, the effect of future solutions needs to be modeled. Without modeling, it is hard to estimate the actual system-level impacts. Modeling can give insight and robustness by indicating the economic implications while simultaneously focusing on decreasing the CO₂ emissions of the system.

Utilizing biomass CHP and TES would increase both the flexibility of the DH system and the use of RES in the heating sector. Waste heat could be utilized more efficiently in industrial sites, for example, in DCs and industrial facilities. Revising DH production pricing mechanisms would lead to increased customer participation and the transparency of pricing in the heat markets, and thus

dynamic pricing is analyzed. Dynamic pricing would potentially lead to increased energy efficiency and, in combination with two-way heat markets, DH energy efficiency could be further improved. Also, these measures would decrease the final heat consumption. Increased energy efficiency and savings in final energy consumption decrease the need for high-cost peaking boilers, and therefore improving the DH systems could decrease prices and price volatility in the heat markets.

This thesis contributes to simulating different solutions in existing networks. Case studies are the focal contribution of this thesis due to the insight they give into how DH networks would adapt to changes in the energy production portfolio during the transition towards carbon-neutral energy systems. The methods for the simulations are presented in the following chapter, Chapter 3.

In this thesis, the focus is on modeling and analyzing the following solutions: HPs, SCs, biomass CHP, waste heat, and storage. DH has many local characteristics (e.g., load, size, and temperature levels) and thus the results are not universal for each DH network. However, most of the DH networks run with the same operating principles. Therefore, a case study between DH networks in Sønderborg, Denmark, and Espoo, Finland, was studied in Publication 5.

3. Methods

Table 2 presents the methods and tools, alongside with the approach used, in the respective publications (I–V). More detailed descriptions of the used methods in individual publications are presented in the subsections below.

Publication I evaluated plans for biomass-based heat and electricity production in the EU-27 in 2020. The publication aimed to analyze the impact of biomass CHP, and therefore scenarios were created for adopting different efficiency levels for plants and the utilization of biomass CHP. In order to give further insight into what is the situation in the EU-27 with biomass utilization, power plant projects were analyzed (according to the available literature) in the UK, Germany, Poland, the Netherlands, and Belgium. According to the NREAP analysis, all of these countries are to increase biomass consumption in both the electricity and heat sectors. Furthermore, all of these countries are heavy users of coal in their energy production. Finally, the plant projects were evaluated in the context of support schemes for biomass in these five EU Member States.

Publication II studied waste heat availability from a DC in Espoo by statistical analysis and the effects of utilizing waste heat in the Espoo DH network. Simulations using energyPRO aimed to analyze the impacts of waste heat utilization on other production units in the existing heat production portfolio. Furthermore, another scenario was produced to predict how much of waste heat could be procured for the network with the monthly pricing of waste heat. Implications for emissions were not considered in Publication II.

Publication III analyzed the potential for DC waste heat utilization in the Nordic countries, mainly in DH. The focus was on the current projects of DCs utilizing waste heat and on analyzing barriers from the perspectives of DCs and DH, and how to tackle these barriers. Also, Publication III offers a brief life-cycle assessment (LCA) on the economic and environmental implications of DC waste heat in an imaginary system with CHP units and solid fuel boilers used in DH production, as well as a high capacity for waste heat.

Publication V studied dynamic pricing in Espoo DH with the Matlab model. Scenarios were created for additional low-margin cost heat production, as well as including TES as a flexibility option. The main contribution was to see how

different technologies would be utilized in simulated dynamic pricing–based heat markets.

Table 2. The methods and contributions of individual Publications I–V.

	Publication I	Publication II	Publication III	Publication IV	Publication V
Main topic	Prospects for biomass utilization in CHP in the EU-27	The impacts of DC waste heat in DH	Possibilities for DC waste heat utilization in DH and how to increase the attractiveness of DC waste heat	The effects of introducing HPs and waste heat into an existing DH network	How dynamic pricing in DH production would affect the heat production costs and emissions of the system
Viewpoints	Low-carbon fuel, efficiency, & future of CHP	Low-carbon heat sources & the pricing of waste heat	Low-carbon heat sources & efficiency	Low-carbon heat sources & low-temperature DH	Low-carbon heat sources, flexibility, & pricing
Methods	A literature review of power plant projects & a scenario analysis on biomass demand	Simulating DH production in the Espoo DH network & statistical analysis of the availability of waste heat from a DC	A literature review of DC projects that utilize waste heat & LCA analysis of waste heat utilization in Finland	Simulating different scenarios for the Helen DH network with an increased amount of HPs and SCs & addressing supply and return temperatures in the network	Modeling marginal cost-based heat pricing in the Espoo DH network
Tool	Calculated in Excel	energyPRO & Excel	Excel	energyPRO	A dynamic pricing model for DH, created in Matlab
Contribution	Scenarios for biomass demand in the EU27 and the impact of biomass CHP Biomass-based power plant projects in the five analyzed countries in 2013	The effects of introducing waste heat into an existing system The impact of waste heat utilization in the Espoo network on the operational hours of other units	Pathway for DC's waste heat utilization LCA analysis of the emissions of waste heat utilization in the network The 8-step process with which DCs can consider waste heat utilization	Impacts on costs and emissions in the Helen network with additional low-carbon heat production The impacts of a lower distribution temperature on energy efficiency in the Helen network	Changes in marginal production costs with dynamic pricing in the Espoo and Sønderborg networks The effects of storage (as a flexibility solution) on CO ₂ emissions and marginal production costs

3.1 Scenarios for biomass demand in the EU-27, according to NREAPs (Publication I)

Biomass demand in the EU-27 was estimated by building three different scenarios according to the development that the Member States' forecasted in their respective NREAPs. Different scenarios are presented in Table 3. Scenario analysis was done in Excel. Efficiencies were studied for biomass plants, waste plants, CHP plants, and co-firing plants. Platt's power plant database of existing plants [57] was used to divide the plants in this categorization by actual technology type, including boilers with steam turbines, internal combustion engines, and combined cycles. Taking conversion efficiencies for each technology type into account, the weighted average conversion efficiency was calculated for each plant category. It was inherently assumed that the technology mix of new plants built up until 2020 will be similar to existing plants, but with higher conversion efficiencies, depending on the scenarios described in Table 3.

Table 3. The scenario assumptions for biomass demand in the EU-27 (Publication I).

	NREAP business as usual (BAU)	NREAP best available technology (BAT)	NREAP Zero-CHP
Biomass-based electricity and heat production	Productions according to the data in the NREAPs	The same production as in the NREAP BAU	It is assumed that none of the electricity and heat are produced with CHP
Plants included	Electricity-only plants Heat-only plants CHP plants	Electricity-only plants Heat-only plants CHP plants	Electricity-only plants Heat-only plants
Plant efficiencies	A slight increase in efficiency from current plant efficiency	Plants are built with BAT	The same efficiencies for heat-only and electricity-only plants as are found in the NREAP BAU

3.2 District heat production simulations for Espoo and Helsinki DH networks using energyPRO (Publications II and IV)

Case studies for DH production in Espoo (Publication II) and Helsinki (Publication III) were simulated with energyPro software.⁶ The commercial software energyPRO is developed by EMD international A/S, and it was suitable for analysis as it is possible to analyze techno-economic operation in a system with both individual CHP plants and HOBs. Electricity sales from the spot markets are also accounted for in energyPRO; thus, it can be conveniently used

⁶ More information about energyPRO is provided at <https://www.emd.dk/energypro/>.

to analyze a DH network with several CHP plants using different fuels. As an input/output model, energyPRO takes into account, for example, heat production plant characteristics, fuel prices, electricity prices, heat demand, ambient temperature, and DH network temperatures. The optimal DH operation strategy is calculated in energyPRO by minimizing the total operational costs of heat production for existing plants in the DH system. The sales from electricity generated by CHP plants are taken into account by energyPRO, which reduce the total operational costs. Figure 3 presents the outline for the energyPRO simulations used in Publications II and IV. Input data was gathered for plant capacities for production units, economic aspects, weather data, and network-related attributes.

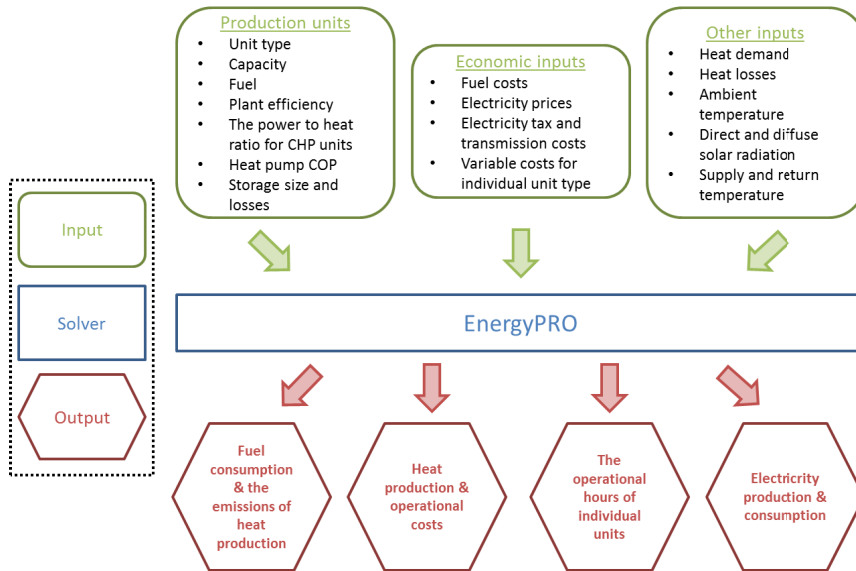


Figure 3. A representation of the simulations made with EnergyPRO.

Espoo is a city located in Southern Finland, and it is Finland's second largest city with over 270,000 inhabitants. The Espoo DH network is operated by Fortum Ltd. Fortum is one of the few non-municipal DH network operators in Finland. Fortum has a variety of different heat production options in their network (see Publication II for the plant capacities), but current heat production capacity is dominated by fossil fuel-based heat production units, namely coal and natural gas CHP.

In Publication II, simulations were carried out by using an hourly resolution and simulating one year at a time. Two years with different characteristics were selected for the simulations: 2013 and 2015. The reason for two separate years was to analyze cases with different outside temperatures and electricity prices. Furthermore, we considered two different methods for introducing waste heat into the network. The first approach assumed that all waste heat would be used in heat production. This approach would be the case if the DH network operator has agreed to procure all the heat available, which might be the case in markets that utilize bilateral contracts. The second approach assumed changing monthly

procurement prices, with higher prices in the coldest months. This pricing model is closer to open DH markets, and waste heat would be utilized if it is cheaper to utilize than alternative heat production in the Espoo network. The main outputs of the simulation are total operational heat production costs and the operational hours of individual units. Table 4 presents the different scenarios used to analyze waste heat utilization in Publication II.

Table 4. The simulated scenarios for waste heat utilization in Publication II.

	Refer- ence	Marginal cost	100% utilization
Produced waste heat, fed to the DH network	0%	Depending on the marginal production costs of the system	100%
The cost of waste heat	-	Seasonal pricing (13.8–40.4 €/MWh)	0€ (100% will be utilized regardless of the price)
The amount of waste heat	-	Constant load 2013 – Moderate: 23.4 MW 2013 – High: 58.5 MW 2015 – Moderate: 18.7 MW 2015 – High: 46.8 MW	Monthly shifting load 2013 – Moderate: 20–28 MW 2013 – High: 50–70 MW 2015 – Moderate: 15–20 MW 2015 – High: 38–50 MW

The Helen (DH provider in Helsinki, Finland) DH system (Publication IV) represents a city-wide system with very efficient, but mainly fossil fuel-based, heat supply. Helen is planning to be entirely carbon neutral by 2050, which is a challenge due to the high fossil fuel-based plant capacity. Helen has already made some plans for future heat production capacity, which include building a new HP-based capacity (22 MW) and 92 MW pellet boiler in 2018, decommissioning the Hanasaari coal-fired CHP unit (with a capacity of 420 MW_{heat}) in 2024 and building a new biomass-based HOB in Vuosaari with a capacity of 150–250 MW by 2024.

The model in Publication IV is based on the hourly simulation of DH production with taking produced electricity into account. Simulations were carried out for four milestone years – namely, 2014, 2018, 2024, and 2030 – decided according to Helen’s plans for future capacity additions. The addition of low-carbon heat capacity was determined by the average DH load during summertime. Additional HPs were sized to match the average DH demand in the summertime (i.e., 140 MW, in addition to the existing capacity of 112 MW, in 2018). In order to analyze and compare the benefits of different technologies, the investment costs were estimated to be approximately MEUR 90 in all of the simulated scenarios, corresponding to the investment cost of the 140 MW HP

capacity mentioned above. Investments in new renewable heat capacity were assumed to take place in two phases, one in 2018 and one in 2024, in all scenarios. The capacity of SCs was determined on the basis of investing MEUR 90, with an initial investment value of 440 €/m². Four scenarios were simulated using business as usual (BAU) as the baseline. Individual scenarios were formed for HPs and SCs and an additional scenario was formed for the combination of these two technologies. The chosen scenarios are presented in Table 5. All the scenarios were evaluated with current and lower distribution temperature levels.

Economic and environmental indicators were used to evaluate the performance of new technologies and a lower distribution temperature. Annual DH production, electricity production, and the total operational costs of the system were the main simulation outputs that were further used analyzing the changes in the shares of available heat production technologies (i.e., CHP, boilers, HPs, and SCs) and to calculate the CO₂ emissions of DH production. Furthermore, a sensitivity analysis was carried out to analyze the economic performance of CHP and HPs with higher electricity prices. Distribution constraints in the Helen network were not considered.

Table 5. A description of the investigated scenarios in the case of Helen (Publication IV).

Scenario	Scenario abbreviation	Description
Business as usual	BAU	This represents the existing system based on the current setup of CHP units, boiler plants, and a large-scale HP facility.
Heat pumps	HP	This is an existing system with increased HP capacity. The resulting increased HP capacity corresponds to the average summertime heat demand in June, July, and August.
Solar collectors	SOL	This is an existing system with added SC-based heat supply. The capacity increase is calculated by matching the investment costs with the HP scenario.
Heat pump and solar collectors	SHP	An existing system with both increased HP capacity and added SCs. The capacities of each technology are half of the values used in HP and SOL scenarios.

3.3 LCA, and economic and environmental analysis (Publication III)

S. Rinne did an LCA analysis in Publication III. LCA analysis takes into account the emission impacts of the new heat production and what production this replaces. Two methods for LCA were studied: consequential lifecycle assessment (CLCA) and attributional lifecycle assessment (ALCA). CLCA analyzes the short-term impacts on production, and it is suitable for analysis if

there is at least a moderate amount of condensing coal or CHP running. In contrast to CLCA, ALCA answers the question about the total emissions of the specific activity over a certain period and does not describe the effect on consumption.

With LCA, it was possible to study the environmental effect of adding waste heat into a system with CHP plants and HOBs. In the case analysis, it was estimated that DCs could supply approximately 20% (7–8 TWh) of DH demand in Finland with a COP of 2.6. The economics of waste heat utilization in DH were also evaluated by assuming that utilizing DC waste heat will replace both solid fuel CHP and HOB production in the DH network. This situation was compared to the reference system where DC waste heat would not be utilized at all. Variable costs of heat production were calculated by taking into account the increased costs of electricity consumption due to HPs, the reduction in fuel utilization for CHP and HOB, and the investment costs for HPs. The decreased amount of income from sold electricity from CHP was also considered.

3.4 Issues with energy efficiency in DCs and a method for the statistical analysis of heat availability from a DC

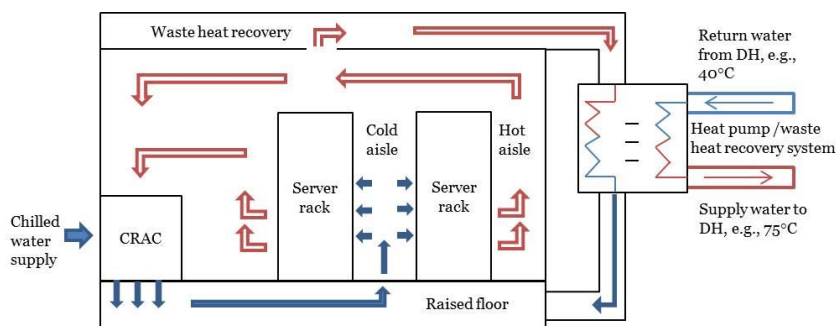


Figure 4. The configuration for waste heat recovery in a DC (Publication III).

Figure 4 presents the basic configuration of waste heat recovery from a DC. Hot air is recovered from the hot aisles in the server room and guided through the waste heat recovery system to the HP. The HP is used to increase the temperature in order to meet the requirements of the DH network. One of the key issues in DC waste heat utilization is that waste heat is hardly addressed in the total energy efficiency of the DC. The most common metric for energy efficiency in DC is currently power usage effectiveness (PUE), which only considers the IT power consumption and total energy consumption of the DC. In order to address the use of waste heat, energy reuse effectiveness (ERE) could be used, but it is not a standard metric in the business.

The availability of waste heat from DCs was studied in Publication II with statistical analysis. The analysis was conducted by M. Pärssinen. Due to seasonal variance in DH demand, it is necessary to evaluate when waste heat is available from DCs. Statistical analysis was based on actual electricity

consumption in a small DC located in Espoo. The availability of heat was calculated and analyzed according to the monthly electricity load profile. This load profile was further utilized in simulating DH production in Espoo with energyPRO (see Section 3.2).

3.5 Simulating DH production and marginal costs

In Publication V, marginal cost-based DH production in the Espoo DH network was simulated with a model based on Matlab.⁷ The code was initially developed by H. Mäkelä [58], and the code has been further used in [59]. DH supply was simulated similarly as the current day-ahead electricity market's work. Heat demands were estimated as fixed, using the real data obtained for the year 2015. The model solves heat production for each hour by utilizing production units starting from the unit with the lowest short-term marginal production costs. The point where the heat supply and demand curve intersect is the price of the heat set for that hour (presented in Figure 5).

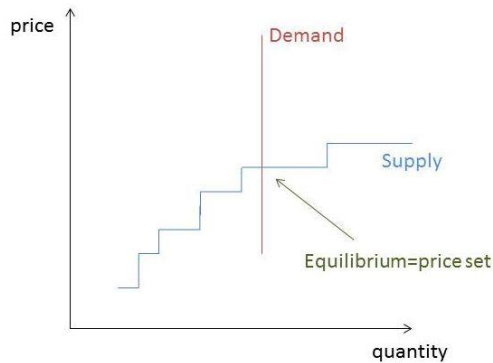


Figure 5. A representation of the demand–supply curve in the simulated dynamic heat market. The vertical demand curve represents the fixed heating demand that was assumed in each hour (Publication V; figure made by Dominković).

When the system operates according to short-term marginal costs, investment costs are ignored. Table 6 presents the input variables and output in the dynamic pricing model. The results of the simulation in the Espoo network were set against the results of a similar simulation in the Sønderborg DH network in order to compare the two different systems with different sizes and production portfolios. The approach used in this paper allowed a more realistic evaluation of the low marginal cost heat in different periods of the year, being especially relevant for the evaluation of future DH systems when more low marginal cost heat is expected to be used, such as industrial waste heat and solar thermal energy. Therefore, different scenarios were modeled in both systems with additional low-carbon DH capacity and heat storage, which bring flexibility to the system.

⁷ For more information about Matlab, see <https://www.mathworks.com/products/matlab.html>

Table 6. The inputs and outputs of heat production in the model (Publication V).

Input variables	Output
Fuel prices and fuel taxes	The total turnover of the dynamically based DH
Electricity spot prices, taxes, and distribution costs	The production of individual units
HP COP	Hourly weighted average marginal costs
Plant capacities	The CO ₂ emissions of heat production
CHP heat to power ratio	
Variable operation and maintenance costs	
The efficiency of the plants	
Heat demand	

The simulated scenarios in the case in Espoo are presented in Table 7. Heat demand, electricity prices, and fuel costs were assumed, based on data from 2015. Scenarios were created based on the upcoming plans for geothermal heat, waste heat, and storage capacity in the Espoo DH network.

Table 7. Scenarios for the Espoo DH network (Publication V).

Scenario	Espoo reference case	Espoo reference case with storage	Espoo waste heat	Espoo geothermal with waste heat	Espoo geothermal with waste heat and storage
Abbreviation	Espoo REF	Espoo REF+STOR	Espoo WH	Espoo GEO+WH	Espoo GEO+WH+STOR
Additional heat supply	-	TES 110MW (800 MWh energy content)	200 GWh waste heat per year, monthly changing load	40 GW geothermal capacity, constant load + DC waste heat	40 GW geothermal capacity, constant load + DC waste heat + TES 110 MW (800 MWh energy content)

Due to the sectoral coupling, HPs and CHP require additional attention. CHP units take into account the electricity spot prices as profit from produced electricity, and profit is then deducted from the heat production costs. Thus, during high electricity prices, CHP may have negative heat production costs. In contrast, it was assumed that HPs account for hourly spot prices as costs, in addition to electricity transmission costs and taxes. Due to this factor, HPs have higher marginal costs during hours with a high electricity price.

Addressing the impacts of storage is also mandatory in dynamic pricing, especially if external producers start to store heat. TES was added to the

production portfolio in both the Sønderborg and Espoo cases. These storages were considered to have external ownership, and they are trying to take advantage of price differences between individual hours. Publication V discusses the bidding strategy for heat storage in detail.

4. Results

4.1 The future of biomass-based CHP production (Publication I)

According to the NREAPs of the EU-27 Member States, they have very different plans for biomass utilization in the heating sector. One-third of the Member States are planning to increase biomass-based heat production by over 10 TWh between 2012 and 2020. France is acting as a forerunner with a planned increase of over 68 TWh. Some countries (Cyprus, Estonia, Malta, and Portugal) are hardly planning to increase at all, or to even decrease biomass-based heat production. This is partly due to the low heat demand in these countries. The situation looks a bit different with a planned increase in CHP production. Over half of the Member States are planning to double their CHP-based biomass production. Ireland and Hungary have extremely ambitious targets as they both plan to increase biomass CHP ten-fold and twenty-fold between 2012 and 2020 respectively.

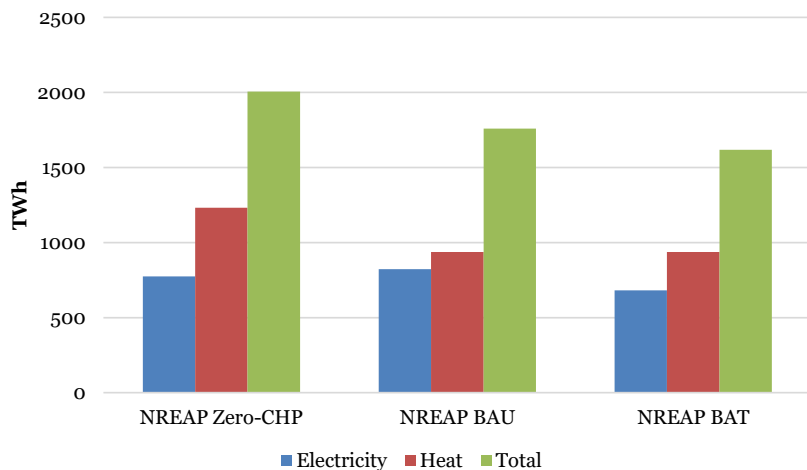


Figure 6. Biomass demand for heat and electricity for 2020 in the EU-27, based on the simulated scenarios (Publication I).

Figure 6 presents the total biomass demand in 2020, based on the NREAPs. In the zero-CHP scenario (total biomass demand: 2005 TWh), less biomass was used for electricity production due to better efficiency in electricity-only plants

compared to the electricity efficiency of CHP. However, the demand for biomass in the heating sector is drastically higher than in the BAU scenario. Furthermore, the best available technology (BAT) scenario outperforms the zero-CHP scenario in both sectors since demand is lower for both electricity and heat. Compared to the BAU scenario, the BAT scenario shows that by utilizing the BAT, 8% of primary biomass could be saved. The results of the scenario analysis show that the utilization of biomass CHP improves total energy efficiency. As the heating sector is still heavily focused on fossil fuels, biomass CHP could be an alternative for sector coupling. Biomass could be used to replace fossil fuels in both HOBs and CHP plants. As far as biomass is considered a carbon neutral or low-carbon source, it will decrease total emissions.

In 2013, the situation did not look good for biomass utilization in CHP. Because of 2020 RES targets, many countries have started to plan and support dedicated biomass-fired electricity-only plants rather than CHP plants. According to plans for energy efficiency, it may not be a suitable option. In 2013, the projects were focusing more on replacing coal in existing plants rather than building new biomass-based capacity. In the studied countries (the UK, Germany, Poland, Netherlands, and Belgium), the support schemes favored electricity-only biomass rather than CHP. Also, the lack of DH networks in the studied countries slowed down the utilization, including underutilization, of residue biomass. Our analysis was conducted in 2013, so the situation may have changed as more emphasis has been put on the sustainability of biomass.

Furthermore, many of the countries have updated their renewable support mechanisms, which have caused political instability for the investments. The EU Member States may have plans for a vast increase in biomass, but the problem remains that these countries are not offering enough incentives for utilities to invest in biomass. Biomass availability in the EU has been estimated at 1400–1600 GWh [27], which suggests that almost 500 GWh of biomass will have to be imported in the BAU scenario in 2020.

The basis for our scope for biomass demand was that each country would reach their targets set in the NREAPs. Some of the countries have already exceeded their overall targets for RES, but many countries are still lagging behind. Concerns regarding biomass sustainability have decreased the rate of biomass utilization, and also the decreasing costs for solar and wind power have lowered interest in biomass.

4.2 Introducing HPs and SCs to the DH system – the cost-efficiency and environmental impacts of the solutions (Publication IV)

Figure 7 presents the share of heat production in the chosen scenarios in Publication IV (see chapter 3.2 for scenario descriptions). The results indicate that HPs have a high share of heat supply due to already existing plans for

increasing HP capacity. At the current price levels, CHP plants cannot benefit from electricity production and thus the utilization of CHP plants decreases. Furthermore, low electricity prices benefit HP production. The currently planned new biomass boilers further reduce the output from CHP plants, as does the decommissioning of the Hanasaari CHP unit that will happen in 2024. Although the emissions of the system decreased (by 16% in the HP scenario compared to the BAU scenario in 2030), the share of fossil fuel-based HOBs increased.

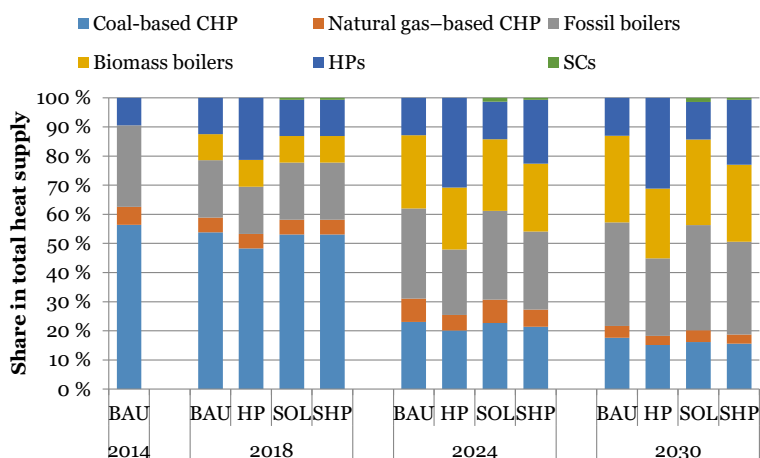


Figure 7. The heat supply in different scenarios in the selected milestone years (Publication IV).

The results indicate that HPs would produce over 30% of the total heat supply in 2030. Based on the results, it is clearly visible that HPs outperform SCs with our base assumptions. SCs produce the expected amount of heat, but with the installed capacity, production is still on a minor level. Considering that the same investment costs were allocated for both options, HPs represent a more economical option with the input assumptions of Publication IV.

It was estimated that the emissions of electricity production will decrease in the future, and therefore HPs would notably decrease the emissions of heat production. The results of the scenario analysis show that the proposed investments were not enough to reach the interim targets of Helen by 2030. The RES share was 45% at highest in the HP scenario (Helen's target: 47%). However, if LTDH could be implemented, the HP scenario would exceed the target with a RES share of 48%. It must be noted that the possible investment costs for LTDH could be much higher than investing more in low-carbon production technologies.

As the future of spot electricity market prices remains uncertain in the near future, the sensitivity of electricity prices was assessed. The results of this sensitivity analysis are presented in Figure 8. Increased electricity prices would

benefit CHP production, but the profitability of HPs would consequently decrease. If the spot electricity prices were to double from the assumed 47 €/MWh in 2030, CHP-based heat production would increase by almost 2 TWh in the reference scenario. Moreover, HP-based production would decrease by almost 300 GWh. The largest cut would occur in HOB- based production. In the HP scenario, the decrease in HOB-based production would proportionally decrease even more (with a 44% decrease in HOB-based production with +100% electricity prices compared to the reference scenario).

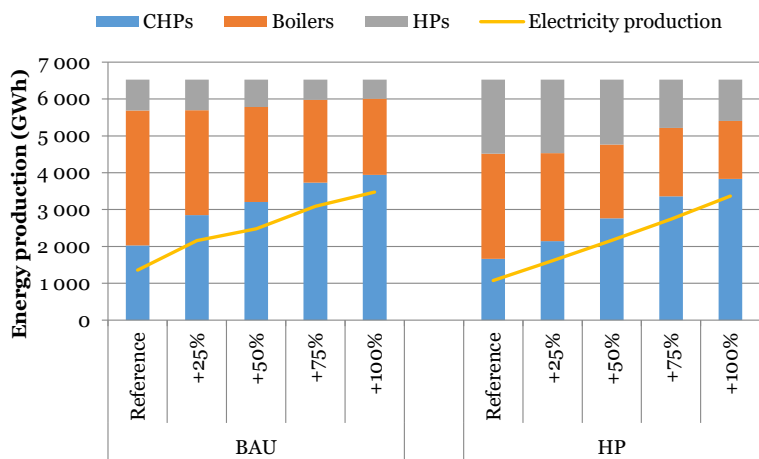


Figure 8. The electricity price sensitivity to heat and electricity production for the BAU and HP scenarios in 2024 (Publication IV).

In the Helsinki case, it must be noted that Helen has a particular advantage as they own the electricity distribution network, and thus it was estimated that electricity transmission prices are rather low for HPs in DH production if Helen owned the HPs. Furthermore, if HPs were owned by other utilities or even at the household level, electricity prices would be higher and would not be utilized as often.

4.3 A case study of DC waste heat utilization (Publications II and III)

This section presents results from Publications II and III on DC waste heat utilization. The structure of the results is as follows. First, the results of the literature review on options for waste heat utilization and suggestions for improving business cases between different parties are presented. Second, the results in the availability of waste heat are presented. Lastly, we present the results of the economic and environmental analysis of DC waste heat utilization.

Barriers for waste heat utilization are depicted in Figure 9. There are challenges regarding the operation of individual parties and also mutual problems that need to be addressed in cooperation with both parties. For the DH network, the most critical issues are that the quality of heat must be

sufficient for the network and that waste heat utilization may affect other production units. The most significant disadvantages and barriers from the DC point of view are the lack of heat supply and business cases. DCs might be located in remote areas due to cheap rent and facility expenses, and therefore there might not be high enough demand for the heat to sell. From the mutual perspective, DCs should be located close to existing DH networks so that significant investments are not needed to connect DC to DH network. Also, as the heat production is not the core business in DCs, investments into heat recovery and capture equipment may be considered riskier.

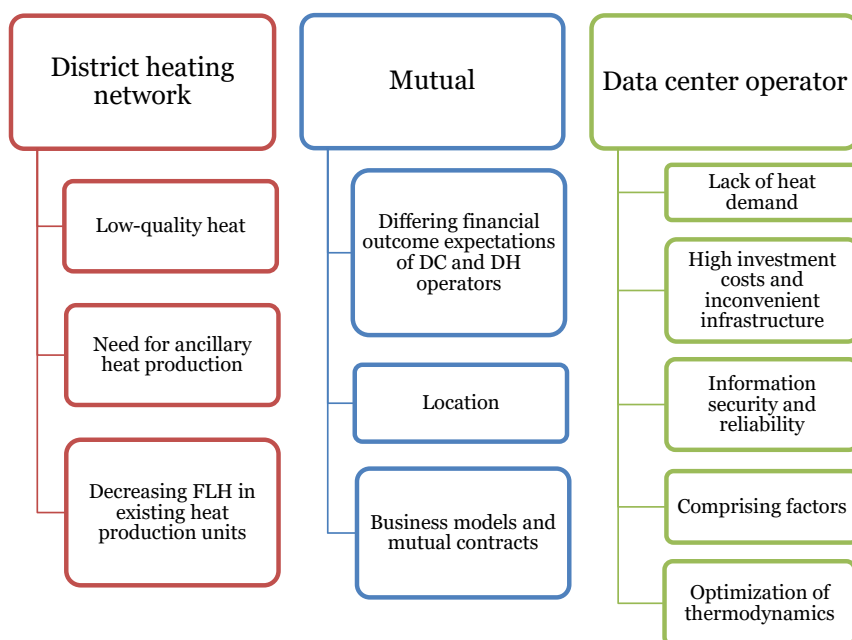


Figure 9. The barriers to DC waste heat utilization in DH (Publication III).

The literature review carried out in Publication III shows that there are already projects on different scales of DC waste heat utilization and that they have been deemed profitable. In some cases (for example, Yandex DC in Mäntsälä) utilizing DC waste heat replaced the need for investing in a new HOB on the DH network operator's side. Utilizing waste heat from Yandex DC has decreased the emissions of DH production in the city of Mäntsälä.

4.3.1 The issue of DC load profiles (Publication II)

From the point of DH, the security of the supply of heat is essential from the point of view of both the stability of the system and the operational hours of existing heat production units. The statistical analysis in Publication II shows that a combination of service traffic and backup traffic forms a rather uniform load for the DC. The total traffic reflects power consumption in the DC, and thus it can be considered that the DC power consumption is close to constant. Figure 10 shows the monthly consumption profile in a DC during January 2012 and June 2016, as well as the outside temperature. DCs consume slightly more

electricity during summertime, which means that heat is more available. Altogether, changes according to outside temperatures are not the determining factor. On the other hand, downgrading data processing in a DC may become an issue, which is highlighted after 2015 in the studied DC.

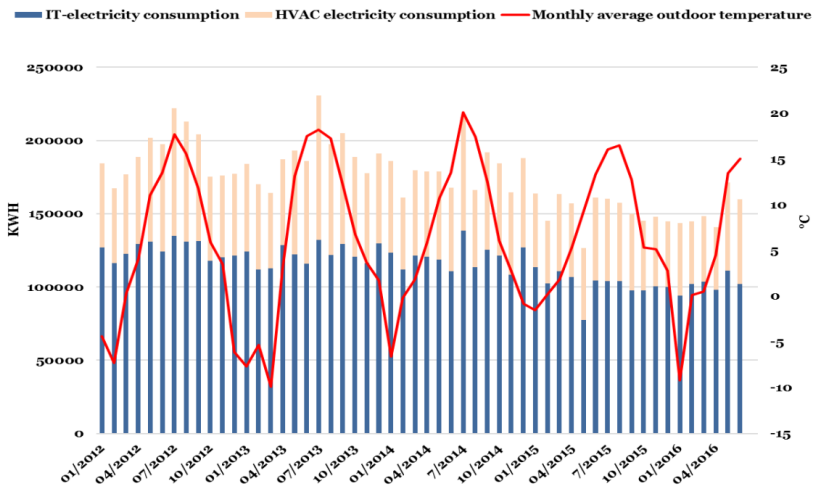


Figure 10. The monthly electricity consumption of an actual DC and the average monthly outside temperatures in Espoo during the period 1.1.2012-30.6.2016 (Publication II).

4.3.2 The implications of DC waste heat utilization in DH (Publications II and III)

Table 8. Cost savings in marginal cost scenarios compared to the reference scenarios (Publication II).

	Marginal cost scenarios			
	2013		2015	
Waste heat capacity	MODERATE	HIGH	MODERATE	HIGH
Total production costs	-5.5%	-12.2%	-4.0%	-9.9%
Profits from sold electricity	-17.1%	-26.3%	-7.7%	-24.1%
<i>Savings in total</i>	-0.6%	-6.3%	-3.2%	-7.3%

Publication II studied the implications of increasing the amount of DC waste heat in the Espoo DH network. Table 8 shows the results from the marginal cost scenarios compared to the reference scenario where waste heat is not utilized (see chapter 3.2 for scenario descriptions). The results highlight the fact that savings are higher during higher electricity prices in 2013. Total heat production costs decreased in each of the scenarios. Investments were not considered in this case, but savings in operational costs indicate that there is room for investments. Altogether, utilizing waste heat decreased the operational hours of both CHP units and HOBs. Profits from electricity sales decreased by up to

26.3% in the 2013 HIGH waste heat capacity scenario. The operational hours of the biggest CHP plant decreased from 82% in the 2013 REF scenario to 62% in the HIGH scenario. Waste heat would be operational for 95% of the annual hours.

Waste heat would be utilized during most of the hours, even in the case with the capacity of 50 MW. Figure 11 presents the load profiles of waste heat in all scenarios. With lower capacity, under the assumed pricing regime, waste heat is utilized during almost every hour. However, in higher waste heat capacity scenarios, there are hours when either heat production is cheaper with other units or the electricity price is high and CHP units are more profitable and used to full capacity. Thus, waste heat would not be sold to a network with full capacity.

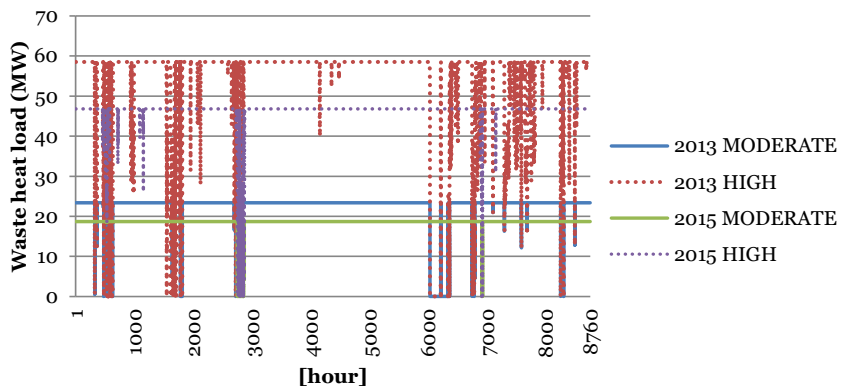


Figure 11. The waste heat load profile in different marginal cost scenarios (Publication II). X-axis depicts hours of one year.

Utilizing DC waste heat in DH will not always decrease emissions, and therefore cases should be individually assessed. The results in Publication III suggest that in a DH network that already has low-carbon production, emissions might actually increase if electricity has a high emission factor. LCA results depend on which method is used to calculate the emissions. The results in Publication III show that with CLCA, waste heat increases emissions as it replaces biomass-based production, which was considered to have an emission factor of zero. In economic terms, if the heat from a DC replaces DH heat – probably mostly produced with CHP or a solid-fuel HOB, supplemented with a peak boiler using oil as fuel – the effect on system cost and emissions depends on the share of the DC heat. The more the replaced DH production is oil-based during peak demand or during solid fuel boiler downtime in the summertime, the better the result.

4.4 The dynamic pricing of heat production and the role of heat storage (Publication V)

This section presents the results from the marginal cost–based dynamic pricing simulations in Publication V (see chapter 3.5 for scenario descriptions). The results indicate that utilizing waste heat decreased both total heat production costs and CO₂ emissions. The addition of low marginal cost heat production decreased marginal prices till they were close to zero during the summertime in both waste heat scenarios. To avoid providing too high prices for third-party heat supply, dynamic heat markets are a viable solution if a considerable amount of waste heat is connected to the grid. Furthermore, the most expensive production that was utilized (i.e., natural gas HOBs) was cut by 58% in the Espoo GEO+WH scenario compared to the Espoo REF scenario.

Figure 12 presents the simulated marginal cost duration curves in the Espoo scenarios. The natural gas HOB was typically the marginal technology that determined the marginal heat production price (i.e., for a natural gas HOB it was 57.8 €/MWh). Natural gas HOBs represented 32%–45% of the marginal cost hours in different scenarios. CHP and HP heat production costs fluctuate and thus marginal costs decrease in small steps when CHP or HPs is the marginal production. Introducing more low marginal-cost production shifts the marginal cost curves to the left (i.e., the average marginal costs decrease). During the summertime, marginal costs are very low and even the low marginal cost producers would make little profit. Finally, the storage decreases marginal costs during high-cost hours but increases marginal cost hours when costs are lower.

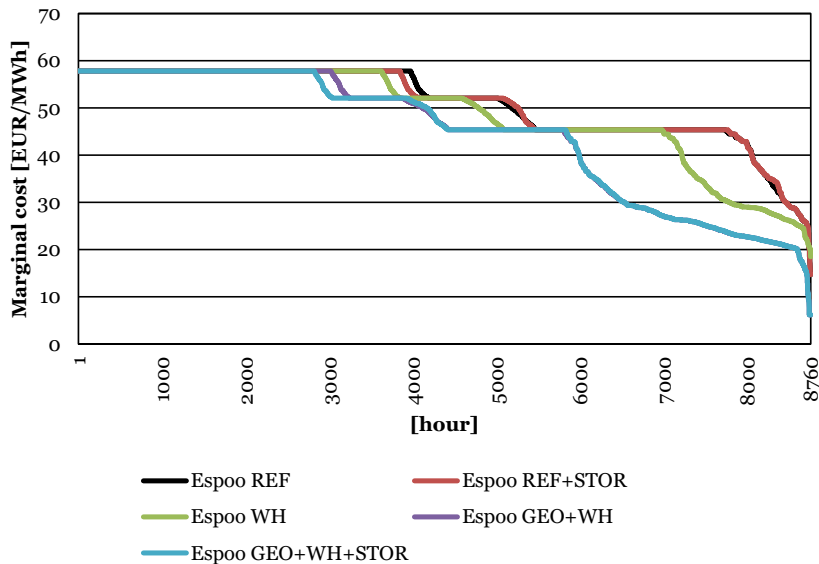


Figure 12. Simulated marginal costs in different scenarios in descending order in the case of Espoo (Publication V).

TES benefits from the price arbitrage between the hours and the turnover for TES was over kEUR 500 in both storage scenarios in Espoo. The analysis in Publication V suggests that the purely economic operation of TES may lead to an increase in emissions in the short term. This derives from the fact that storage may be charged heat during more emissive periods if the cheaper technology is, for example, coal-based and storage is discharged during times of higher prices. Therefore, it is questionable if heat storage units should act in the market as individual units trying to maximize profits. Figure 13 presents the hourly operation of TES in the Espoo scenarios. Since TES is considered to act as a short-term operation, it has a high number of cycles. TES seemed to have less impact during the summertime in the case when there is more low marginal-cost production available, remaining almost unused. Therefore, the storage operation would need a bit more tweaking during these times.

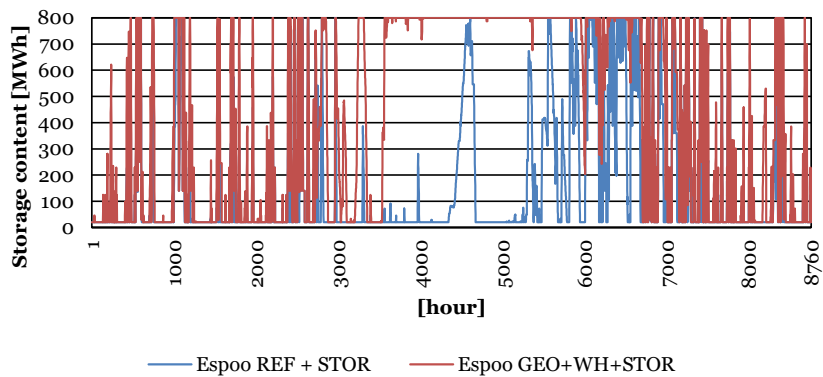


Figure 13. The operation of TES in the Espoo scenarios (Publication V).

The case study with Sønderborg in Publication V shows similar results to those of the Espoo DH network. Comparing the two different systems provided the insight that dynamic pricing would decrease both marginal costs and emissions in both cases. The results showed that in both the Sønderborg and Espoo cases the behavior of different plants caused similar effects on the dynamic prices of DH networks. Both case studies showed that the inclusion of low marginal-cost producers caused a shift in the marginal price curves to the left, putting a downward pressure on the prices. During the summertime, when heat demand is lower, marginal prices moved close to zero. In most of the low marginal-cost hours, CHP plants would be unviable. In Sønderborg there was proportionally more low marginal-cost production and therefore average marginal costs decreased even further.

Since the dynamic pricing was based on short-term marginal costs, investment costs were excluded from the analysis. In reality, many low-carbon technologies may have high initial investment costs, and thus they would add a premium in prices when bidding in the market. This would probably be highlighted if the market were populated with more capital-intensive technologies.

4.5 Low-temperature DH networks and the potential for introducing more low-grade heat into the system (Publications II and IV)

Publication II identified some of the issues that LTDH could bring to the system and the barriers related to it. LTDH would decrease heat losses in the system and increase the HP COP value, thus promoting energy efficiency. In the best case, waste heat could be directly fed to the DH network. In DCs with liquid cooling technologies, waste heat could be captured at 50–60°C, which would be suitable for the supply side in LTDH. There are still many barriers for lower temperatures. Without demonstration projects, it is hard to know the actual costs of implementing LTDH.

The effects of a lower distribution temperature were analyzed in Publication IV, and Figure 14 presents these effects (see chapter 3.2 for scenario descriptions). Low-temperature distribution clearly improved the performance of any system; including the BAU scenario, representing current plans for developing the system. SCs would produce almost 20% more with a lower distribution temperature in the SOL scenario, while HPs produced at least 5% more in all scenarios with an initial COP value calculated at 4.0 with lower temperatures. A low distribution temperature also increases the efficiency of CHP and boiler-based production (especially biomass-based boilers due to flue gas condensation), but the effect is not clearly visible in our scenario as HPs perform much better with LTDH. CHP- based heat production decreased by over 5% in each scenario with lower distribution temperatures (except in the HP scenario where CHP production actually increased). The low-temperature distribution reduced heat losses by 22%, but since the relative heat losses were low already (5.6%), the effect is not very significant.

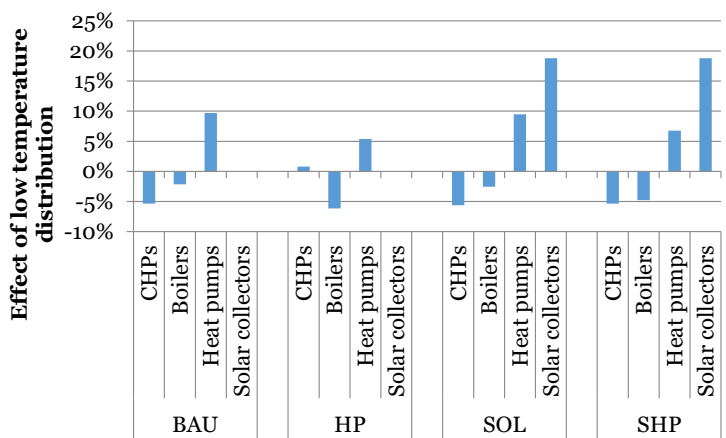


Figure 14. The effects of low-temperature distribution on heat output by specific sources of heat in 2030.

5. General Discussion and Conclusions

This dissertation analyzed and modeled solutions for low-carbon technologies in future DH systems using the viewpoints of efficiency, low-carbon technologies, the pricing of DH production, and flexibility. Modeling is required to analyze the actual effects of integration. Without modeling it is hard to estimate the effects on individual plants and the impacts on heat production costs or emissions of DH. DH is operating in competitive markets, and thus the solutions for production should be cost efficient. The research in this thesis assessed the economic and environmental efficiency and operation of HPs, waste heat from DCs, and SCs in existing systems. The following chapter discusses the main findings of the publications (I–V).

5.1 The main findings

DH is a highly efficient method for distributing heat in places with high population density and it should be considered that it will remain as one of the primary methods in areas with existing infrastructure. It should be noted that investments into networks have already been made, and even though they are considered sunk costs, networks still have value and can be used in future smart systems. One of the major points in the public discussion regarding heating solutions in Finland has been the competition between HPs as individual heating solutions and DH. Neglecting the existing DH infrastructure could become costly, and therefore the discussion should aim towards combining individual HPs with DH.

In terms of cost-efficiency and environmental impact, HPs proved to be a far more attractive option than SCs (or a combination of SCs and HPs). HPs have high operational hours throughout the year in all simulations, which suggests that they are cost-efficient during most hours of the year in Finland. Currently, solar thermal does not seem to be an attractive solution for DH with the assumed price levels in Helsinki, but the introduction of LTDH networks could make the investment profitable.

The results in this thesis show that biomass CHP should be an essential part of the electricity and heat production if the EU wants to avoid heavy imports of primary biomass for energy production. Biomass has been proposed to replace coal in many situations in both electricity and heat production. However, the

pressing concern of biomass sustainability and biomass as a limited resource may hinder investments in new biomass capacity, especially investments in CHP units with their high investment cost. Therefore, on a European level, the future for biomass does not look promising for CHP based on investments in the EU.

As it was presented in Chapter 4.1, the EU would need to import approximately one-quarter of the primary biomass, mainly from North America and Russia, to meet the targets presented in NREAPs. Transporting biomass increases life-cycle emissions of biomass heavily, and further questions the criteria for sustainable biomass utilization. Furthermore, it is also questionable whether primary biomass should be used for electricity- and heat-only purposes or not. Since the amount of sustainable biomass is limited, primary biomass should be used mainly for higher value products, such as biofuels. Nonetheless, residual biomass from industries should be used for energy production, if the residues cannot be further processed.

Waste heat from DCs seems to be profitable from the DH system perspective, but the environmental impact depends on the replaced fuel. If waste heat replaces fossil fuel-based production, it typically decreases emissions. It must be noted that improving waste heat temperature with HPs increases electricity consumption, and therefore the emissions of electricity production affect the overall situation. In the case that CHP production decreases due to waste heat utilization, electricity must be produced with alternative methods, which should be assessed. In the best scenario, waste heat could replace the need for the DH network operator to invest in new capacity.

Furthermore, there are still barriers that slow down the utilization of waste heat sources and most of these are related to business cases and opportunities for both parties. Currently, waste heat utilization is not dominating the designing criteria for DCs. Without proper incentives for DCs to capture heat, such as energy efficiency metrics guiding towards utilization of excess heat, waste heat utilization may not be considered in future DC investments. Moreover, DH networks are mainly located in urban areas where both rent is higher and space is limited for the infrastructure, while DCs consider more remote areas. DCs should be located closer to heat consumption areas and therefore including them in city planning is essential.

The results from the publications in this thesis suggest that introducing new low-carbon production technologies not only reduces the FLHs of peaking boilers but also the FLHs of CHP units. CHP plants may prove to be unfeasible when they have to operate on fewer hours. In addition, with recent spot electricity prices, CHP plants often cannot make enough profit on electricity, and it may be that not all the CHP units are able to operate in heat-only mode. Anyhow, spot prices in the Nordic countries have shown a slight increase in 2018, but it is uncertain how the spot market prices will develop in the near

future. However, increasing the amount of HPs in the system may increase electricity demand and, consequently, spot market prices. Thus, CHP could become more profitable with larger HP capacities as it was suggested in [18]. The sensitivity analysis of electricity prices in Publication IV indicated that in the case of Helen, HPs would still prove slightly profitable with higher electricity prices. Ultimately, in the current environment, the future for CHP does not seem too bright and there are not enough incentives for investing in new large-scale CHP units. Alternatively, smaller units could be used, for example, small biomass-CHP units are more flexible and have a higher power-to-heat ratio, which means that the units could operate more on the electricity market basis.

There are several risks associated with current electricity spot market pricing mechanisms, and it remains to be seen whether current spot markets are adequate for changing electricity production portfolios. If electricity systems are gradually moving towards more RES-based systems with very low or even zero marginal production costs, producers can hardly make any profit and producers cannot cover their investment costs. Therefore, it might be necessary to redesign the electricity markets. This may radically change the income structure of coupled heat and electricity units.

Lower distribution temperature in the heat supply would increase the energy efficiency of DH. CHP production would benefit from lower distribution temperatures, but LTDH networks would be ideal for adopting more HPs, waste heat, and SCs into the systems. Lower distribution temperatures increase the amount of energy captured with SCs and increase the COP values of HPs. Therefore, it should be analyzed if LTDH networks could be built or if it would be possible to decrease the temperature levels in some parts of the network, for example, by investing in new heat exchangers in the most demanding parts of the network.

Dynamic pricing could be one of the solutions for DH production in the future, in order to increase customer interaction in the heat markets and allow heat consumers to become heat prosumers. TPA should be promoted, as third-party heat could prove to be more profitable in the system than heat produced by a DH operator, as the results in this thesis suggest. The results in Publication V showed that dynamic pricing could promote emission savings, and the adoption of low marginal-cost heat production capacity in the networks in Finland and Denmark would decrease the average marginal costs of heat production. The current monopolistic nature of DH networks in Finland hinders transforming DH systems into open two-way DH markets as it not mandatory for DH network operators to buy external heat into their systems.

Production diversity is required in future DH networks, especially in large-scale systems. HPs perform well, but in the case of swift changes in fuel or electricity prices, the costs may increase, and therefore it is beneficial that there are other alternatives for producing the heat. The availability of sufficient

production capacity during peak times is required. Electricity demand is typically high during times when heat demand is high, and therefore electricity prices may increase. Thus, HPs may not be economical in every hour. Flexibility solutions, such as TES, can provide much-needed balancing on during fluctuating heat production costs, but the optimal capacity of flexibility solutions should be measured case by case. The simulated TES operation in dynamic pricing-based DH markets in Publication V showed that storage can indeed decrease the average marginal costs of heat production. Nonetheless, if TES operates purely on economic terms, storage may increase emissions. This finding is in accordance with other recent modeling efforts [49].

Finally, in this thesis, the possibilities for smarter DH systems were studied. Certain technologies seem to be more profitable, both in terms of costs and technical investments. There are multiple solutions for carbon-neutral heat supply in the DH network. However, in the future DH will still rely on electricity markets (due to HPs), even if CHP capacity decreases. In addition, business models and transparency are required to fully utilize, for example, the waste heat in DH. Temperature, timing, and price are essential in designing TPA. The results of this thesis are not purely universal for all DH networks since the networks differ in size and location. However, the results raise the awareness of the implications and issues of different technologies in large systems with many production technologies.

5.2 Restrictions and limitations

This section summarizes the general restrictions and limitations considering the subjects related to this dissertation. Individual limitations and restrictions in each publication are discussed in their respective papers.

First, network constraints and bottlenecks were neglected in all publications, due to limitations of the simulation tools. This means that every heat production unit could supply heat throughout the network. Moreover, supply and return temperatures were estimated to be coherent inside the network. This is a key challenge, especially in large networks. In reality, it is not efficient or even possible to distribute heat from all heat production units.

The investment costs of network-related attributes were often neglected, especially in the case of LTDH networks. Due to the lack of knowledge on the actual costs of integrating LTDH networks, it is hard to estimate the actual benefits of LTDH networks. LTDH networks would require investments both on distribution-grid level and on the level of household appliances. Furthermore, the investment costs for DCs were neglected in Publication II.

Spot electricity prices were included in most of the simulations in the publications. However, the effects of decreasing electricity production from CHPs and increased electricity demand due to HPs on electricity prices were

mainly neglected. If a high amount of electricity production from CHPs were to be removed, it is likely that electricity prices would consequently increase. Vice versa, if the amount of HPs were to increase, it would increase electricity demand and therefore heat prices. These effects should be modeled in future research.

Finally, most of the parameters used in the simulations contain uncertainty. The uncertainty was not studied in a systematic manner in most cases, only through different scenarios. Uncertainty should be considered in the modeling, especially if modeling is conducted with a longer time horizon. Most importantly, conflicting arguments have been presented regarding how fuel costs, electricity prices, and DH demand will develop in the following years and decades.

5.3 Further research and recommendations

In this thesis, the focus on waste heat utilization was on DCs. In order to increase waste heat utilization further, the potential for locally available heat sources should be systematically mapped and evaluated. This is also important when considering increasing the amount of HPs in the networks since low-temperature waste heat often requires boosting temperature with HPs to suitable levels for DH. Additionally, networks have different possibilities for how much of the total heat supply can be produced with HPs, and therefore the limits should be analyzed individually for each network.

Investment costs and the economic impacts of supplying DC waste heat to DH for DC operators was left out of the scope of this dissertation, but it requires a thorough assessment. The authors of Publications II and III have studied these implications further in [60]. Additionally, there are other alternatives for DC waste heat utilization, such as greenhouses, and the profitability of waste heat should be assessed in these cases.

Further research into the costs and measures of implementing LTDH networks for specific systems is required. Piloting LTDH networks could be taken into account in city planning, for example, in planning new housing areas. Apart from piloting, a detailed, network-level analysis of distribution temperatures and heat demands should be conducted in order to find and analyze the bottlenecks in the network and evaluate whether it would be possible to lower temperatures in some parts of the network.

The policy aspects of developing DH were not considered in this thesis, but since the EU is starting to put more effort into decarbonizing DH, there are several aspects to be considered in making smarter systems possible through policymaking. For example, TPA requires a level playing field, and political guidance determines whether TPA is heavily regulated or not.

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Appendices

Appendix A: Publication I

Wahlroos, Mikko; Cross, Sam; Syri, Sanna. 2014. Prospects for biomass use in large power plants in the EU-27 and the role of Combined Heat and Power production. IEEE 11th International Conference on the European Energy Markets (EEM), Krakow, Poland, 28-30 May, 2014. Pages 1-5. DOI: [10.1109/EEM.2014.6861250](https://doi.org/10.1109/EEM.2014.6861250)

Appendix B: Publication II

Wahlroos, Mikko; Pärssinen, Matti; Rinne, Samuli; Syri, Sanna; Manner, Jukka. 2017. Utilizing data center waste heat in district heating – Impacts on energy efficiency and prospects for low-temperature district heating networks. Elsevier. Energy, volume 140, issue 1, pages 1228-1238. ISSN: 0360-5442. DOI:10.1016/j.energy.2017.08.078.

Appendix C: Publication III

Wahlroos, Mikko; Pärssinen, Matti; Rinne, Samuli; Syri, Sanna; Manner, Jukka. 2018. Future views on waste heat utilization - case of data centers in Northern Europe. Elsevier. Renewable and Sustainable Energy Reviews, volume 82, issue 2, pages 1749-1764. ISSN: 1364-0321. DOI:10.1016/j.rser.2017.10.058.

Appendix D: Publication IV

Rämä, Miika; Wahlroos, Mikko. 2018. Introduction of new decentralised renewable heat supply in an existing district heating system. Elsevier. Energy, volume 154, pages 68-79, ISSN: 0360-5442. DOI: 10.1016/j.energy.2018.03.105.

Appendix E: Publication V

Dominković, Dominik Franjo; Wahlroos, Mikko; Syri, Sanna; Pedersen, Allan Schrøder. 2018. Influence of different technologies on dynamic pricing in district heating systems: comparative case studies. Elsevier. Energy, volume 153, pages 136-148. ISSN: 0360-5442. DOI: 10.1016/j.energy.2018.04.028



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