

Department of Mechanical Engineering

District heating with low-carbon heat sources and low distribution temperatures

Miika Rämä



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Energy supply sector is the largest source of anthropogenic emissions with a share of more than a third in global greenhouse gas (GHG) emissions. In terms of energy demand, the heating and cooling sector corresponds to more than a half of the global final energy consumption. Urban areas have been evaluated to be responsible of 76 % of global energy use and 37-49 % of the GHG emissions. The relevance of cities in the context of climate change mitigation and the significance of the heating and cooling sector imply that solutions for urban areas are an essential part of the mitigation measures needed. This is where district heating (DH) and district cooling (DC) technologies can play an important role. Both DH and DC are energy solutions designed for densely populated areas.

This thesis focuses on developing DH systems by studying means for improving their efficiency and integrating more low-carbon heat sources for heat supply. The potential impact of low temperature distribution is also assessed. The heat sources considered in the scope of the presented research are heat pumps (HPs), solar collectors (SCs) and nuclear district heating (NDH).

Centralized SCs provide 4-5 times higher heat output than decentralised building-specific units with the same total investment. However, HPs outperform the centralized SCs in Finnish DH systems by producing 9-30 times more heat with the same investment. The feasibility of NDH is strongly linked to the DH demand and distance between the site and the DH system.

Low temperature distribution reduces the heat losses and, more importantly, improves the efficiency of connected heat supply. A fair and transparent allocation of benefits and costs is a prerequisite for the transition due to stakeholders involved. The benefits are for heat supply and distribution (DH company) while costs mainly result from required building-level changes (customer). The use of low temperature distribution requires more careful management of the temperature levels, making network simulation tools both in planning and operational phase important. Both HPs and SCs benefit from low distribution temperatures.

Keywords District heating, energy systems, low-carbon heat, low temperature distribution, heat pumps, solar collectors, nuclear district heating

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Energian tuotanto on nykyisellään suurin ihmisen toiminnan seuraksena syntyvien kasvihuonekaasupäästöjen (KHK) lähde yli kolmanneksen osuudellaan globaaleista KHK-päästöistä. Energian kulutuksesta lämmitys ja jäähditys puolestaan vastaavat yli puolta koko maailman energian loppukulutuksesta. Kaupunkialueiden on arvioitu vastaavan 76 %:sta globaalia energian kulutusta ja 37-49 % KHK-päästöistä. Kaupunkien olennainen rooli ilmastonmuutoksen hillinnässä yhdistettynä lämmitys- ja jäähdityssektorin merkitykseen osoittavat kaupunkialueiden olevan avainroolissa pohdittaessa tarvittavia päästövähennystoimia. Tämä on myös se ympäristö, jossa kaukolämpö (KL) ja kaukojäähdytys (KJ) voivat näytellä tärkeää roolia. Molemmat edustavat energiaratkaisuita tiheästi asutetuille alueille.

Tämä väitöskirja keskittyy KL-järjestelmien kehittämiseen tutkimalla mahdollisuuksia parantaa järjestelmien tehokkuutta ja lisäämällä uusiutuvien lämmönlähteiden osuutta. Osana kokonaisuutta arvioidaan myös matalamman KL:n siirtolämpötilan merkitystä. Lämmönlähteistä työssä arvioidaan lämpöpumppujen, aurinkokeräimien ja ydinkaukolämmön toimintaa.

Samana suuruusella investoinnilla keskitetyt aurinkokeräimet tuottavat 4-5 kertaa enemmän lämpöä kuin hajautetut rakennuskohtaiset keräimet. Lämpöpumput puolestaan peittoavat keskitetyt keräimet 9-30 suuremmalla tuotannolla, olettaen saman investoinnin. Ydinkaukolämmön toteutettavuus on taas voimakkaasti kytköksissä kaukolämmön tarpeeseen sekä laitoksen ja KL-järjestelmän väliseen etäisyyteen. Matala siirtolämpötila pienentää lämpöhäviöitä ja parantaa järjestelmään kytkettyjen lämmönlähteiden hyötysuhdetta. Sekä lämpöpumput että aurinkokeräimet hyötyvät matalasta siirtolämpötilasta. Hyötyjen ja kustannusten reilu ja läpinäkyvä kohdistaminen on esivaatimus siirtymälle matalampiin siirtolämpötiloihin stelmän eri toimijoiden roolien johdosta. Hyödyt näkyvät lämmön tuotannossa ja siirrossa (kaukolämpöyhtiö), mutta kustannukset ovat pääosin seurausta vaadittavista rakennustason muutoksista (asiakkaat). Matalammat siirtolämpötilat edellyttävät myös tarkempaa lämpötilojen hallintaa siirtoverkossa, joka puolestaan korostaa simulointityökalujen merkitystä sekä suunnittelussa että operatiivisessa toiminnassa. Sekä lämpöpumput että aurinkokeräimet hyötyvät matalasta siirtolämpötilasta.

Avainsanat Kaukolämpö, energiajärjestelmät, vähähiilinen lämpö, matala siirtolämpötila, lämpöpumput, aurinkokeräimet, ydinkaukolämpö**ISBN (painettu)** 978-952-60-3974-9**ISBN (pdf)** 978-952-60-3977-0**ISSN (painettu)** 1799-4934**ISSN (pdf)** 1799-4942**Julkaisupaikka** Helsinki**Painopaikka** Helsinki**Vuosi** 2020**Sivumäärä** 125**urn** <http://urn.fi/URN:ISBN:978-952-60-3977-0>

Acknowledgements

This dissertation is something that did not appear even in my wildest dreams when I started my research career as a research assistant in the Helsinki University of Technology and the Laboratory of Applied Thermodynamics in 2002. Of course back then I did not know we would be talking about a career. In some ways, I still do not even see it as such – but rather as a long chain of agreeable choices that have kept me interested. What a journey it has been!

Even though continuing directly from the University to VTT Technical Research Centre of Finland to work on my master thesis in 2005, and staying further on to become a research scientist, a senior scientist and finally, a team leader, I did not actively consider pursuing a PhD for a very long time. This all changed in 2016 when I had motivation, funding – and encouragement from a very special person all at the same time. Also, after ten years of experience in research, I realised that I actually might know something about my research topic; district heating and cooling.

The research presented in this thesis has been carried out between 2016-2018 and made possible by funding from several projects including EU's Horizon 2020 programme projects INDIGO and mySMARTLife as well as support from VTT Technical Research Centre of Finland. I am thankful for the funding.

I wish to thank professor Sanna Syri from the Aalto University School of Engineering and the Department of Mechanical Engineering for both guidance and patience. Both were very much needed and more than welcome for an easily-distracted research scientist such as me.

A very profound thank you has to go to Kari Sipilä, who hired me to VTT and is also responsible in introducing me both to the world of research and of district heating and cooling. For many years, we worked together as a working pair. I value greatly this time and all the experience Kari shared with me.

I am also very grateful to all my co-authors. All the papers included in this thesis are results from different cooperation opportunities. Aforementioned Kari Sipilä is an example of internal cooperation within VTT. With Itzal and the whole Tekniker crew we have had years of continuous cooperation in EU-funded projects. Soma Mohammadi I got to know during her research exchange period in Finland at VTT. She is both hard-working and brilliant. Mikko Wahlroos was a PhD student of Sanna Syri at Aalto University, and more than a pleasure to work with. We simply connected from day 1. Finally, I am truly indebted to Martin Leurent who in addition to managing our cooperation in CEA that led to several research papers to helped me to realise a visiting researcher period in Paris. This period turned out to be one of the most memorable and interesting years of my life so far.

I have been lucky to have worked and got to know a brilliant and funny group of people here at VTT. These smart men and women have long been much more than mere colleagues and I

hope the friendships formed will be there for the rest of our lives. It is crystal clear I would not be where I am now without this community, not professionally and definitely not as a person.

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Helsinki, 26th January 2020

Miika Rämä

Contents

Acknowledgements	1
List of Abbreviations and Symbols	5
List of Publications.....	6
Author’s Contribution.....	7
1. Introduction	9
1.1 Global outlook on DH.....	10
1.2 Assessing DH potential in Europe	11
1.3 Finnish DH industry.....	12
1.4 Research questions and scope	13
2. Literature review.....	15
2.1 4 th generation district heating.....	15
2.2 Low temperature distribution.....	16
2.3 Flexibility and sector coupling.....	17
2.4 Biomass.....	18
2.5 Heat pumps	18
2.6 Solar thermal collectors.....	19
2.7 Nuclear district heating	19
3. Approach and methods	21
3.1 DH systems considered	22
3.1.1 DH in low heat demand areas.....	22
3.1.2 Large-scale DH system	23
3.1.3 Future DH systems	23
3.2 Modelling methods	24
3.2.1 Heat demand estimation	24
3.2.2 Network simulation model.....	25
3.2.3 Heat supply modelling and optimization	25
3.3 Economic analysis.....	27
4. Results	29
4.1 Low-carbon heat sources for DH systems.....	29

4.2	Benefits and challenges of low distribution temperatures	33
4.3	Economic impacts.....	37
4.4	Overall impact and required changes for existing systems	40
5.	Discussion and conclusions	44
	References	49

List of Abbreviations and Symbols

DH	District heating
DHC	District heating and cooling
HP	Heat pump
SC	Solar collector
NDH	Nuclear district heating
RES	Renewable energy source
RED	Renewable Energy Directive
RED2	Renewable Energy Directive 2
CHP	Combined heat and power
DHW	Domestic hot water
SH	Space heating
VRE	Variable renewable energy
4GDH	4 th generation district heating
LCOH	Levelized costs of heating

List of Publications

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

- 1.** Rämä M, Sipilä K. Transition to low temperature distribution in existing systems. *Energy Procedia*, 2017. doi:10.1016/j.egypro.2017.05.055.
- 2.** del Hoyo Arce I, Herrero López S, López Perez S, Rämä M, Klobut K, Febres JA. Models for fast modelling of district heating and cooling networks. *Renew Sustain Energy Rev* 2018;82:1863–73. doi:10.1016/j.rser.2017.06.109.
- 3.** Rämä M, Mohammadi S. Comparison of distributed and centralised integration of solar heat in a district heating system. *Energy* 2017. doi:10.1016/j.energy.2017.03.115.
- 4.** Rämä M, Wahlroos M. Introduction of new decentralised renewable heat supply in an existing district heating system. *Energy* 2018. doi:10.1016/j.energy.2018.03.105.
- 5.** Leurent M, Da Costa P, Rämä M, Persson U, Jasserand F. Cost-benefit analysis of district heating systems using heat from nuclear plants in seven European countries. *Energy* 2018. doi:10.1016/j.energy.2018.01.149.

Author's Contribution

Publication 1: Transition to low temperature distribution in existing systems

Miika Rämä is the main author. He developed the approach and carried out the supporting calculations. Kari Sipilä commented on the paper.

Publication 2: Models for fast modelling of district heating and cooling networks

Itzal del Hoyo Arce is the main author. Miika Rämä was responsible for developing and defining Apros© simulation models that were used in validation of the developed Modelica© library simulation model components.

Publication 3: Comparison of distributed and centralised integration of solar heat in a district heating system

Miika Rämä is the main author and defined the case study system, built and ran the network simulation model and analysed the results. Soma Mohammadi was responsible for the solar collector modelling.

Publication 4: Introduction of new decentralised renewable heat supply in an existing district heating system

Miika Rämä is the main author responsible for selecting and defining the case study system, approach and analysis of results. Mikko Wahlroos built, configured and ran the energy system model used.

Publication 5: Cost-benefit analysis of district heating systems using heat from nuclear plants in seven European countries.

Martin Leurent is the main author. Miika Rämä provided information on district heating technology as a basis for the analysis and checked the assumptions made. He also commented on the paper.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) special report on impacts of global warming of 1.5 °C and related global greenhouse gas (GHG) emission pathways [1] highlights the urgency of climate change mitigation actions. It indicates that significant emission reductions are needed during the next decade to maintain peak warming close or below 1.5 °C. In addition to the current unconditional Nationally Determined Contributions (NDCs) [2] within the Paris Agreement [3], 42-57 % additional emission reductions are needed by 2030. Net zero emissions are to be reached around 2050 [1].

Energy supply sector is the largest source of anthropogenic emissions with a share of more than a third in global GHG emissions. In terms of energy demand, the heating and cooling sector corresponds to more than a half of the global final energy consumption. It has been evaluated that while the global heat demand will keep on increasing slowly until 2050, the cooling demand is already growing, and is projected to surpass heat demand in the 2050s [5].

The global trend of urbanization is expected to have a significant impact on climate change mitigation measures. Urban areas create approximately 80 % of world gross domestic product (GDP) and have been evaluated to be responsible of 76 % of global energy use and 37-49 % of the GHG emissions. [4] The relevance of cities in the context of climate change mitigation and the significance of the heating and cooling sector imply that solutions for urban areas are an essential part of the mitigation measures needed. This is where district heating (DH) and district cooling (DC) technologies can play an important role. Both are energy solutions designed for densely populated areas.

DH and DC are technologies for distributing efficiently produced heating or cooling to the consumers through a network of insulated pipes, most often using water as a transport medium. The specific emissions and overall efficiency of the district heating and cooling (DHC) systems depend on all energy sources, production and distribution technologies used. Together with energy efficiency in buildings, district energy solutions provide an opportunity for cost-optimization; investments in building energy efficiency can be evaluated together with investments in low-carbon heat supply and DH as demonstrated by Möller et al. [6]. This supports the implementation of the most cost-optimal emission reduction measures. Suitable policies, regulation and cooperation between numerous involved stakeholders are all required.

An additional benefit of DHC in the context of energy system decarbonization is its integration potential. The integration can be combined heat and cooling production or use of, e.g., excess heat sources within the connected buildings otherwise wasted. Electricity-based heat supply technologies like heat pumps (HPs) or CHP units enable DHC systems to provide flexibility for the power system with a large share of variable renewable energy (VRE) based electricity production. The heating and cooling storages represent an economic option for large-

scale energy storage solution – as long as there is significant heating and cooling demand connected to the system.

This thesis focuses on the pathways for developing different, existing DH systems in order to improve their efficiency and to integrate more low-carbon heat sources. The heat sources considered in the scope of the presented research are heat pumps (HPs), solar collectors (SCs) and nuclear district heating (NDH). The potential impact of the low temperature distribution is also considered in the thesis. Although the research includes mostly case studies for specific, existing systems, many of the lessons learned are applicable in planning of new DH systems. New systems are also of interest as the changes proposed are the easiest to implement for new areas and buildings. The thesis consists of an introduction (Chapter 1) presenting the background, an outlook on the status of DH in global, European and Finnish contexts, the research questions and the scope of the research carried out. Chapter 2 presents a literature review describing an overview of the current, related DH research. Chapter 3 describes the approach and methods used in the presented research, Chapter 4 presents the results of the research and finally, Chapter 5 discusses the findings and summarizes the main conclusions.

1.1 Global outlook on DH

The market share of DH in the global heating sector is 8 % with 20 556 TWh of heat supplied in 2013 [7]. On a country level, the situation varies greatly. The Nordic, Baltic, many Eastern European countries and Russia all have market shares of around 40 % or more. In terms of DH supplied (2013), Russia (1 278 TWh) and China (888 TWh) clearly stand out with Germany, South Korea and the Nordic countries also having a strong DH sector [7,8]. Figure 1 presents the DH deliveries and market shares of notable DH countries globally, excluding the aforementioned Russia and China.

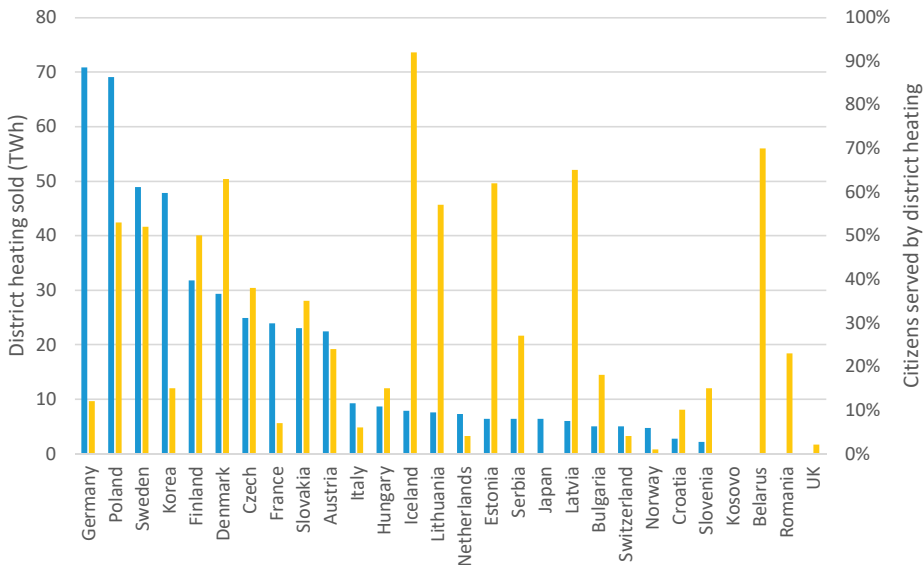


Figure 1. DH deliveries and percentage of citizens served by DH in selected countries in 2013 [8].

While more than 90 % of global district heating is supplied by fossil fuels, there is a substantial potential for increasing the use of renewable sources of heat. The implementation of low temperature distribution would make the systems well suited for, e.g. solar thermal, geothermal and excess heat sources [9]. Renewables could feasibly supply over 20 % of energy needs of the DHC systems in just a few years. Depending on the characteristics of a specific country, this figure could be much higher by 2030 [10]. The UN Environment's initiative, District Energy in Cities, supports this development by increasing awareness, demonstration of viability and developing enabling frameworks on a country level [11].

The potential of DH has been further explored and discussed by Werner [7], who states that while the policy makers have been in search of energy technologies with higher supply security, lower costs and lower GHG emissions, the DHC industry has not grown during the last two decades. Werner points out that in order to change this, a new approach and creating awareness around DHC is needed. The implementation of DHC systems is always linked to the local conditions and characteristics, while a fossil-based society can apply the same, generic solutions globally.

1.2 Assessing DH potential in Europe

The potential for DH implementation in Europe has been widely studied within the Heat Roadmap Europe project series [12–15]. The projects include an analysis of large-scale expansion of DH within EU and study the role of DH in context of a whole energy system. Following paragraphs describe the work carried out in more detail.

The first pre-study [12] found that the estimations made in the Energy Roadmap 2050 [16] by the European Commission concerning the potential for DH are modest; a 20 % increase by 2030 and a 40 % by 2050 was expected. The pre-study concluded that DH consumption could grow by a factor of 210 % by 2030 and 330 % by 2050. The second pre-study [13] strengthened the connection between the energy system modelling and the mapping of heat demand and excess heat sources. Persson et al. [17] assessed the energy and industry sector excess heat resources and identified synergy regions within EU27 for large-scale implementation of DH. Connelly et al. [18] developed a European Heat Atlas for detailed evaluation of heat demands within the EU27. They also carried out a scenario-based study similar to the first pre-study. The updated study compared an energy efficiency-based scenario based on the Energy Roadmap 2050 [16] to a scenario including a large-scale expansion of DH. The DH scenario was based on aforementioned detailed mapping of heat demand and excess heat sources. The scenarios were modelled using the EnergyPLAN [19] energy system model. Connelly et al. [18] concluded that the actions within the heating and cooling sector enable reaching the EU27-level CO₂ emission reduction targets and were 15 % cheaper in the DH-heavy scenario than with a low share of DH. This supports the argument that balancing investments between energy efficiency, DH and heat supply options leads to a cost-optimal outcome.

The third [14] and fourth [15] Heat Roadmap Europe studies refined the approach by forming country-level strategies for heating and cooling, and then defining detailed EnergyPLAN models, first for five member states and later expanding the number of countries to 14.

The third study with national heating and cooling strategies for the five member states found a potential for 15 % savings, over 1 000 TWh reduction in energy demand and total CO₂ emission reductions of 275 Mt/year compared to the business-as-usual scenarios [14].

The fourth study combined long-term development of the national energy systems modelled by JRC-EU-TIMES [20], Pan-European Thermal Atlas [21] and FORECAST [22] for energy savings costs curves for industry and built environments as input data for a country-specific EnergyPLAN [19] analysis. The results for the 14 countries included 6 % savings in total costs of decarbonization by redesigning the heating and cooling sector, 10 400 TWh reduction in use of fossil fuels and 4 340 Mt CO₂ emission reductions. The conclusions emphasize the potential of DHC and point out that it should be viewed as an essential infrastructure. DH was envisioned to provide at least 50 % of the supplied heat. The heat supply technologies consist of CHP-based production (25-35%), HPs (20-30 %), excess heat utilization (25 %), geothermal and solar thermal heating (5 %) and peak boilers (10 %). The role of the CHP units would be to provide flexibility for the power system, and not operate as a base-load [15].

As observed in the Heat Roadmap Europe project series, the heating and cooling sector have curiously been long neglected in European energy policy despite having a significant share in the final consumption of energy. DH and DC are present in the original renewable energy directive (RED) [23] and energy efficiency directive (EED) [24]. However, their content has been mainly to encourage the member states to evaluate the potential of DHC and efficient co-generation (i.e. CHP) with less concrete targets or measures to support this. EED and its Article 14 on promotion of efficiency in heating and cooling calls for a potential mapping and a cost-benefit analysis regarding realization of this potential for all member states. However, as evaluated by the Joint Research Centre (JRC) assessment of the implementation of EED and Article 14 [25], the implementation of the directive and the article vary between countries as they mainly used their own approaches rather than followed the non-binding guidelines. Article 14 itself was considered to be imprecise and ambiguous in terms of its wording. The heating and cooling sectors are also different in member states and the lack of data reduced the accuracy of the analyses. This all made the comparison of the results difficult. Thus, addressing the issue of data quality and availability as well as defining a more standardized format for the assessments was recommended.

The European heating strategy [26] represents a clear milestone in the role of heating and cooling in the European policy context, recognizing the sector as a major element in reaching European emission reduction targets along with the electricity and transport sectors. The strategy highlights the potential of DHC, building energy efficiency, use of industrial excess heat, renewable heat sources, CHP and interaction with the electricity sector. The revised renewable energy directive (RED2) [27], and especially its Article 24 on DHC, promotes most of the aforementioned items with more concrete wording than before.

1.3 Finnish DH industry

From the global perspective of the DH industry, Finland has a noticeably high market share of DH. Within cities, the share is even higher; e.g. over 90 % in the capital, Helsinki. The Finnish DH systems are characterized with high efficiency and a large share of CHP-based heat supply. The CHP plants make up 42 % (7 270 MW) of the total national installed electricity production capacity with the shares of industry and district heating co-generation being 18 % and 24 %, respectively [28]. Although the total installed capacity in MWs is not in practice used due to demand and import options, the CHP plants are estimated to represent more than 40 % of the domestic electricity production during periods of peak consumption in winter time [29].

However, the back-pressure and base-load CHP plant design common in Finland is not an ideal match for the envisioned future Nordic energy system with the increasing penetration of wind power as a more flexible operation is required. Moreover, the most large-scale CHP units currently in operation are using fossil fuels and will be phased out at some point. Coal-fired CHP plants are to be phased out already at 2029 when the ban of coal [30] in energy use takes effect. The share of CHP-based production in total DH supply is already declining, from 75 % in 2008 to 67 % in 2018 [31].

The national and European emission reduction targets and the low-carbon energy transition taking place within the surrounding energy system have already been shaping the development of the DH industry. The use of renewable fuels and heat recovery has increased and the specific emissions of DH in Finland have decreased substantially during the past 10 years (Figure 2).

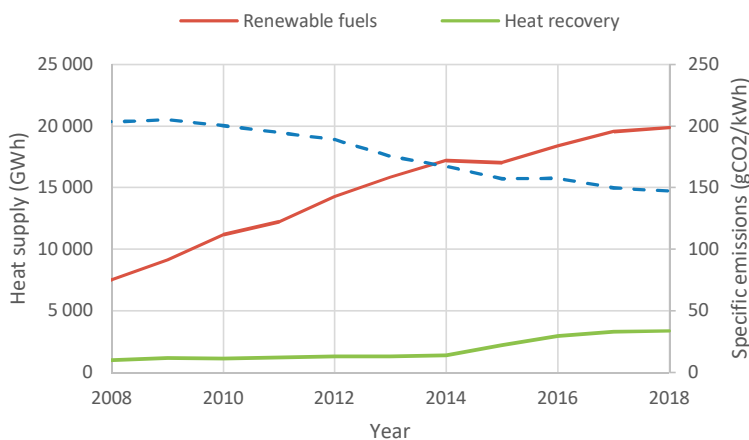


Figure 2. Renewable fuels and heat recovery in DH supply (solid lines) and specific emissions of Finnish DH [31].

The main challenges within the Finnish DH industry are linked to the continuation of this development. The March 2018 decision to ban the use of coal in energy production by 2029 [30] and the national target of reaching emission neutrality by 2035 set by the current government [32] both create an environment for the DH industry where the current planning and operation of the systems will need to be examined and developed.

The more concrete items for the development of DH systems in Finland are the integration of low-carbon heat sources, the possible transition to the low distribution temperatures and the solutions enabling flexibility services for the power system.

1.4 Research questions and scope

The research presented in the thesis aims to answer the following main research questions:

- Q1: How should the integration of **new low-carbon heat sources** be modelled in DH systems?*
- Q2: What are the benefits and challenges of implementing **low distribution temperatures**?*
- Q3: What are **the techno-economic impacts for existing DH systems** concerning integration of new heat sources and implementing low temperature distribution?*

The publications included in the thesis aim to find answers for these questions by developing different approaches and methods, and applying these to different case studies. The scope and type of each paper is summarized in Table 1.

Table 1. Type and scope of the publications included in the doctoral dissertation.

Publication	Type of a paper	Scope
Paper 1	Discussion	Presenting a framework for assessing the benefits and costs of transition to low temperature distribution in DH systems.
Paper 2	Method development	Developing DH simulation tools needed for control and research-related activities.
Paper 3	Case study	Investigating the operation of distributed and centralized SCs as a heat source for a low-heat density DH system.
Paper 4	Case study	Studying the impacts of introducing new HP and SC capacity in an existing large-scale DH system.
Paper 5	Case study	Carrying out a cost-benefit analysis for NDH in 15 alternative systems in Europe.

In addition to the main research questions, the individual papers address more specific questions that can be categorized under the main questions. The specific questions and their relation to the main questions are presented in Table 2.

Table 2. The specific research questions for each publication and their connection to the main research questions.

Publication	Main research questions	Publication specific questions
Paper 1	Q1, Q2 and Q3	What are the component-level impacts in a transition to low temperature distribution in DH? How can the transition process be assessed as a whole?
Paper 2	Q2 and Q3	What are the technical challenges in network simulation of a large-scale DH network? What is a reasonable accuracy for a network model connected with a model predictive controller (MPC)?
Paper 3	Q1, Q2 and Q3	How do solar collectors perform as distributed and centralized units? What is their local impact on the DH network? What is the benefit of having low temperature distribution?
Paper 4	Q1, Q2 and Q3	What impact will added heat pump and/or solar collector capacity have on an existing DH system? How does low temperature distribution impact the results?
Paper 5	Q1	What is the potential of nuclear-based heat as an emission-free heat source for DH?

2. Literature review

This chapter discusses the current DHC-related research focusing on topics closely related to the research presented in the thesis. Some of the topics are directly linked, while others provide background and reasoning for the choice of scope. The main topics are low-carbon heat sources, low distribution temperatures for DH and coupling between DH and electricity sectors:

- 1) The main low-carbon heat sources are biomass, utilization of heat sources with or without a heat pump, solar thermal collectors and nuclear heat with each heat source having different implementation options and specific challenges.
- 2) Low temperature distribution improves distribution system efficiency and the utilization of any heat source.
- 3) Due to heat storages, CHP-based production and HPs there is a natural connection between the electricity sector and DH, and a potential for providing flexibility.

All three can be considered to be part of the 4th generation district heating (4GDH) concept.

2.1 4th generation district heating

When addressing pathways for developing DH systems, the concept of 4GDH cannot go unmentioned. The term was coined by Lund et al. [33] in 2014. It is a concept wherein the main characteristics are:

- 1) Closer links to other long-term infrastructure planning processes such as city planning
- 2) Low temperature heat distribution systems within consumer buildings
- 3) A smart low temperature DH distribution network
- 4) Excess heat and renewable heat source integration
- 5) Closer connections with the surrounding energy system

The 4GDH concept is present in most research articles included in the literature review.

Lund et al. describe a development path through the DH generations from steam-based systems towards 4GDH with increasing variety in heat sources, lowering distribution temperatures, increasing efficiency, including energy storages and more integration with cooling and electricity production. Shortly put, the 4GDH is a low-carbon, high efficiency DHC system integrated into the surrounding energy system.

Li and Nord [34] discuss the possibilities, bottlenecks and challenges for a 4GDH transition. They define the first step in the transition to be the introduction of lower distribution temper-

atures. Li and Nord also state that while changes in the physical system are required, development is also needed in online control, communication, data collection and analysis. Li and Nord also point out that decreasing heat demand will have an impact on the desirable future system design. Volkova et al. [35] proposed a methodology for evaluating the transition progress in terms of KPIs based on identified barriers.

Ziamele et al. [36] present an approach combining an empirical case study with a system dynamics model and input from the decision-maker level to model the transition to 4GDH. The results show potential pathways for the transition. The approach offers a fresh perspective concerning a research question that is often answered only by operational and investment optimization models.

The overall assessment of the transition needs to be carried out from a system perspective to take advantage of each component's potential, level or stakeholder connected. This is a challenge due to the large number of stakeholders involved, the ownership of assets and the uneven allocation of benefits and costs due to the transition.

2.2 Low temperature distribution

A key element of the 4GDH concept is low temperature distribution, which has its roots in earlier research focusing on improving the economic feasibility of DH systems in areas of low heat demand by decreasing the relative heat losses. For this purpose, smaller pipe sizes, minimizing the network length and low distribution temperatures were proposed [37–39].

In the current research, the focus is much more on the new heat sources enabled by low distribution temperatures than the heat losses. The main benefits for the heat sources are improved potential for heat recovery from flue gas condensation in combustion of, e.g. biomass and waste, enabled use of geothermal and industrial excess heat, increased yield of solar thermal-based heat supply, increased electrical capacity for CHP units with the same heat demand and higher COP values for heat pumps [33,40]. Lund et al. [41] compared different levels of DH distribution temperatures in an energy system analysis, concluding that 55/25 °C as supply and return design temperatures have the lowest overall costs. Reduction of the DH temperature levels in general was confirmed as a feasible strategy in the development towards a renewable energy-based energy system.

For achieving the desired low distribution temperatures, Averfalk and Werner [42] identified the undesirable design aspects of the current DH systems and offered compatible solutions for implementing the 4GDH concept.

The definition of low temperature distribution itself in terms of temperature level is not fixed. However, the temperature requirement for domestic hot water (DHW) and space heating (SH) define a certain threshold for the supply temperature. Depending on country-specific regulations, DHW requirements are in the region of 55-60 °C [43]. SH requirements depend on the building heat distribution systems, where supply temperatures are commonly outdoor temperature dependent. Maximum supply temperatures of 53-81 °C for radiator-based systems were encountered in a study by Jangsten et al. [44], while typical floor heating systems used temperatures 30-40 °C [45]. These temperatures correspond to the secondary side temperature and thus, actual primary side supply temperature depends on heat exchanger design.

Using a lower supply temperature than required means that additional heating or changes in the heating system design in consumer buildings are needed to provide DHW, SH or both. The

thresholds for the need to provide additional measures can be considered a logical method for defining specific temperature levels for different low distribution temperature systems.

As an example of a special case in terms of temperature levels, Prasanna et al. [46] present a combined heating and cooling system where the distribution network is purely used as a heat source for heat pumps or a heat sink for cooling purposes. Supply and return temperatures, 8-22 °C and 4-17 °C, respectively, are close to typical DC temperature levels. The presented design can recover excess heat and efficiently utilize natural heat sources, such as geothermal energy. It is also well-suited for locations where peak heating and cooling demand, i.e. required network capacity, are in balance.

Implementing low temperature distribution can require changes in existing buildings and to the design principles of new buildings. In practice, the DH industry is likely to extend its responsibilities into the building side in the future. This opens up new service-driven business models for the industry and could also help in providing the data supporting the operation of a more complex system envisioned in current research.

2.3 Flexibility and sector coupling

Flexibility for the power system and overall closer integration with the surrounding energy system are issues that are likely to steer the development of DHC systems. The heating and cooling sector is also where demand response systems and energy storages are currently very affordable. The significant thermal mass of buildings and heat distribution systems within buildings connected to DH allow demand response to be implemented easily and the large connected demand increases the potential impact. Thermal energy storages have low unit costs in terms of investment compared to the alternative energy storages.

These are both evident in many studies. However, Salo et al. [47] found that the demand response measures result only in modest cost savings (0.7 %) for the DH system itself with a connected thermal storage increasing these savings up to 1.4 %.

In the context of the energy system, and especially integration of VRE based electricity production, flexibility provided by the heating sector can have a more significant impact. Kiviluoma and Meibom [48] studied the use of heat storages, heat pumps, electric boilers, CHP units and plug-in electric vehicles as flexibility measures to incorporate more wind power. The heating sector-related measures increased the optimal wind power penetration more than the electric vehicle based flexibility measures.

Yu et al. [49] compared different types of energy storage technologies and heat pumps for promoting wind power integration in a system with CHP plants. Heat pumps represented the best option, followed by thermal storage. Thus, Yu et al. argued that the best outcome could be reached with a combination of the two technologies.

Schweiger et al. [50] studied the potential of power-to-heat based DH production in integration of wind and solar power. The potential was estimated to be up to 8.6 TWh with high penetration (54-64 %) of wind and solar power. Base-load heat supply such as use of excess heat and/or waste incineration reduced the potential.

Mathiesen et al. [51] carried out an analysis for a 100 % renewable energy system including biomass usage, gas distribution and storage, electric vehicles, electrofuels and DH. Although feasible, such a fully integrated system needs to be carefully designed.

Combining the findings concerning the flexibility enabled by DH for an energy system with high penetration of VRE-based electricity production [48–51] and the results by Salo et al. [47]

indicate that the flexibility potential on an energy system level is undisputable, but the value for providing this flexibility has not yet materialized.

2.4 Biomass

Biomass can be used directly in combustion by CHP units and boilers or as feedstock for various biofuel production processes with excess heat. As a result of the various uses, the biomass availability, price, logistics and sustainability in large-scale use are to be taken into account in its role in DH heat supply. This point is recognized in the work of Ericsson and Werner [52] concerning the future of direct use of biomass in Swedish DH systems. They emphasize the fundamental ability of a DH system to utilize recycled heat that could be recovered from, e.g. biofuel production processes.

This competition for biomass as a resource is also the topic of a study by Gerssen-Gondelach et al. [53]. Although not addressing the potential of heat recycling, the study presents the various uses for different kinds of biomass in addition to direct energy use. Hannula [54] proposes that dimensioning a biorefinery should be based on maximizing the use of by-products with recovered heat being one of these.

Lund and Mathiesen [55] investigate the role of large-scale CHP plants in a sustainable energy system, recognizing that efficient use of the biomass resource is an essential feature of a sustainable system. A regulatory framework steering the long-term planning of CHP plants is needed. Combined cycle gas turbine plants using gasified biomass as fuel should be preferred as a flexible and efficient CHP plant design and an economic constraint, such as a tax on direct combustion of biomass in HOBs, is recommended.

2.5 Heat pumps

A HP is not actually an energy production technology. It transfers thermal energy from a heat source in a lower temperature level to supply a thermal energy demand in a higher, useful temperature - with an input of work. The efficiency of the heat pump depends on the temperature levels in question and its potential on the available heat source itself. Heat pumps are an integral part of the power-to-heat concepts present in many studies.

David et al. [56] carried out a survey on an existing large-scale heat pump-based DH supply in Europe and analysed the four defining aspects for assessing the future for large-scale heat pumps in DH; the heat sources, available refrigerants, temperature levels and type of operation.

Lund and Persson [57] investigated the topic by carrying out a mapping of low temperature heat sources for heat pumps. Focus was on heat sources unavailable without a heat pump with energy production plants, boilers, solar and geothermal excluded from the analysis. The study recognized the relevance of the results to be limited to Denmark, also pointing out that temporal availability of the resources should be studied further.

Back et al. [58] studied the integration of large-scale heat pumps in the DH system of Greater Copenhagen utilizing three identified major heat sources, drinking, sewage and sea water. The total heat pump capacity considered was 260 MW, representing 11 % of the other base-load heat supply such as CHP units (2000 MW), geothermal and waste incineration (100 MW). With the temperature-dependent COPs taken into account, the results varied greatly between scenarios where heat pumps were connected to the distribution (with lower temperature level)

or the transmission network. The full load hours (FLHs) for these cases were 3 500-4 000 h and 2 500-3 000 h, respectively.

Averfalk et al. [58] studied the use of large heat pumps in Swedish DH systems from the 1980s to 2017. A remarkable growth was experienced during the 1980s with total heat pump capacity reaching almost 1300 MW in five years. 80 % of peak capacity installed (1527 MW) is still in use. Since 2000, there has been a decline both in capacity and especially in heat production. This development has been due to increasing electricity taxes and the improved competitiveness of biomass.

Heat source potential evaluation, operation within a DH system and improving efficiency by implementing low temperature distribution are the focus of the research concerning HPs and DH.

2.6 Solar thermal collectors

Solar thermal collectors utilize solar irradiation for producing heat. Their usage is strongly affected by the seasonal and daily variation in availability. This is why daily or seasonal thermal storage is a reasonable combination within a solar heating system.

Hirvonen et al. [59] studied high latitude communities of different sizes from 50 to 500 buildings equipped with photovoltaic panels, SCs, a local DH network, a seasonal heat storage and a heat pump. High solar fractions (~90 %) were found to be possible for all community sizes, although large communities could achieve this with 20 % lower costs. The life cycle costs per heated floor area were 252-477 €/m² in studied cases.

Renaldi and Friedrich [60] investigated a hybrid solar-gas system in the UK with both short- and long-term thermal storages included. The conclusion was that while technically feasible, financial incentives such as a carbon tax are needed. Reducing the capacity of the seasonal storage did not improve the economic feasibility of the system considerably, but decreased the solar fraction.

Denmark represents the largest solar DH market in the world with 1.3 million m² of SCs installed. Tian et al. [61] reviewed the development within the Danish DH heating sector. The current solar DH capacity has almost completely been developed over the past 10 years. The main drivers for this development have been the reasonably low price of solar DH (20-40 €/MWh) and widely-spread DH systems. In Denmark, solar DH can be cost-competitive against gas boilers (~60 €/MWh), biomass boilers (~25-33 €/MWh) and heat pumps (~37 €/MWh).

2.7 Nuclear district heating

Nuclear heat has challenges in terms of public acceptance and the required regulative framework, although often represents an option with techno-economic feasibility. Due to its massive scale compared to all but the largest DH systems, large-scale utilization of NDH has also a significant impact on the other connected heat supply options.

Jasserand et al. [62] evaluated the economic performance of NDH in France with a case study in Paris and the Nogent-sur-Seine nuclear site. The heat transmission pipeline represents a significant investment due to the long distance (90 km) between the site and the city. The ac-

tual realised investment costs have a decisive impact the economic feasibility of the whole project. An optimistic scenario resulted in positive NPV in 12 years, while a pessimistic one did not reach positive values during the evaluated technical lifetime of 40 years.

Leurent et al. [63] investigated the driving forces and obstacles in the Loviisa NDH project in Finland. Most relevant stakeholders were identified and interviewed, and the barriers for a megaproject such as the implementation of nuclear co-generation were examined. The stakeholders viewed the project very differently depending on their background, interests and stake. Shared ownership of the company in charge of the implementation, i.e. long-term commitment and financial ties, as well as a transparent and credible assessment of the benefits could be a solution for successful completion of such projects.

Paananen and Henttonen [64] carried out a simulation of the transmission pipe related to the aforementioned Loviisa NDH project, representing a detailed technical background applicable to any similar design. Hirsch et al. [65] presented a method for evaluation of long-distance heat transportation. The method enables the optimization of properties of the transmission pipeline with objective functions for construction-, pumping power- and heat loss-related costs.

Lindroos et al. [66] studied the feasibility of different types of small modular reactor (SMR) designs as a heat supply for the DH system in Helsinki, Finland. The results showed good economic performance with an average internal rate of return between 7-20 %. The SMRs were outperformed by biomass boilers if the biomass price was below 20 €/MWh, and by heat pumps with an average COP of 3.5 if the total electricity price was less than 75 €/MWh.

3. Approach and methods

This chapter presents the approach and methods used in all Publications. This introduction provides an overview of the research carried out and summarizes the topics, methods and contribution of each Publication. The rest of the chapter goes into more detail on modelling methods, main assumptions and different viewpoints on DH systems considered.

Publication 1 establishes a framework for assessing a transition to low temperature distribution. The impacts on the main components of a DH system, heat supply, distribution and consumers are identified and explained. The typical properties of the components in a Finnish DH system are used as examples in describing the impacts.

Publication 2 focuses on model development and validation through comparing the results of different simulation models. The challenges concerning the DH network simulation tools found in the literature, such as artificial diffusion, are studied and possible solutions discussed. The DH network simulation components are used in Publication 3.

Publications 3-5 study specific case systems with new low-carbon heat sources and Publications 3-4 study also the impact of low temperature distribution. The process includes a definition of the system studied, establishing scenarios for future development in terms of heat demand and costs, modelling and possible simulation of the system, studying the long-term economic performance of the scenarios and finally, an overall analysis of the results.

The topics, simulation and optimization tools, and contribution of each Publication is presented in Table 3.

Table 3. Topics, tools, approach and the main contribution of each publication.

Publication	Publication 1	Publication 2	Publication 3	Publication 4	Publication 5
Topic	Transition to low temperature distribution in DH systems.	Network and storage simulation model components for DHC systems.	SC performance as distributed or centralized heat supply for DH.	SCs and HPs as a low-carbon heat sources for an existing large-scale DH system.	Cost-benefit analysis of NDH for 15 locations in Europe.
Tools and the approach	Identification of critical components, example calculations.	Apros and Modelica modelling environments.	Apros, IDA ICE and solar collector modelling, NPV calculations.	Scenario definition, EnergyPRO optimization model, NPV calculations.	Economic analysis.
Contribution	The principles of transition process evaluation and identification of the main components and the related restrictions.	Modelling tools for studying operation of a DHC network and insight on their limitations.	Comparison between two alternative options for integration of solar heating into DH systems.	Performance of new low-carbon heat sources with current or low distribution temperatures and impact of their operation on other heat supply options in an existing system.	Extensive cost-benefit analysis and comparison of potential NDH systems in Europe.

3.1 DH systems considered

The case studies in Publications 3-5 have different challenges, a point of view and an overall approach. Publication 3 deals with a low heat demand area where the challenges are to maintain a high enough supply temperature, to keep heat losses at an acceptable level and to handle the integration of a distributed local heat source. Publication 4 focuses on a large-scale DH system where the challenges are related to the impact of new centralized low-carbon heat sources on the existing heat supply and the overall scale of the required changes in transforming a mostly fossil-based system into a low-carbon DH system. Publication 5 considers future DH systems extended to cover most of the selected urban areas and the costs and benefits of such systems to utilize a massive heat source such as NDH. Table 4 describes the different kinds of DH systems in more detail.

Table 4. Description, key characteristics and analysis carried out for case studies in Publications 3-5.

	DH in a low heat demand area (Publication 3)	Large-scale DH system (Publication 4)	Future DH systems (Publication 5)
Short description	A local DH system located within the city of Hyvinkää supplying heat to detached and terraced houses.	A city-wide DH system in the city of Helsinki.	15 potential systems for NDH utilization in Europe.
Heat demand	1 231 MWh	5 984 GWh	36 - 50 318 GWh
Network length	1.7 km	1 351 km	42 - 12 241 km
Heat demand density	0.74 MWh/m	4.43 MWh/m	0.85 - 5.24 MWh/m
Heat supply	CHP and HOB-based heat production, SCs.	2-3 CHP plants, several HOBs, large-scale HPs, SCs, heat storages.	Nuclear cogeneration plants, peak boilers.
Scenarios studied and/or analysis carried out	SCs as distributed or centralized heat supply options with current or low distribution temperatures.	Scenarios for introducing HPs, SCs or both in an existing DH system with current or low distribution temperatures.	Cost-benefit analysis for potential locations for NDH-based DH systems.

3.1.1 DH in low heat demand areas

Low heat demand area is considered to be a location where a DH system has a linear heat density¹ below 1.0 MWh/m. In the system studied in Publication 3, the linear heat density was 0.74 MWh/m. A low heat demand area can be a separate local system or simply a part of a larger DH system, but the same challenges apply; temperature level and heat loss management is required.

Relative heat losses in a low-demand area are typically high, 10-20 % on a yearly level. Outside the heating season they can reach up to 30-50 %. The low demand during summer also means that the areas often face challenges in maintaining temperature level high enough for DHW supply. This can be managed by increasing the flow in the network by a by-pass valve circulating water from supply to return line at the end of the network. While reacting to the immediate problem, this arrangement further increases the heat losses by raising the return

¹ Heat demand divided by trench length.

temperature. The main solutions for addressing the high heat losses are implemented in the design phase of the systems, and are also related to the need for minimizing the investment costs for the low heat demand areas. The solutions include minimizing the network length and pipe sizes, use of twin pipes instead of single pipes, cost-optimal insulation thicknesses and simply by having a high connection rate.

Due to the local high heat losses and thus low overall efficiency of heat supply, the local solutions such as SCs are interesting; replacing a HOB-based heat supply with SCs with minimal operation and maintenance costs can result in savings due to reduced fuel consumption. This case was studied in Publication 3.

Due to the nature of the challenges, realistic data on heat demand (Publication 3) and use of accurate modelling methods (Publication 2) for the distribution network are necessary. The significance of the summer time load makes especially the quality of the DHW demand data an important factor.

3.1.2 Large-scale DH system

Large-scale DH systems supply heat in densely populated urban areas and commonly have high heat demand densities, e.g. 4.8 MWh/m in Publication 4 for Helsinki's DH system.

High heat density generally results in low relative heat losses. This makes the significance of heat losses less important than in low heat demand areas, assuming that the network is adequately insulated. The typical heat losses are below 10 %. In the studied DH system in Helsinki, the yearly losses were 6.5 %.

The focus in large-scale DH systems is on the operation and possible changes in heat supply. The systems are likely to have several heat production plants with different roles, technologies, capacities, possible fuels and efficiencies.

Systems with CHP units or HPs represent an interesting case as electricity prices influence the operation of both types of plants. Heat sources such as SCs (variable production) or NDH (base-load) have an impact on the system depending on what heat supply they replace.

However, despite the minor role of heat losses for the overall system, the distribution network and its temperature level is still relevant as argued in Publication 1. The temperature level increases the efficiency of the conventional heat supply technologies and HPs and increases the production of SCs.

As the focus is more on the supply side, the most important input assumptions are related to the operation of heat supply. Total heat demand of the DH system, technical parameters and operational costs of the heat supply are the most important input assumptions. The more complex the heat supply, the more relevant it is to model the dependencies accurately. DH system-level optimization is needed as presented in Publication 4.

3.1.3 Future DH systems

Future DH systems are considered in Publication 5. Publication 4 also deals with the future development of a specific DH system and its heat supply, but the system itself exists. The lessons learned from Publication 3 can benefit the development of future systems and Publication 1 provides a framework for evaluating the development of existing systems and planning new ones.

In Publication 4, the heat demand of an existing system is declining, while new heat sources are introduced into the system over time. The future heat demand estimation is based on a

previous study [67]. In Publication 5, the DH demand is estimated for 2030 in chosen locations based on Heat Roadmap Europe [21] data. The locations themselves are chosen based on the potential utilization of NDH due to a nearby nuclear plant site, and an existing DH system or systems.

As the systems in Publication 5 are expected to grow, also the extension of the distribution network is taken into account. Here, a method proposed by Persson et al. [68] is utilized, linking the estimated future heat demand to the needed investment in the DH distribution network.

Estimation of heat demand remains the single most important, albeit uncertain, input assumption when considering future DH systems.

3.2 Modelling methods

The methods used in the research presented can be categorized as heat demand estimation tools, simulation models and heat supply modelling and optimization methods.

3.2.1 Heat demand estimation

Four different methods for estimation of heat demand were utilized. The IDA Indoor Climate and Energy simulation tool [69] and Apros Process Simulation Software [70] based calculation model were used in Publication 3 for simulating building-specific space heating demand time series and generating DHW demand time series, respectively. An MS Excel-based tool was used for approximating the outdoor temperature dependency of heat demand in Publication 4. Lastly, an estimation based on measured, daily sample profiles representative of summer, winter and spring/autumn were used to estimate heat demand in Publication 5. The methods and the corresponding input and output data are described in Table 5.

Table 5. Methods used in estimation of DH heat demand.

Method	Description	Input	Output
IDA Indoor Climate and Energy	Building a simulation tool for detailed modelling of a SH for a single, specific building.	Structure definition and construction material properties, weather data.	Hourly space heating demand time series of the modelled building.
Apros DHW generator	Apros based DHW demand time series generator for individual dwellings.	Weekly probability of DHW consumption for a single occupant, number of occupants in a dwelling.	Consumer-specific, year-long hourly DHW demand time series.
Outdoor temperature dependent demand estimation	MS Excel calculation tool approximating DH heat demand based on the impact of outdoor temperature dependency.	Year-long hourly temperature time series, weighing factors for dependency on temperatures during the last 24h and the last hour, a temperature when heating is no longer needed, yearly heat demand for the whole DH system. Representative time series for domestic hot water consumption for a large number of buildings.	Hourly heat demand time series for a DH system with a specific yearly heat consumption.
Seasonal, sample profile based demand estimation	Python algorithm for approximating the DH heat demand based on sample profiles.	Daily sample profiles for summer, winter and spring/autumn, yearly heat demand, length of the seasons.	Hourly heat demand time series for a DH system with a specific yearly heat consumption.

IDA ICE modelling software was used to generate a representative SH time series for a single building. This time series was scaled to represent the SH demand in the other buildings in the studied area based on their respective floor areas in Publication 3.

Apros DHW generator enabled the generation of consumer-specific demand time series for DHW demand, providing a realistic temporal distribution in demand peaks (Publication 3). The generator was also used to provide a DHW sample profile for DH demand estimation (Publication 4).

Outdoor temperature has a direct impact on SH demand, and thus can be used to evaluate DH heat demand if measured or modelled data is not available. Combined with a representative time series for DHW demand, a realistic DH demand corresponding to a defined outdoor temperature time series can be generated (Publication 4).

Sample profiles based on measurement data representing daily variation in heat demand can also be used in demand time series generation. These are further scaled to match a yearly heat demand of a specific system (Publication 5).

3.2.2 Network simulation model

A district heating network model is implemented and Apros Process Simulation Software [70] is used for carrying out the network simulations in Publications 2-3. Apros is a modelling platform with decades of development and a component library validated against experimental data. In addition to its thermo-hydraulic simulation capabilities, Apros is also equipped with control system components enabling a realistic investigation of a studied system. The model developed consists of a DH pipe, consumer substation and generic heat supply components. The DH pipe component was developed during Publication 2, while other two components were planned and implemented as part of Publication 4.

3.2.3 Heat supply modelling and optimization

Heat supply modelling in Publication 3 was carried out using two separate methods. Calculation of the SC heat output was based on a set of equations given in a guide [71] to European Standard EN12975 on solar thermal collector testing. Input assumptions are based on local weather data; outdoor temperature, direct and diffuse solar irradiation.

The operation district heating heat supply in Publication 3 was determined after the simulations and is based on a merit order approach and a load duration curve consisting of the building heat demands and the heat losses within the network. A CHP supplies most of the heat if the demand is higher than the assumed minimum output. An HOB unit supplies the summer time and peak heat loads. The method for heat supply allocation is visualised in Figure 3.

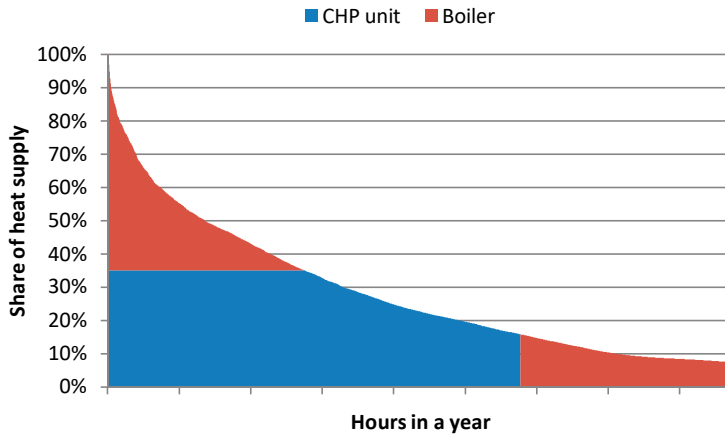


Figure 3. Heat load duration curve with allocated shares for CHP- and HOB-based production in Publication 3.

The cost-benefit analysis in Publication 5 includes a model for the heat supply, implemented in Python programming language. The main heat sources included in the model are a nuclear co-generation plant, gas boilers and daily heat storages. In addition to the heat supply, the model developed also includes the loss of electricity production due to co-generation operation of a nuclear plant, transport pipeline and DH network heat losses and pumping electricity consumption. The model calculates the energy flows, costs and emissions of operating a defined system. The model structure is visualised in Figure 4.

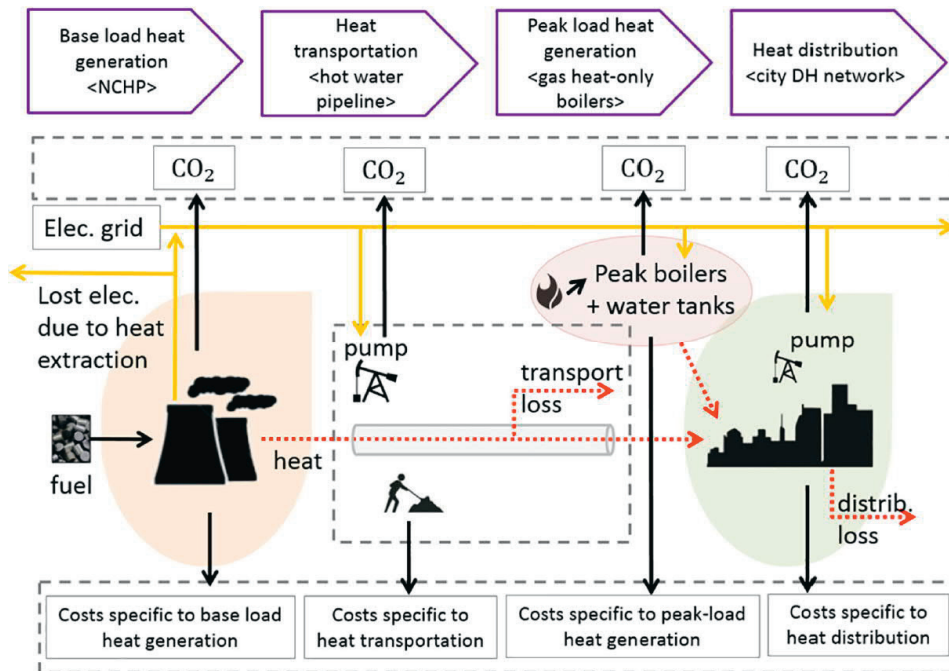


Figure 4. The structure of the techno-economic model used to estimate the costs and GHG emissions of DH + NCHP systems in Publication 5.

EnergyPRO software [72] was used in Publication 4 for studying the operation of a large-scale DH system. EnergyPRO is an input-output model accounting for both electricity and heat markets that carries out a techno-economic optimization of a defined system. EnergyPRO determines optimal operation of heat production units based on operational costs of plants with different capacities, efficiencies and fuels. Income from sold electricity generated by CHP plants is included in the optimization. Input and output data is listed in Table 6.

Table 6. Inputs and outputs of the EnergyPRO model used in Publication 4.

INPUTS	OUTPUTS
Technical parameters for heat sources <ul style="list-style-type: none"> - Capacities, fuel, efficiencies, heat to power ratio for CHP units, heat pump COPs, storage sizes and losses 	Fuel consumption and emissions Heat production and operational costs Operational hours of individual units
Economic parameters <ul style="list-style-type: none"> - Fuel costs, electricity prices, taxes and transmission costs and variable costs for each unit 	Electricity production and consumption
Other <ul style="list-style-type: none"> - Heat demand, distribution heat losses, ambient temperature, solar irradiation data, supply and return temperatures for DH 	

Electricity price assumption has a strong impact on the optimization results of a DH heat supply consisting of CHP plants and HP-based heat production. A sensitivity analysis on electricity price assumption is included in Publication 4 in order to consider this.

The total electricity price consists of the market price, the distribution and transmission tariffs, and the electricity taxes. In Publication 4, the hourly prices are based on historical market data in Nordpool Spot [73] for the year 2014, and scaled according to projected future prices until 2030. The future electricity and fuel price assumptions are based on Nordic Energy Perspectives 2016 [67].

The assumed electricity distribution tariff includes only the transmission tariff (2.7-9.0 €/MWh) as both the DH system and the electricity distribution in Helsinki is owned by the city. This assumption is slightly controversial, and thus discussed in Chapter 5. Finnish electricity taxes (22.53 €/MWh) are included.

3.3 Economic analysis

The main result of the economic analysis carried out for case studies in Publications 3-5 is the comparison of net present values (NPV) of alternative systems. These alternatives can be different scenarios with varying amounts of low-carbon heat source included. The analysis includes a comparison with a business-as-usual (BAU) scenario.

In both Publications 3 and 4, economic analysis corresponds to 20 years in operation. Investments are taking place at year 0 with the operational costs and possible revenues discounted using a discount rate of 6 %. In Publication 3, revenues from selling heat are not included. In

Publication 4, revenues from both heat and electricity sales are taken into account. In both cases, NPV after 20 years of operation is defined in equation (1) as:

$$.. V = I_0 + \sum_{t=1}^{20} \frac{(C_t - R_t)}{(1+r)^t} \quad (1)$$

In Publication 4, the results are presented as ranges of costs based on initial assumption on the lowest and highest possible investment costs. In Publication 3, the changes in the system itself in terms of heat demand and heat supply are included. Development of commodity prices of, e.g. electricity and fuels are taken into account in both Publications 3 and 4.

Publication 5 uses a slightly different approach by introducing capital recovery factor (CRF) into the NPV calculation, defined in equation (2) as:

$$CRF = \frac{1}{1 - \left(\frac{1}{1+i}\right)^t} \quad (2)$$

Here, the NPV is defined in equation (3) as:

$$NPV = -\sum_{t=2017}^{2070} I_t CRF + \sum_{t=2030}^{2070} (R_t - C_t) CRF \quad (3)$$

Publication 5 also calculates other economic indicators like internal rate of return, payback period and levelized costs of heat (LCOH). A discount rate of 3.5 % corresponding to an EU recommendation for large-scale infrastructure projects is used in Publication 5.

4. Results

This section summarises the main results of the presented research. The structure corresponds to the research questions posed in Chapter 1.4. First, performance of low-carbon heat sources in district heating is analysed. Second, the benefits and challenges of low distribution temperatures and the economic impacts are studied. Finally, the overall impact and required changes for existing systems are discussed. The main conclusions are given at the end of each section.

4.1 Low-carbon heat sources for DH systems

Three different low-carbon heat sources are considered in this study; solar collectors (Publications 3 and 4), heat pumps (Publication 4) and nuclear heat (Publication 5). As a renewable heat source, biomass-based heat and electricity production is also present in Publications 3 and 4. However, the focus is more on what happens to utilization of biomass in an existing system due to the aforementioned new heat sources than comparing biomass directly with them.

Publication 3 analyses the performance of distributed or centralized SCs with the same total investment costs for a low heat demand area located within the Hyvinkää DH system. When considering the specific investment cost (€/kW) of SC systems, the centralized systems (309 - 918 €/kW) seem much more favourable than distributed systems (1412 - 2119 €/kW). However, the heat losses in a DH distribution network and lower temperature levels within the building heat distribution systems benefit the distributed systems compared to centralized systems. This reduces the impact of the difference in investment costs to some extent.

Figure 5 presents the SC output per collector area for all the studied scenarios and the amount of excess production. The excess production takes place in situations where solar heat is available, but there is no heat demand and the heat storage is full. Distributed building-specific SC systems are combined as one here as they only differ in costs. The results show the higher specific output of a distributed system, but also the highest share of excess heat production.

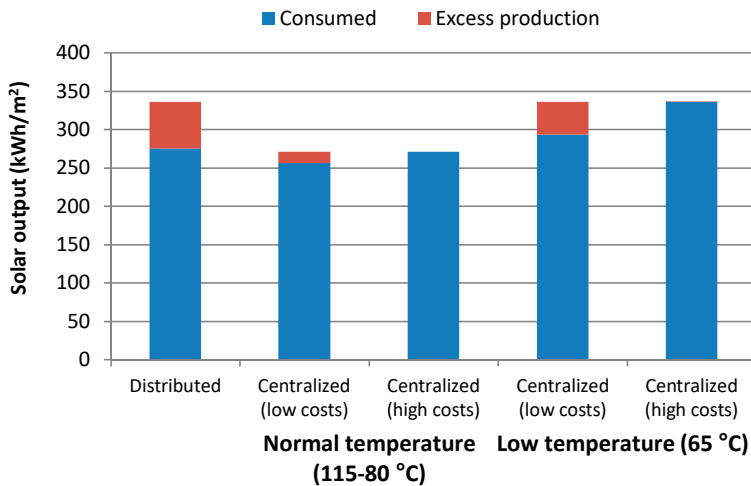


Figure 5. Specific production (kWh/m²) of SCs for each studied case in Publication 3 (an area within the Hyvinkää DH system) with shares of consumed and excess heat production given.

When studying the same scenarios on the case system level and the corresponding yearly output of each scenario, the differences related to installed capacity become clearer. Figure 6 presents the yearly heat output and the share of excess production for all the scenarios.

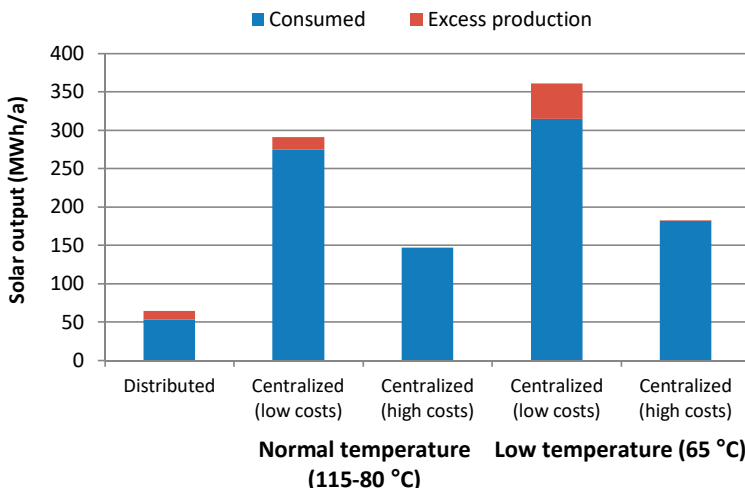


Figure 6. Yearly SC heat output (MWh/a) for each studied case in Publication 3 (an area within the Hyvinkää DH system) with shares of consumed and excess heat production given.

Centralized systems clearly produce more heat than distributed systems with the same investment. The yearly excess production was 18 % for distributed systems. For normal and low distribution temperature, excess production for the low cost scenarios was 5 % and 13 %, respectively. In centralized, high costs scenarios (with less collector area), the excess production was insignificant or zero.

The Helsinki DH system was used as a case study in Publication 4 to investigate how the integration of HPs and SCs would change the heat supply in a more complex system with numerous HOBs, 3-4 CHP plants, heat storages and existing HP-based heat production.

The objective of the study was to show how HPs and SCs would perform in a future system and how their shares in heat supply would compare to each other. Special attention was paid to the operation of the CHP plants in different scenarios. The scenarios were business-as-usual (BAU) representing the existing plans during the time of the study, HPs as the new heat supply (HP), SCs the new heat supply (SOL) and both HPs and SCs as new heat supply options with the same investment put in both (SHP). As in Publication 2, both options compared had the same investment costs in order to make the results comparable.

Figure 7 shows the results for shares of each heat source in all investigated scenarios at milestone years of 2014, 2018, 2024 and 2030. The results correspond to systems using the current distribution temperature levels.

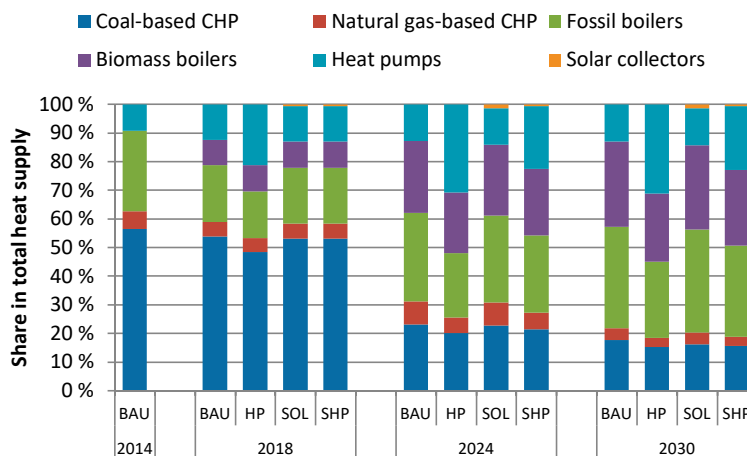


Figure 7. Share of each heat source in heat supply for Helsinki DH system at milestone years with current distribution temperatures (Publication 4).

The results show that HPs clearly outperform SCs, producing 9 to 30 times more heat on average in scenarios where SCs were included: SOL (8.5-9.3) and SHP (28.7-31.9). HPs and the assumed increase in biomass-based HOB capacity replaced CHP-based heat production. The reduced CHP output is also due to the planned decommissioning of one coal-based CHP in 2024.

Publication 5 presents a cost-benefit analysis of using nuclear heat from nuclear cogeneration plants in 15 locations within Europe. As the potential implementation for nuclear cogeneration as a source of heat is a long-term target, the study assumes a future heat demand (2030) for the studied DH systems. The investigated systems and their estimated yearly heat demands are presented in Figure 8 as a function of estimated linear heat density.

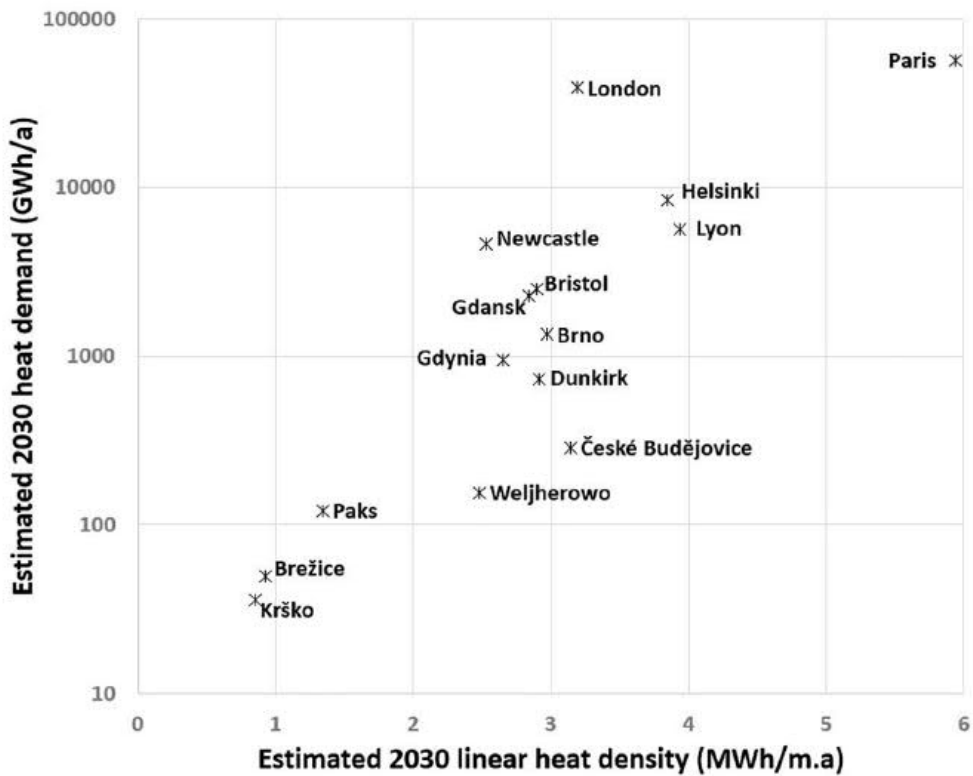


Figure 8. Estimated 2030 heat demand and linear heat density of the modelled DH networks in Publication 5.

The feasibility of a NDH by cogeneration NPPs is strongly affected by the distance between the plant and the DH system. Cases where the distance is less than 100 km were included in the study. Table 7 presents the studied DH systems and their specific locations, countries and the distance for the required heat transport pipeline.

Table 7. The fifteen case systems addressed in the NDH cost-benefit analysis study in Publication 5.

Country	Metropolitan area (DH system)	Plant location	Estimated 2030 heat demand (GWh)	Transport pipeline length (km)
Czech Republic	České Budějovice	Temeline	288	25
	Brno	Dukovany	1 350	35
Finland	Helsinki	Loviisa	8 463	80
France	Dunkirk	Gravelines	734	15
	Lyon	Le Bugey	5 687	30
	Paris	Nogent-Sur-Seine	50 318	90
Hungary	Paks	Szekszard	122	30
Poland	Weljherowo	Zarnowiec	156	18
	Gdynia, Rumia, Weljherowo	Zarnowiec	946	40
	Gdansk, Gdynia, Rumia, Weljherowo	Zarnowiec	2 273	85
Slovenia	Krško	Krško	36	2.3
	Brežice + Krško	Krško	50	7
UK	Bristol	Oldbury	2 481	20
	Newcastle	Hartlepool	4 660	40
	London	Bradwell	39 050	70

All the three heat sources considered in Publications 3, 4 and 5 have different properties that influence their implementation in practice. The required investment is a relevant issue for all the alternatives, but especially for NDH due to the scale of the solution. SCs also have to deal with the variable nature of the resource and HP potential depends in practice on the availability of low-grade heat sources and the electricity price. In addition to the high investment, NDH also has significant social acceptance issues and heavy regulation.

The key findings concerning new low-carbon heat sources for DH systems can be summarized as:

- Centralized SC systems connected to Finnish DH have 4-5 times higher heat output than decentralized building-specific systems with the same initial investment costs
- HPs outperform SCs in Finnish DH systems; HPs produce 9 to 30 times more heat than SCs with the same investment
- The feasibility of NDH implementation depends on the heat demand of the potential DH system and the distance between the DH system and the site

4.2 Benefits and challenges of low distribution temperatures

Publication 1 discusses how the transition to low temperature distribution in existing DH systems should be evaluated and what are the impacts on the main components in a DH system.

The direct benefit of the low temperature distribution is lower heat losses due to the reduced temperature difference between the water within the DH pipes and the surrounding soil. However, it also improves the efficiency of virtually all heat supply technologies. Low temperature distribution can also make new sources of heat available, economically feasible or increases the potential of the existing sources. The overall benefit of lower heat losses or positive impact on heat supply depends on the DH system in question.

However, the low distribution temperatures can also cause issues due to the reduced heat transport capacity. Increased electricity consumption for pumping or even new investment on larger or additional pipelines may be required.

Table 8 describes the component-specific benefits and challenges related to the transition.

Table 8. Benefits and challenges related to transition as presented in Publication 1.

Component	Benefit	Challenges
Heat supply	Improved efficiency, opens up new possibilities for supply	Potentially negative effects on existing heat supply, more complicated operation and maintenance
Distribution	Less heat losses	Transport capacity issues, possible investment and additional management required
Consumers	Possibly reduced price of heat due to efficiency improvements in the system	Heat exchanger and internal heat distribution-related capacity issues, needed investment

The distribution temperature level in the DH network has a key role in the evaluation process. This makes DH network simulation models (Publication 2) very important for evaluating the transition. As noted above, the temperature level in the distribution network has impacts on both consumer buildings and the heat supply. These relations and the input required for the overall evaluation process are illustrated in Figure 9.

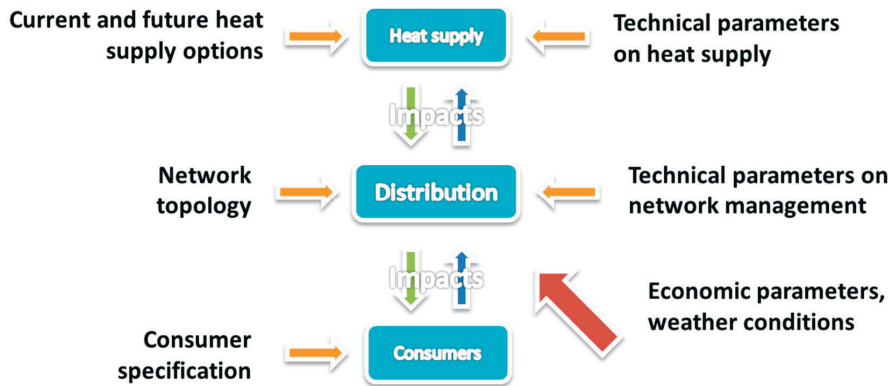


Figure 9. Input information for each component in the evaluation process discussed in Publication 1.

The main conclusions from Publication 1 are that the optimal outcome should be investigated from a system point of view, i.e. not taking into account the ownership of different components of the system or stakeholders involved at first. After determining the least-cost option on a system level, the benefits of the transition should be allocated to involved stakeholders. If the solution reached is acceptable for all the stakeholders, the outcome is feasible also in practice.

DH systems can vary significantly in terms of heat supply options, heat demand and heat demand density, pipe design and network structure. Therefore, it is not reasonable to generalize, e.g. a specific optimal temperature level for all DH systems.

The heat demand of the building stock is expected to decrease as energy efficiency measures are implemented for both new and existing buildings. At the same time, there is a push for lowering the temperature levels in order to improve the efficiency of the heat distribution and to enable more efficient integration of new heat sources as indicated in Publication 1.

This development makes the modelling and simulation of the distribution system more relevant. More attention should be paid to maintaining a high enough supply temperature level in the DH distribution network so that the needed heat demand can be provided.

Publication 2 addresses this issue by developing and presenting tools for detailed simulation of a DH distribution network. The detailed models were implemented in Modelica, IDA ICE and Apros modelling environments. The results from the detailed simulation models were compared with each other. The final objective was to provide input for the development of a reduced model with an acceptable accuracy suitable for a model predictive controller (MPC). The Apros model components developed in Publication 2 were further utilized in a distribution network simulation carried out in Publication 3. The components are also integrated into the current Apros modelling library.

The concrete benefits of the low temperature distribution were investigated using case studies in both Publications 3 and 4.

In Publication 3 and the studied case of a low heat demand area, the low distribution temperatures increased the yearly specific output (336 kWh/m^2) of a centralized SC system by 24 % compared to the output (271 kWh/m^2) with normal distribution temperature levels. The impacts of the low temperature distribution on the fuel consumption of the heat supply consisting of a CHP unit and a boiler are visualized in Figure 10.

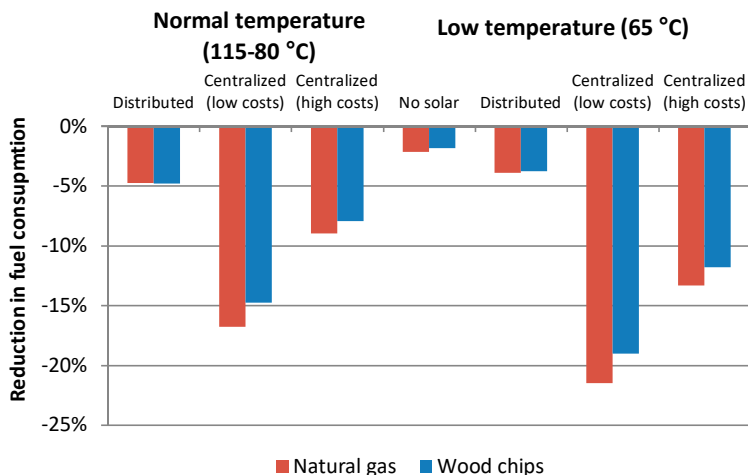


Figure 10. Reduction in total fuel consumption of the boiler and the CHP unit due to introduction of SCs for each studied case in Publication 3 (an area within the Hyvinkää DH system).

Figure 10 also shows the impact of reducing the supply temperature as the only change in the case system (“no solar” option, 1-2 % reduction in fuel consumption) compared to the centralized SCs (8-22 % reduction). The “no solar” option corresponds to the benefit of low temperature distribution in reducing heat losses.

The relative heat losses with normal temperature level are 15.6-15.8 % compared to 13.6-14.0 % for low temperature distribution. The losses can be considered typical for a low heat density area, but the values are high compared to a densely populated area (losses of 6 % for the case study in Publication 4). The relative heat losses varied during the year. During the summer months they reached up to 30 %. During winter-time the losses are less than 10 %. This can make SC-based heat supply an interesting option especially for systems where it would replace an inefficient boiler-based heat supply.

Publication 4 studies the impact of low temperature distribution in the larger system of Helsinki. The low temperature distribution is found to reduce losses by 22 %. However, as the relative heat losses in the Helsinki system were very low in the first place (6 %), the impact is relatively small. The heat supply has more significant differences. Figure 11 shows the changes for different types of heat supply for all studied scenarios in 2030. HP- and SC-based heat production is increased by 5-10 % and 19 %, respectively. CHP- and boiler-based heat production is decreased 0-6 % at the same time, although not due to the temperature level, but being replaced by HPs and SCs.

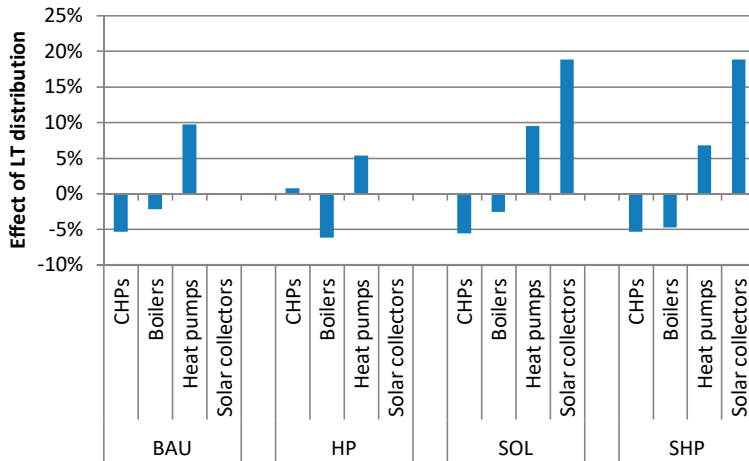


Figure 11. The impact of low temperature distribution on output of specific sources of heat in Helsinki DH system in 2030 studied in Publication 4.

HPs represent a stable source of heat, while the output of SCs has monthly variation. Figure 12 illustrates this variation for the SOL scenario at 2024 when the all the assumed SC-based capacity is present. The monthly output (GWh) and solar fraction² (%) as monthly values, and the increase due to low temperature distribution is shown.

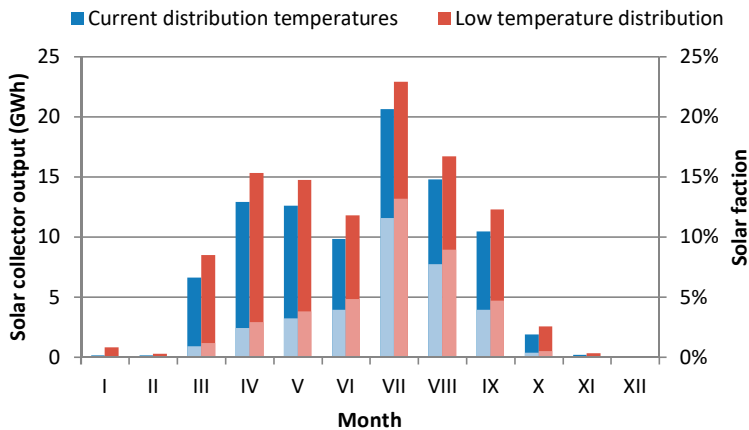


Figure 12. Monthly SC output and solar fraction (light colour) for SOL scenario in Helsinki DH system study in Publication 4 at milestone year 2024.

Figure 13 presents how the renewable energy source (RES) share with low temperature systems compares to systems with current distribution temperature levels. The impact is 2-5 % more RES in heat supply. The dashed line represents an interpolated target between RES share at 2016 (10 %) and the long-term objective of carbon neutrality by 2050.

² Solar collector output divided by total heat supply.

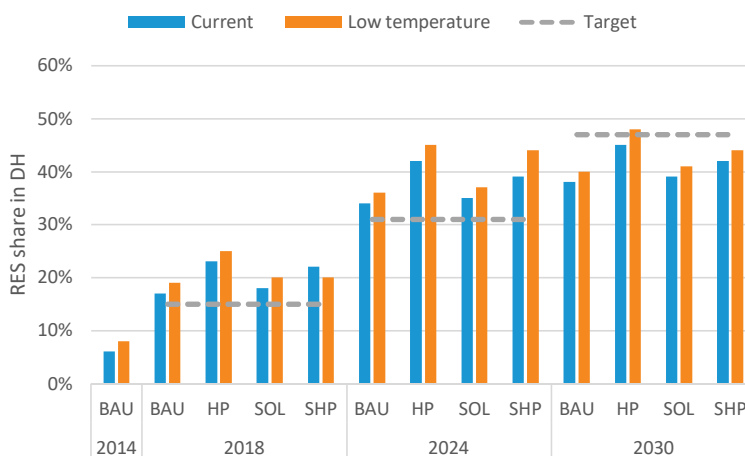


Figure 13. RES shares at the milestone years with the current and low distribution temperature levels in the Helsinki DH system studied in Publication 4. Dashed line represents the Helen target.

The key findings on the benefits and challenges of low distribution temperatures can be summarized as:

- The main benefits from low temperature distribution for DH concern distribution and heat supply, while the costs and actions required are mainly borne by the consumers - usually represented as different stakeholders; a fair distribution of both costs and benefits can be considered as a prerequisite for the transition
- Low temperature distribution enables significantly more (24 %) output from centralized SCs than current, traditional DH distribution temperatures
- The use of low temperature distribution requires more careful management of the temperature levels, making network simulation tools both in planning and operational phase important
- Centralized SCs reduce the fuel consumption of a CHP and boiler-based heat supply during summer time when the relative heat losses of the distribution network are the highest
- Low distribution temperatures generally increase the efficiency of all heat supply options, but heat HPs and SCs benefit more than conventional combustion-based technologies like CHP units and HOBs

4.3 Economic impacts

Publications 3, 4 and 5 all include an analysis on the economic impacts of both low temperature distribution and different new heat sources.

In Publication 3 and the case of a low heat demand area, all studied scenarios resulted in yearly savings in terms of operational costs. However, the yearly savings with distributed SCs were at the same level as savings due to the change from normal to low temperature distribution; around 2.0-2.5 % (“no solar”). The savings with centralized SCs in normal and low temperature distribution systems are presented in Figure 14. The variation in savings corresponds to a range between low and high limits for assumed investment costs. The results show that

even if low temperature distribution does not result in significant savings on its own, it does boost the performance of the SCs significantly.

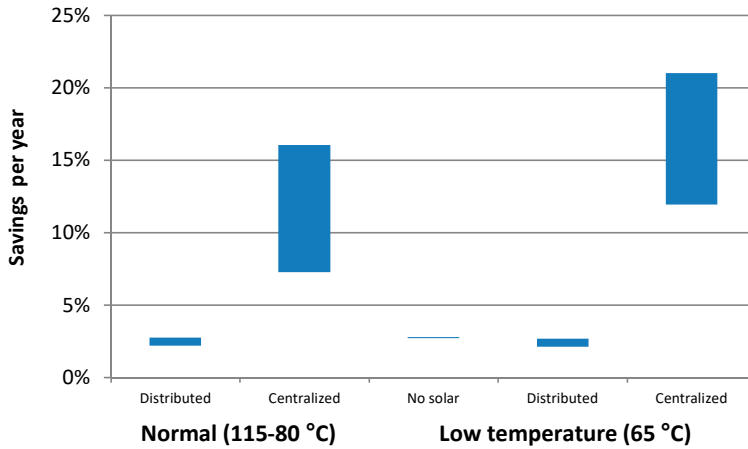


Figure 14. Operational cost savings with distributed, centralised or no SCs for both normal and low temperature distribution compared to reference system without SCs with normal distribution temperatures (Publication 3, an area within the Hyvinkää DH system).

A net present value (NPV) calculation for Helsinki’s large-scale system with HPs, SCs or both was carried out in Publication 4. Figure 15 presents a NPV comparison between the BAU and all the investigated scenarios after 20 years of operation. The calculation assumes a 6 % discount rate and average DH price of 64.9 €/MWh with a yearly increase of 2 %.

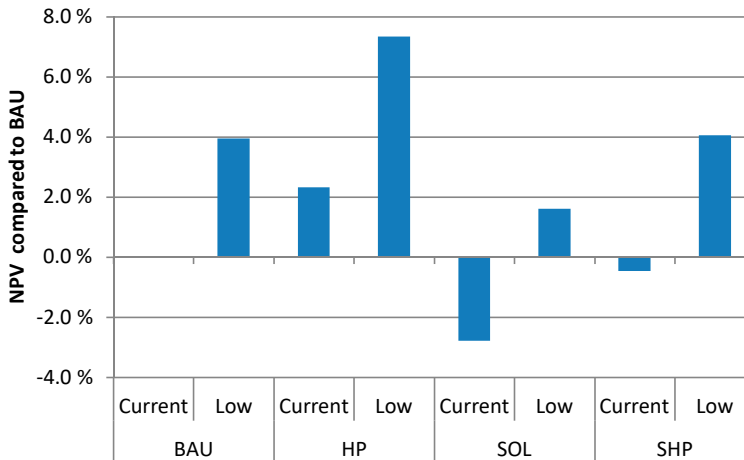


Figure 15. NPVs of all studied scenarios for Helsinki DH system with current and low distribution temperature levels compared to the BAU scenario with current distribution temperatures (Publication 4).

The scenarios with SCs (SOL and SHP) showed a negative impact with the current distribution temperatures. The best-performing scenario was HP with low temperature distribution, resulting

in a 7.3 % higher NPV than the BAU scenario. This needs to cover the costs of low temperature distribution in general; 200 M€ over the studied 20 years.

Publication 5 includes the calculations of LCOH for 15 case systems that could potentially utilize nuclear heat as a heat source for city-wide DH systems.

Figure 16 illustrates the LCOH and its breakdown for nuclear heat-based DH heat supply for the investigated 15 case systems. The breakdown includes costs of distribution, transportation, peak load and base-load for both investment and operation & maintenance. Distribution corresponds to the DH system itself and transportation to the heat transportation line between the nuclear site and the DH system. Peak-load is additional heat production capacity needed and base-load relates to the costs of nuclear heat production. LCOHs of less than 60 €/MWh are reached for all systems in Finland, France and the UK.

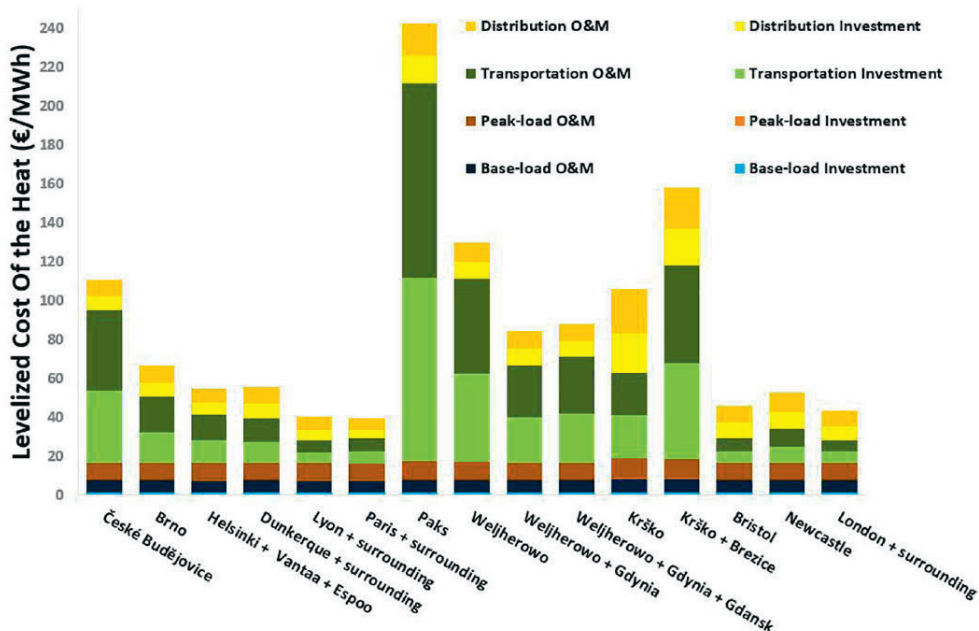


Figure 16. LCOH breakdown of DH + NCHP systems in Publication 5 considering 25% connection rate. Includes capital costs, fixed and variable operational costs.

When the LCOH for the same systems are considered in terms of the distance between the DH system and the nuclear site, it is apparent that the systems with low LCOH have either short distance or high heat demand.

The key findings on economic impacts of new low-carbon heat sources can be summarized as:

- Low temperature distribution alone results in minor (2-3 %) savings in operational costs in a year, which is still more than decentralized SCs
- Centralized SCs benefit from low temperature distribution more; savings in operational costs in a year increase from 7-16 % to 12-21 %

- In an existing, efficient large-scale DH system, low temperature distribution is required for SCs to have a positive change in NPV after 20 years of operation compared to the BAU scenario
- HPs are clearly a more economic option than SCs with 7.3 % improved NPV compared to the BAU scenario in Finnish operational environment
- LCOH calculations reveal that nuclear sites with short distances to an urban area or these areas having a high heat demand lead to LCOH lower than 60 €/MWh for NDH with realistic connection rates assumed

4.4 Overall impact and required changes for existing systems

Publication 1 presents an overall approach for evaluating the transition to low temperature distribution. The process of evaluation is discussed in Chapter 4.2 where it was stated that most of the requirements and costs are related to consumer buildings. These requirements result from temperature constraints of both SH and DHW.

The temperature requirements of SH are usually outdoor temperature dependent. Figure 17 plots a temperature duration curve for a sample year where outdoor temperatures vary between -20 °C and 30 °C. The duration curves are prepared for outdoor temperatures and supply temperatures of a 70/40 °C radiator system common in Finland, assuming a linear relation between the outdoor and supply temperatures. Maximum supply temperature of 70 °C is reached at an outdoor temperature of -26 °C.

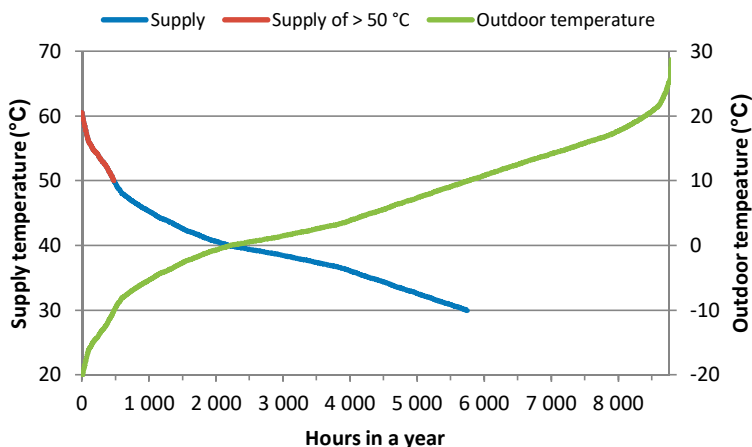


Figure 17. Duration curve representing a typical outdoor temperature dependency for supply temperature in a radiator-based space heating system (Publication 1).

Supply temperatures of over 50 °C are needed only for 3-4 weeks (<500 hours) during the year. Minimum DH supply temperature for DHW would be around 62 °C assuming a terminal temperature difference of 4 °C. For SH, this temperature is not needed during the sample year. SH is not necessary when outdoor temperatures is higher than 10 °C.

The result shows that current supply temperature levels (>75 °C, around 100 °C during the heating season) for SH are not often needed from a pure consumer building point of view. Temperatures can drop below the assumed -20 °C, so additional means of heating might be needed temporarily. However, in terms of energy the additional requirement is not high.

In Publication 3, the amount of displaced HOB- and CHP-based production in different SC capacities and distribution temperature levels was investigated for a low heat demand area. Solar fraction for the system with distributed SCs was found to be 4 %. The centralized SC systems with normal distribution temperatures had solar fractions of 18 % and 10 % with low and high costs, respectively. With low temperature distribution, solar fractions were 21 % and 12 %. The corresponding changes in HOB- and CHP-based heat production are illustrated in Figure 18. The SC-based heat supply mainly decreased the HOB heat production.

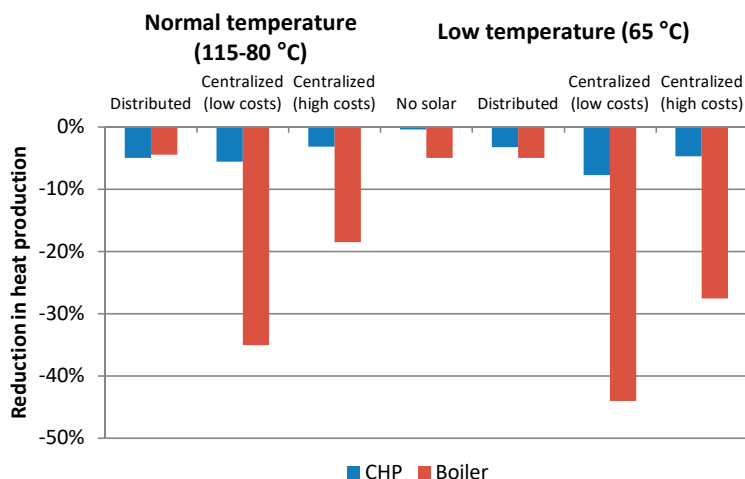


Figure 18. Reduction in utilization of CHP- and boiler-based heat production due distributed, centralised or no SCs in low heat demand area (within the Hyvinkää DH system) studied in Publication 3.

Publication 4 showed that for the same investment, HP-based heat supply is clearly a better option than SCs in a large-scale DH system (Helsinki) when targeting maximum output for a new heat source. The specific output of SCs was the expected amount (436 – 513 kWh/m²), but the total output was very small compared to the HPs.

The performance of the SCs is partly due to the geographical location of the case system in Helsinki. The solar irradiation would be significantly higher in Central or Southern Europe; e.g. Paris and Rome have 29 % and 79 % higher horizontal irradiation levels than Helsinki, respectively.

As the CHP plants were still supplying a significant share of the DH demand, the electricity price was expected to have an impact on the operation of the systems; CHP operation and HP based production. Figure 19 shows the results of a sensitivity analysis where electricity prices are increased up to 100 % for the BAU and HP scenarios for the milestone year of 2024. In the BAU scenario, the doubling of electricity prices increased CHP-based production by 94 %, while reducing the HOB and HP output by 44 % and 39 %, respectively. In the HP scenario, changes for the CHP, HOB and HP output where 131 %, -45 % and -44 %, respectively.

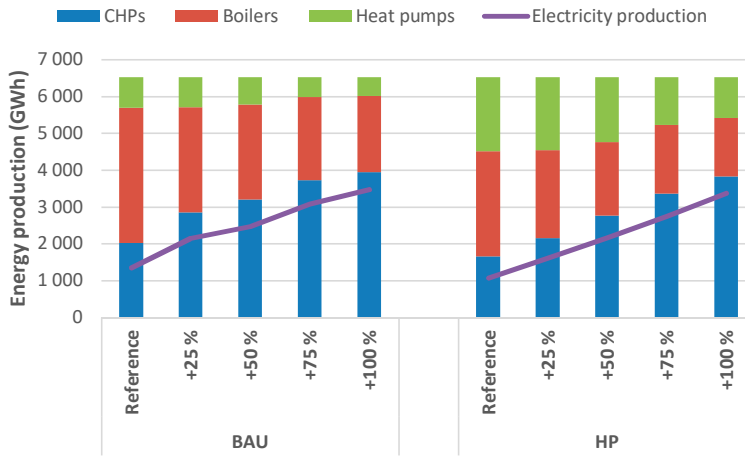


Figure 19. Electricity price sensitivity on heat and electricity production for BAU and HP scenarios at the milestone year 2024 for the Helsinki DH system studied in Publication 4.

The CO₂ emissions of all scenarios with the current distribution temperatures are presented in Figure 20. The emissions of electricity production were taken into account when calculating emissions of HP-based heat production. The assumed emissions were calculated for each milestone year using the 2017 specific emissions in Finland (175.1 gCO₂/kWh) and an assumption that they would continue to decrease and reach zero by 2045.

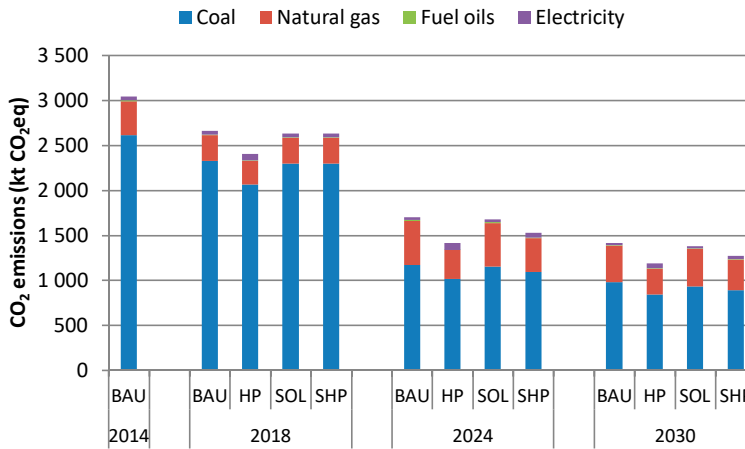


Figure 20. CO₂ emissions for all scenarios with current distribution temperatures in Helsinki DH system studied in Publication 4.

Decreasing specific emissions naturally benefits the HPs in terms of emissions compared to any fossil-based combustion technology. Low temperature distribution further reduced the emissions from 2 % to 5 %, depending on the scenario and milestone year investigated. The SOL and HP scenarios with low distribution temperatures had the highest emission reductions in 2030; 4.1 % and 4.0 %, respectively.

The key findings on the overall impact and required changes for existing systems can be summarized as:

- Higher supply temperature within the building heat distribution systems than what is required for DHW supply is needed only for a small fraction of hours in a year or not necessarily at all depending on outdoor temperatures
- SCs work best in a small-scale DH system with high relative heat losses and a fossil-based HOB by reducing the inefficient use of the boilers
- Electricity price has a defining impact on how a DH supply based on CHP and HPs is operated; increased prices lead to higher CHP and lower HP utilization and vice versa
- Impacts of electrification on CO₂ emissions for a DH system with increased use of HPs depend on the specific emissions of the electricity production; in the case of Finland, the emissions are reduced with more HP-based heat production

5. Discussion and conclusions

The heating and cooling sector is a major energy consumer. Much of the energy demand is supplied by fossil-based energy sources, making the improvement of energy efficiency and increasing the use of low-carbon heat sources a priority action in reaching the emission reduction objectives in climate change mitigation.

DH can potentially play a major role in reducing the CO₂ emissions. It can make the best local resources available for many consumers, especially in densely populated urban areas where the distribution efficiency is the highest. A thermal network makes a city connected, enabling distribution, trade and storage of otherwise unused low-grade heat. Future energy systems with high penetration of VRE-based electricity production will require flexibility, e.g. in form of energy storages. While a heat storage cannot be a substitute for an electricity storage, storing heat can provide flexibility to the energy system and remains much less expensive than storing electricity – if there heat demand to make this feasible. A city-wide DH system would represent demand in the scale needed.

The research presented in this thesis focuses on low-carbon solutions for DH in the form of HPs (Publication 4), SCs (Publications 3-4) and NDH (Publication 5). Low temperature distribution is also a key concept in the work carried out and its role, benefits and requirements are present in Publications 1-4. The case studies in Publications 3-5 represent different kinds of DH systems and points of view; a low heat demand area (Publication 3), the large-scale DH system of Helsinki (Publication 4) and future DH systems in a European scale analysis (Publication 5) are considered.

HP technology does not actually produce heat, but it transfers heat energy from a lower temperature heat sources to a higher, more usable temperature level required, e.g. in DH. These heat sources can be, e.g. excess heat from industrial processes, urban sources such as condensing heat from cooling systems or natural sources such as heat recovered from geothermal sources or bodies of water. HPs consume electricity, thus combining well with the decarbonizing electricity sector. Electricity-based heat production like HPs combined with heat storages can provide flexibility for a power system with a significant share in VRE-based electricity production.

SCs transfer solar heat directly to the point of use; a building heating system or a DH system. SCs and solar heat represent a VRE option that requires a heat storage or complementary heat production for a continuous supply of heat. Both decentralized building-specific installations and centralized SCs connected to DH are viable, but as presented in Publication 3, the lower unit costs of large-scale SC plants make them a much more economical choice. If the relative heat losses of a system are high, the SCs can be an attractive option, especially if replacing inefficient fossil-based HOBs. However, in the Finnish environment SCs are significantly more expensive compared to HPs.

NDH is an option that requires a large-scale DH system nearby (approximately 100 km or less) in order to be feasible. The exact distance depends on the heat demand. On the European level considered in Publication 5, large-scale DH systems are not common. This makes the development of the DH systems a prerequisite for the implementation of NDH. The research presented considers only back-pressure co-generation nuclear plants, but other options exist as well, although they are not yet on the market. These are the small modular reactor (SMR) design, heat-only reactors and a more flexible co-generation nuclear plant where the generated steam is rerouted to adjust the power and heat production of a unit. The SMRs and heat-only reactors could be easier to place closer to the city and their heat output would be more likely to match the heat demand of a DH system. The heat-only reactors with low pressure and temperature level would also be less expensive to build and would have a higher degree of safety. The flexible co-generation design as such has not been implemented, but the bleeding of steam is already present in normal nuclear plant design and common in normal condensing power plants. The design would also work well with a future energy system with a high penetration of VRE-based electricity production. All nuclear options come with public acceptance issues making their implementation impossible, challenging or at least slow - depending on the location. However, given the high potential for CO₂ emission reductions, it is hard to disregard NDH as an option.

HPs, SCs and NDH are not the only measures towards the low-carbon DH systems. Building energy efficiency and demand response can help in reducing the heat demand and shaping the demand profile, respectively. Biomass combustion is a widely used option, although the sustainably available biomass resources set limits for its use globally. Locally, biomass can be a perfect solution for heat supply. Excess heat recovery from industrial processes is an attractive option as well, usually an economic choice for both the industry and the DH system utilizing it.

The use of HP technology can make use of a wide range of potential heat sources, both natural and urban. The main natural heat sources would be geothermal energy and heat recovered from bodies of water; the sea, lakes and rivers. The most common urban sources are heat recovery from ventilation, cooling or refrigeration systems - or larger point sources such as waste water treatment plants. One specific heat source is data centres. Although situational, they too present a large-scale point source.

Simple electric boilers are also an option. Depending on the specific emissions for electricity production in the energy system in question, they can represent a low-carbon option. Although depending on electricity market price, the electric HOBs tend to have high operational, but low investment costs. As such, they represent a good option for peak demand management.

The discussion on DH systems and their emissions tends to revolve around the choice of heat sources, which does seem logical. Secondly, the heat demand and energy efficiency measures are correctly emphasized as well. However, the distribution system and its temperature level have a decisive impact on the system and especially on how it could be developed. Firstly, low distribution temperatures result in lower heat losses. The impact depends on specific temperature levels, but is usually in the range of 20-30 %. If the heat losses of the DH system are below 10 % (a normal figure in urban, high heat density areas) the impact in terms of total heat losses is 2-3 %. A more important consequence is the improved efficiency of heat supply, e.g. for biomass boilers, HPs and heat recovery. Biomass boilers can take advantage of low DH temperatures by recovering condensing heat of evaporated water in wet fuels such as wood

chips. Impact on the heat pump efficiency or amount of recovered heat depends on temperatures of DH distribution and the heat sources. In practice, the improved efficiency translates into increased potential of new heat sources.

When supply temperature of a DH system is lowered close to the minimum temperature required for providing DHW supply and/or heating by, e.g. radiators for the consumers, maintaining the adequate temperature level becomes more challenging. However, the traditional DH systems where a few large production plants pump high-temperature water to supply the farthest corners of the network with high enough temperatures might not be the optimal solution either. Without improved cooling at the consumer substations, lower supply temperatures also reduce the heat transport capacity of the network. This highlights the importance of well-functioning substations in low temperature DH systems. A more decentralized heat supply can actually help in temperature management, and will undoubtedly become one key input for controlling future, low temperature DH systems. This new constraint, as well as the complexity resulting in a more distributed system, are features that a future DH needs to cope with. New simulation tools similar to those developed in Publication 2 and used in Publication 3 will become more important in both planning and operation of DH systems.

The low-carbon heat sources considered are all mature technologies and there are no major technical challenges related to their implementation, other than the management system for a more distributed DH system with a large share of small-scale HPs. Low temperature distribution does come with a few technical challenges - some of which have been already discussed above. The main challenges are in consumer buildings; heat distribution systems and DHW supply. Secondary issues are the potential bottlenecks in the distribution network due to lower temperature difference between supply and return flows, i.e. lower heat transport capacity. Many of the problems are simply related to design principles of the existing system.

More than a technical challenges, the transition to low temperature distribution and enabled increase in the use of low-carbon heat sources faces socioeconomic barriers. There are numerous stakeholders involved; residential buildings and their inhabitants, commercial and industrial actors, potential 3rd party heat suppliers, cities and DH companies themselves. This complex setting makes transition management a challenging task. As stated in Publication 1, the greatest benefit of low temperature distribution are new heat supply possibilities, while the costs of enabling this rest mainly on the demand side of a DH system. An overall assessment is needed to determine the optimal, lowest-cost system. Then, a fair and transparent allocation of the benefits, costs and associated risks and/or uncertainties is needed in order for the transition to take place. The specific level of the new distribution temperature level should also be based on this type of analysis. Lund [74] shows that there can be a trade-off between the benefits of moving to lower distribution temperatures and the associated costs. In his work, the cost-optimal distribution temperatures were found to be 55/25 °C.

HPs stand out from the research results as the most interesting heat supply technology. However, the actual heat sources for the HPs are not considered. This represents the most important topic for further research if a significant increase in HP-based heat supply is targeted. A systematic method for mapping urban and natural heat sources should be established and tested for a city with a DH system.

The electricity prices have a significant impact on the feasibility of both HP- or CHP-based heat production, as visualised in the sensitivity analysis on electricity prices (Figure 19) representing results of Publication 4. Although future price projections are available, there is always

a good degree of uncertainty involved, as the lifetimes of large-scale DH heat supply investments are long. The electricity price composition itself can also change. In Publication 4, only a national-level transmission tariff was included in the distribution tariff, as both the DH system and the electricity distribution grid are owned by the city. In practice, the full distribution tariffs would still be paid – and as the profits of electricity distribution are regulated and balanced in long-term, the assumption made could also be different. However, all the distribution regulation, electricity taxes and the Spot market prices are uncertain. The average market prices in 2018 were 30 % higher than in 2014 used as a base year for Publication 4. The structure of the electricity distribution regulation has recently been criticized and could change. A possible reform of energy and electricity taxation [75] has also been studied with a recommendation to significantly lower the electricity taxes. All these aspects can potentially outweigh any specific assumptions on distribution tariffs, and represent the uncertainty related to electricity prices in general.

While electricity prices are a source of uncertainty, it is not the only one. Assessing e.g. investments, costs, energy demand and future technological development 20-30 years forward implicitly results in a degree of uncertainty. This makes the analysis and discussion on the results at least as important as the results themselves. An option to consider is to present ranges rather than exact values when presenting results. This approach was used in Publication 3, where NPVs were shown as ranges and thus representing the uncertainty related to investment costs.

Adding new heat sources to an existing system has an impact on the operation of the existing heat sources. This seems trivial, but the feasibility of new technologies is often carried out without assessing the system-level impact. For this impact, studying the heat demand profile and how this demand is satisfied by the alternative sources of heat during a year of operation is important. New solutions are typically more expensive than conventional technologies, thus requiring a higher utilization rate to be feasible. High utilization rate means that the new heat supply has a relatively high impact on the rest of the system. This happens also when the new heat source is inexpensive, e.g. nearby industrial excess heat. At first, new sources usually fit into the system well. As the heat demand profile allows less and less operational hours for new, possibly more expensive units, the economic performance and sometimes efficiency deteriorates. An example of this would be a CHP-based DH system where the new heat sources (e.g. heat pumps) replace base-load plants. At a certain point, the operation of the old base-load plants becomes too costly and HOB-based heat production increases. This can lead to increased costs and emissions. Regardless of the DH system in question, considering the changes both in the short and long term with a system-level perspective will provide the best possible solution for managing the transition.

Case studies in Publications 3, 4 and 5 focus on techno-economic feasibility and the system impact of selected technologies with specified capacities. There are several possibilities for developing the approach towards a broader assessment of potential low-carbon heat sources. The most obvious one is to extend the techno-economic analysis to include building energy-efficiency measures and costs related to the transition to low-temperature distribution. Another option is to utilise multi-objective optimisation to consider costs, energy demand, and environmental impact together. However, rather than targeting a specific approach, the focus should be on addressing decision-makers' need for information on how to develop a new or a specific existing DH system towards a low or zero-emission future.

The concepts, solutions and actions related to developing new or existing DH systems are always dependent on local characteristics. Cities and their heat demand profiles are different; the environment and the local resources are rarely the same. As the DHC systems become more connected, the properties of the surrounding energy system start to impact what solutions work the best.

The results of the international research effort along with the presented research already offer many alternative solutions and viewpoints on how to develop new and existing DH systems to increase efficiency and reduce GHG emissions. The role of the distribution temperature is emphasized. For countries with more developed DH systems, the focus now needs to shift to implementation. For countries still developing their DHC systems, there are many valuable examples from which to learn and the improved solutions can be implemented directly.

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