Replacing fossil fuels in district heating - modelling investments, impacts, and uncertainties

Tomi J. Lindroos
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A doctoral thesis completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall E-sali (Y124) Otakaari 1 on 30th May 2024 at 12:00.

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Abstract

Heating and cooling, including industrial heat, consume half of the final energy use in the EU and only 20% of it is produced from renewable sources. District heating (DH) could help decarbonizing heating, but DH sector must reduce its current emission first. In this Thesis, energy system modelling is applied to study investments to fossil-free DH production and related uncertainties.

This Thesis uses an existing long-term energy system model TIMES-VTT and develops new more detailed DH models that capture additional real-life constraints and have faster solve times allowing extended uncertainty analysis.

The electrification route includes many scalable technologies to replace fossil fuels in DH generation. Large heat pumps were the most robust of the studied investment options unless suffering from high electricity grid fees and taxes. However, local excess heat sources are often significantly smaller than the heat demand, especially in large cities. Ambient heat sources, such as sea water or air, could complement the available heat sources, but this depends highly on local conditions and heat demand density.

The biomass route provides a range of well-rounded technologies to replace fossil fuels in district heating. However, this Thesis further strengthens the conclusion that there is not enough biomass available to replace all fossil fuels in DH even in Finland. Increasing biomass demand and decreasing forest sinks in the EU create significant uncertainties over the future availability and price of sustainable biomass.

Certain upcoming technologies, such as nuclear district heating and bioenergy with carbon capture and storage, seem promising future decarbonization options, but they need technology development and demonstration units first.

In the course of work, large system models proved to be more flexible the more detailed DH models. As a result, large system models indicated faster decarbonization leading to a situation where studies giving background information for climate and energy policies have lower-cost and faster decarbonization of heating sector than what may be achievable.

Each modelling study should consider a large range of uncertainties, or they risk drawing flawed conclusions based on too narrow set of modelled cases and assumption ranges. The main sources of uncertainties in the results of this Thesis were related to the variability of electricity generation and price, biomass availability and price, natural gas price, investment costs of new units, breakthrough of new technologies, and the required phase of emission reductions.

Keywords District heating, Energy system modelling, Investments, Heat pumps, Biomass, Nuclear, uncertainty analysis

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I was actively avoiding any additional academic studies at least for ten years after my master’s Thesis. This was despite the great examples and encouragements by the surrounding research community. I admired the efforts and stubbornness that others showed when completing a PhD, but the very same thing pushed me further away from achieving the same.

It is difficult to say when my mind started turning. What I do know, is that I have been fortunate enough to be able to collaborate with many great persons learning a lot. Each Publication of this Thesis has been a result from a wide collaboration, long-term development of tools, and skills learned within project work. None of this would have realized alone. I want to thank few particularly influential individuals.

Sanna Kaasalainen, my supervisor during the summers in the Finnish Geodetical Institute, was the first real scientist I learn to know. She was bursting with new ideas and solutions and was curious, resourceful, and creatively crazy in front of the problems. She also showed the human side of research with lot of laughter and emotions.

Ilkka Savolainen was a professor at the VTT and guided me through my first projects. He knew how to give enough responsibility while helping when needed. I still marvel how genuinely interested he was on the results and could suggest improvements and further ideas to study.

Esa Pursiheimo introduced me to linear optimization. Nothing important for a mankind, but a giant personal step out from the comfort zone of the Excel. A good start is better than a bad one.

Juha Kiviluoma provided a significant share of resources for this Thesis, but more importantly, he has been an example of qualified and ambitious developer.

Niina Helistö is the best companion I could wish for a journey like this.

Espoo, 26 March 2024
Tomi J. Lindroos
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<tr>
<td>bio-CLC</td>
<td>Biomass Chemical Looping Combustion</td>
</tr>
<tr>
<td>biorefinery</td>
<td>In this Thesis, an industrial unit producing transport fuels from forest residues.</td>
</tr>
<tr>
<td>BECCS</td>
<td>Bioenergy with Carbon Capture and Storage</td>
</tr>
<tr>
<td>BioB</td>
<td>Biomass heat only boiler, same as Bio HOB</td>
</tr>
<tr>
<td>CCS</td>
<td>Carbon Capture and Storage</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>DH</td>
<td>District Heating</td>
</tr>
<tr>
<td>DHC</td>
<td>District Heating and Cooling</td>
</tr>
<tr>
<td>DC</td>
<td>District Cooling</td>
</tr>
<tr>
<td>DSM</td>
<td>Demand Side Management</td>
</tr>
<tr>
<td>Fixed O&amp;M</td>
<td>Fixed operation and maintenance costs that needs to be paid whether the unit is used or not e.g. annual maintenance</td>
</tr>
<tr>
<td>FosB</td>
<td>Fossil heat only boiler. Includes natural gas, coal, and oil. Same as Fossil HOB.</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
</tr>
<tr>
<td>HOB</td>
<td>Heat Only Boiler</td>
</tr>
<tr>
<td>HP</td>
<td>Heat pump</td>
</tr>
<tr>
<td>HPU</td>
<td>Heat pump, same as HP</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel of Climate Change</td>
</tr>
<tr>
<td>IRR</td>
<td>Internal Rate of Return</td>
</tr>
<tr>
<td>LULUCF</td>
<td>Land Use, Land Use Change, and Forestry</td>
</tr>
<tr>
<td>NGCC</td>
<td>Natural Gas Combined Cycle</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>Operation and Maintenance</td>
</tr>
<tr>
<td>RCP</td>
<td>Representative Concentration Pathway</td>
</tr>
</tbody>
</table>
RCP26  IPCC scenario leading to 2.6 W/m² radiative forcing leading likely below from 1.5 to 2 °C global warming compared to 1850-1900 levels.

RCP45  IPCC scenario leading to 4.5 W/m² radiative forcing likely from 2 to 3 °C global warming compared to 1850-1900 levels.

SMR    Small Modular nuclear Reactor

VRE    Variable Renewable Energy. Typically wind and solar power.
List of Publications

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


3. Lindroos, Tomi J.; Ryden, Magnus; Langørgen, Øyvind; Pursiheimo, Esa; Pikkarainen, Toni. 2019. Robust decision making analysis of BECCS (bio-CLC) in a district heating and cooling grid. Elsevier. Sustainable Energy Technologies and Assessments, Volume 34, August 2019, Pages 157-172. DOI: 10.1016/j.seta.2019.05.005


Author’s Contribution

Publication 1: Impacts of climate change and its mitigation in the Barents region


Publication 2: A techno-economic assessment of NuScale and DHR-400 reactors in a district heating and cooling grid

Tomi J. Lindroos: Developing the model, Collecting data for the modelled system, Modelling, Writing - Original Draft, Writing - Review & Editing. Esa Pursiheimo: Developing the model, Writing - Review & Editing. Ville Sahlberg: SMR technical parameters and description. Ville Tulkki: Conceptualization, Writing - Review & Editing.

Publication 3: Robust decision making analysis of BECCS (bio-CLC) in a district heating and cooling grid


Publication 4: Replacing fossil fuels with bioenergy in district heating – Comparison of technology options

**Publication 5**: Modeling the Baltic countries’ Green Transition and Desynchronization from the Russian Electricity Grid

1. Introduction

1.1 Heating and cooling are decarbonizing too slowly

Heating and cooling consume roughly half of the final energy consumption in the EU and renewable energy sources provided only 23% of that consumption in 2020 [1]. At the national level, the renewable share varies from 6% in Ireland to 81% in Iceland (Figure 1). Norway and Iceland provide energy statistics to Eurostat though they are not part of the EU.

![Figure 1. Renewable share of heating and cooling in 2020](image)

The current rate of heating and cooling decarbonization is not enough to achieve the EU’s 2030 targets [3]. The EU aims for a 55% reduction of GHG emissions from 1990 levels by 2030 in the European Green Deal, though this target is not yet implemented throughout the EU legislation [4]. The EU’s Climate Law is a legal objective for the EU to be climate neutral in 2050 [5]. This is based on the Paris Agreement where countries agreed that the anthropogenic emissions and sinks should be in balance in the second half of the 21st century [6].

Heating and cooling should be one of the major contributors to reaching these targets, because they consume roughly half of the final energy consumption in the EU [2]. However, the share of renewable heating and cooling has increased slowly, only from 12% to 23% from 2005 to 2020 (Figure 2) [2]. Assuming a
linear rate of development, the sector would be fossil fuel free around the year 2120, which is utterly too late.

More worrying is that Germany, the largest GHG emitter of the EU member states [8], is below the average development with only a 7-percentage point increase in 15 years. A few smaller countries, particularly Denmark and Estonia, have managed to increase their share of renewable heating and cooling by almost 30 percentage points in 15 years.

![Figure 2. Change in the renewable share of heating and cooling from 2005 to 2020 [2].](image)

Solid biomass is the largest source of renewable energy for heating and cooling with an 80% share in 2020, but the amount of solid biomass has been relatively stable at the level of 9300 TWh for the last 10 years [8]. Renewable energy from heat pumps is the fastest growing type of renewable energy for heating and cooling with an increase from 580 TWh in 2010 to 1700 TWh in 2021. Compared to biomass, the amount is still small and needs to grow much faster, because the amount of biomass has not been growing anymore.

### 1.2 District heating could speed up decarbonization

Researchers have envisioned that district heating and cooling (DHC) could speed up the decarbonization of the whole heating and cooling sector by expanding current networks [9], combining the best sides of centralized and distributed solutions [10], enabling demand side solutions on a larger scale [11], balancing variable electricity generation [12], and allowing new markets such as selling excess heat to the grid.

However, the DHC sector must mitigate its emissions from the current DH generation before the expansion. To succeed in that, the industry needs large scale investments to clean its generation capacity throughout Europe.
Approximately 500 TWh of district heating (DH) was produced in the EU in 2017, and in total DH systems serve more than 60 million Europeans [13]. Measured by the share of the population served by district heating, the largest European countries were Denmark (63% of the population, 38 TWh), Lithuania (57% of the population, 9 TWh), and Finland (52% of the population, 36 TWh) in 2017 (Figure 3). By production volumes and number of customers, Germany (75 TWh, 12 million customers, 15% of the population) and Poland (61 TWh, 17 million customers, 43% of the population) are the largest DH countries in Europe.

District heating is a technology for distributing generated heat as efficiently as possible. It benefits from the economy of large units and decentralized integration but is limited by costs and construction delays of the distribution grid. Large, centralized units have traditionally been cheaper per produced MW or MWh than distributed smaller units, but currently, smaller easily scalable units, such as heat pumps, are challenging this thinking.

According to Euroheat & Power, combined heat and power (CHP) units produced 65% of the district heating in European countries where data was available in 2017 [13]. A notable exception was France where only 20% of the generation was from cogeneration units (Figure 3).

Similarly, most countries still rely heavily on fossil fuels in their district heating generation. In total, 60% of European DH (300 TWh) was generated using fossil fuels [13]. The largest volumes of fossil DH were produced in Poland (68 TWh, 89% of total DH generation), Germany (68 TWh, 81% of total DH generation), and the Czech Republic (30 TWh, 89% of total DH generation) in 2017 (Figure 3). The smallest share of fossil DH (5%) was in Sweden, which has heavy national taxation on fossil fuels in district heating [14].

Figure 3. The share of the population served by DH, the share of cogeneration in DH, and the fossil share of DH in 2017 [13]. Data for Switzerland and Slovakia from 2015. Data for Bulgaria and Estonia from 2013.
The replacement of large, centralized units can be decided and administrated centrally enabling larger impacts from fewer decisions. The installation of smaller units, on the other hand, might be driven autonomously by companies and consumers with or without supporting policies. Both decarbonization routes are possible in countries with DH grids and might partly explain why the Nordic and Baltic countries have been able to increase the share of renewable heating and cooling faster than Central European countries which have smaller DH shares (Figure 2).

1.3 Research questions and scope

This thesis aims to explore and provide answers to the following main research questions:

- Q1: How will district heating develop as part of decarbonizing energy systems?
- Q2: Which uncertainties have the largest impact on the economy of investments?
- Q3: What kind of system level impacts do technologies have?
- Q4: How do local conditions impact the optimal technology mix of clean DH production?

This thesis includes five publications each modelling a specific case study and focusing on analysing the main research questions from the perspective of the case study. Table 1 lists the modelled case studies, scopes, and timeframes of each publication.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Modelled area</th>
<th>Scope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Publication 1</td>
<td>Region: Finland, Sweden, Norway, Russia</td>
<td>Decarbonization pathways of four Barents Region countries up to 2050 and the impacts of the climate change.</td>
</tr>
<tr>
<td>Publication 2</td>
<td>City: Helsinki (FIN)</td>
<td>Techno-economic modelling of large heat pumps, CHP SMR, and heat only SMR in a DHC grid in 2030s.</td>
</tr>
<tr>
<td>Publication 3</td>
<td>City: Helsinki</td>
<td>Techno-economic modelling of a biomass CHP unit, a biomass heat only boiler, and a bio-CLC unit in a DHC grid in 2030s.</td>
</tr>
<tr>
<td>Publication 4</td>
<td>Region: Northern Europe City: Helsinki</td>
<td>Techno-economic modelling of the forest residues value chain from supply to use in the power and heat sector to replace fossil fuels in a DHC grid and in the Northern European power system in 2030s.</td>
</tr>
<tr>
<td>Publication 5</td>
<td>Region: Baltic countries Cities: Baltic capitals</td>
<td>Modelling how Baltic countries could simultaneously desynchronize from the Russian electricity grid and replace fossil fuels in their power and heat systems. The transition is modelled up to 2030.</td>
</tr>
</tbody>
</table>

Each publication analyses and discusses the main research questions from slightly different perspectives. Table 2 summarizes how the publications contribute to the main research questions and highlights publication-specific questions which are particularly relevant to the results and conclusions of this thesis.
Table 2. The contribution to the main research questions and specific research questions of each publication.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Main research questions</th>
<th>Publication-specific questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Publication 1</td>
<td>Q1, Q4</td>
<td>How will the power and heat sector develop as a part of long-term decarbonization, how will it integrate with other sectors, and what risks does it face from climate change?</td>
</tr>
<tr>
<td>Publication 2</td>
<td>Q2, Q3, Q4</td>
<td>Are nuclear CHP and nuclear heat the only viable options to replace fossil fuels in the district heating and cooling grid from the techno-economical viewpoints? What are the main economic uncertainties of the modelled investments?</td>
</tr>
<tr>
<td>Publication 3</td>
<td>Q2, Q4</td>
<td>Which market conditions (prices, policies) favour heat pumps, traditional biomass units, or the upcoming bio-CLC technology? What subsidy level would be enough to fund a large-scale bio-CLC unit?</td>
</tr>
<tr>
<td>Publication 4</td>
<td>Q1, Q2, Q3, Q4</td>
<td>Will there be enough sustainable domestic biomass available for all planned investments? Which technological options would be the best ways to use the available biomass to replace fossil fuels in the power sector and in district heating?</td>
</tr>
<tr>
<td>Publication 5</td>
<td>Q1, Q3</td>
<td>How will the power and heat sector develop in the Baltic countries for the next ten years during fast systemic changes? How can the Baltic countries balance the targets of emission reduction, energy security, and affordable energy?</td>
</tr>
</tbody>
</table>
2. Literature review

2.1 Modelled development and decarbonization of DH

2.1.1 EU-level studies

The European Commission publishes country-level modelling results for their reference scenario up to 2050 [15] and specific energy and climate policy scenarios supporting legislative proposals, e.g. the European Green Deal [16]. The Commission’s long-term scenarios do not typically have country-level data but describe the overall EU development.

District heating has been often poorly modelled in the Commission’s scenarios. The EU 2030 climate policy impact assessment was modelled with an older model version in which district heating was modelled with few details as a part of the power sector. There was discussion on the importance of district heating, but no actual modelling results.

From the overall European perspective, this might be due to model development prioritizations, as the Commission estimates that district heating units produced only slightly less than 100 MtCO2 emissions in 2010 [15]. This estimate is in line with Euroheat & Power country-by-country reports [13]. Calculating the CO2 emissions from the amount of fuel consumption, assuming 90% efficiency, the total emissions of DH from the reported countries amounts to approximately 60 MtCO2. This was approximately 2% of the total EU’s CO2 emissions in 2010 [7].

The EU Reference Scenario, published in 2021 [15], was the first official EU scenario with a new model version that included the district heating sector in detail. The new model version should be able to cover industrial and tertiary heat demand, the demand shift to/from DH, heat boilers, CHP units, and industrial producers.

In the modelled reference 2020 scenario, the share of district heating increases but the total demand for district heating remains stable from 2005 to 2050, due to increasing energy efficiency. The share of CHP generation increases from 51% to 64% in 2050, and fossil fuels are replaced slowly with biomass and ‘other’ technologies including direct electricity, heat pumps, and solar DH. Most of the coal in DH generation is phased out by 2035, but 43% of DH is still generated with natural gas in 2050.

Despite the advancements in modelling capabilities, this scenario is largely outdated with the recent adoption of strict 2030 energy and climate targets, and energy trade and security issues related to the Russia’s war in Ukraine.
Recent DH market outlooks find a growing trend in central European countries both due to energy security and decarbonization aspects. The Euroheat & Power and power market review expects the European DH market to grow by 5.5 million households by 2030 [17], which would be an approximately 20% increase from 2017 assuming 2 persons per household [13]. Heat Roadmap Europe has modelled district heating to grow by a factor of 2 by 2030 and by a factor of 3 by 2050 [18].

Academic studies on the DH’s role in the future scenarios hold large uncertainties and different results. Manz et al. reviewed 16 different scenarios for the DH market share in 2050 and found that different models and scenarios led to a DH market share from 5% to 45% in the EU [19]. According to the Commission’s reference 2020 scenarios, the DH share from residential heating was 9% in 2020. Thus, some of the reviewed scenarios anticipated a slight decrease in the share of DH while the scenarios in the other extreme would see DH share growing five-fold.

### 2.1.2 Nordic modelling studies

Several studies have been published specifically covering the Nordic region. Nordic Energy Technology Perspectives 2016 modelled decarbonization scenarios for the five Nordic countries (Denmark, Iceland, Finland, Norway, Sweden) and the results showed a gradual replacement of fossil fuels with heat pumps and electric boilers by 2050 [20]. At the same time, the modelling shows an increasing share of cogeneration to provide balancing capacity for increasing VRE generation.

The total amount of biomass for district heating remained at 2020 levels. The report sees the total demand for biomass in the Nordics increasing from 1100 PJ to 1500 PJ from 2013 to 2050 due to the increased use for bioliquids. The report states that this increase cannot be sourced sustainably only from the Nordic countries raising questions about the availability and price of sustainable biomass.

The share of district heating increased in the household heating, but the total demand for district heating decreased from 150 TWh in 2020 to 140 TWh in 2050. The building energy efficiency improved in the modelled scenario reducing the total heating demand of buildings despite the increasing population.

Nordic Clean Energy Scenarios 2021 modelled three carbon neutral scenarios varying the amount of biomass, electrification, and the energy demands [21]. In general, the modelling sees a decreasing trend in district heating production from 2020 onwards in the Nordic countries, from 160 TWh in 2020 to 140 TWh in 2040. This result is like the previous report, but the actual production was at a higher level than modelled in the previous report.

In the modelled scenarios, fossil fuels and bioenergy in district heating are replaced by large heat pumps and waste-to-energy solutions. The total amount of available biomass was assumed to be lower than in the previous report and the model prioritized biomass for industrial use and bioliquid production instead of the DH sector. The model recognizes synergies with power-to-x produc-
tion by utilizing the waste heat from production and liquefaction in district heating grids. The report found that bioenergy with carbon capture and storage (BECCS) units would be profitable from the emissions reduction perspective. However, the report revealed a possible lock-in effect in the use of biomass resources, which could possibly block heat pump investments and the industrial use of biomass. The study published a technology catalogue of modelled technologies [23].

Neither of those publications covered energy taxation, grid fees, or local variations in investment costs, regulations, or technical configurations, as these areas are particularly laborious and difficult to capture with large system models. Large system models can model these differences through commodity prices, but still miss out many local conditions, such as higher land prices in large cities. Sandberg et al. studied local differences and showed over 10% variation in the levelized cost of heat (LCOH) of an example biomass unit and almost a 100% difference for the LCOH of large heat pumps in the Nordic countries [23].

2.1.3 Baltic modelling studies

Baltic Energy Technology Scenarios 2018 present 3 climate policy scenarios for the Baltic Countries (Estonia, Latvia, Lithuania) [24]. The study modelled national policies including domestic generation, renewable energy, and non-ETS emission reduction targets and found that such national targets have a high impact on technologies and investment rates.

The study also found that Baltic countries’ domestic generation targets are particularly difficult to achieve because local CHP production with natural gas will become uncompetitive due to new wind power investments. This also led to a situation where district heating was produced with natural gas boilers, biomass heat only boilers, and large heat pumps. Sensitivity studies of high wind power scenarios favoured large heat pumps. The share of district heating slightly increased also in this study, but the total amount remained approximately at the same level from 2010 to 2050.

Volkova et al. focused on the expansion of large heat pumps in the Baltics and concluded that heat pumps could supply up to 70% of the DH in the Baltics, but the current regulatory framework would not enable this development [25], a detail which was missing from the previous study. High shares of large heat pumps would compete directly with biomass investments as in the NCES 2021 study. The study includes an open data set of already completed large heat pump projects, Baltic district heating networks, and heat sources for large heat pumps.

The scientific literature hosts a body of Baltic electricity system studies, but typically these do not focus on DH, but electricity investments [26, 27], energy security [28, 29], or policies [30, 31] instead. Even though power system modelling includes CHP units, district heating is mentioned typically in the introduction and in the discussion while the results focus on electricity. The DH topic seems to be slightly understudied compared to its significance to Baltic energy systems.
2.1.4 City-level modelling studies

City-level modelling of district heating is a highly varied topic covering studies on DH demand, DH distribution, and DH supply, including large storages. Studies on DH demand include many perspectives from hourly demand projection [32, 33] to demand side management [34] and from the impact of building stock development to DH systems [35] to how climate change impacts the DH demand [36].

DH distribution studies have a similar range of subtopics ranging from the simulation of DH networks [37] to retrofitting existing networks for lower temperatures [38] and from district heating network optimization [39] to developing new business models [40]. There are a very wide range of simulation tools with slightly different focuses and strengths [41], but these are not the focus of this thesis.

Modelling of the DH supply is at the centre of this thesis, and it has been studied extensively in different previous case studies. Olsthoorn et al. [42] list 35 case studies that model adding new units or energy sources to DH grids. In total, 14 of these studies focussed specifically on a certain city and the rest either on the unit or national level. The studied technologies and heat sources included CHP with coal and gas, geothermal systems and heat pumps, waste to energy, solar DH, and industrial excess heat.

The topic is widely studied at the city level as tools and datasets are easier to build for smaller systems, and many real-life DH research questions are highly linked to a city-level decision making.

2.2 Low carbon technologies for district heating

2.2.1 Production technologies

Table 3 summarizes technologies from the reviewed studies to produce district heating without fossil fuels. The technologies are grouped into three categories: units that convert fossil free energy sources into district heating either primarily or as a side product, low temperature heat sources that require a heat pump to raise the temperature for district heating, and high temperature heat sources that can be used directly in district heating grids.

<table>
<thead>
<tr>
<th>Category</th>
<th>Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil free fuels/energy sources</td>
<td>Bioenergy (solid, gas, liquids)</td>
</tr>
<tr>
<td></td>
<td>Direct electricity</td>
</tr>
<tr>
<td></td>
<td>Electrofuels</td>
</tr>
<tr>
<td></td>
<td>Nuclear</td>
</tr>
<tr>
<td>Low temperature heat sources (heat pump)</td>
<td>Ambient heat</td>
</tr>
<tr>
<td></td>
<td>Solar</td>
</tr>
<tr>
<td></td>
<td>Waste heat</td>
</tr>
<tr>
<td>High temperature heat sources (direct)</td>
<td>Geothermal</td>
</tr>
<tr>
<td></td>
<td>Heat from industry</td>
</tr>
<tr>
<td></td>
<td>Waste incineration</td>
</tr>
</tbody>
</table>
The table includes mostly mature and commercially available technologies with a few exceptions. Electrofuels are yet not widely available and traditional fuels and nuclear energy might require changes in legislation and regulation in countries that do not already have nuclear district heating. Additionally, large heat pumps are still developing rapidly and estimates of their technological parameters are being updated regularly [43]. Low temperature heat sources with heat pumps are a highly diverse group as the size, temperature level, and availability of the heat sources vary. Each group might also include less developed technologies such as BECCS.

### 2.2.2 Storage, distribution, and demand side technologies

Studies in the literature review stressed that the cost-efficient decarbonization of European district heating requires a combination of production and non-production technologies, such as storage, low temperature distribution, and demand response.

Current district heating networks with large production units typically have small heat storage units to provide intraday and day-to-day flexibility to the generation of large units. Recently, companies have started to invest also in larger storage facilities, providing flexibility over multiple days and weeks [44]. The largest new investments have a capacity up to 200 MW / 2600 MWh [45] and 120 MW / 11600 MWh [46]. Large heat storage units can reduce emissions by avoiding the start-ups of fossil units during a short demand peaks or single colder days.

Some seasonal heat storages have been implemented in combination with solar heating in Denmark [47], and some are planned for waste heat sources [48], but their economy would typically require very cheap sources of heat or multiple cycles in a year [49]. Technology developers are trying to develop a cheap and efficient heat storage technology to revolutionize the district heating sector, but only water storages are currently mature enough [50].

Low temperature district heating supports decarbonization in several critical ways, most importantly it improves the efficiency of heat pumps (Table 3) due to the lower temperature lift [51]. In addition, a lower distribution temperature reduces heat losses, but this has less significance than improved efficiency [52]. However, the transformation to a lower distribution temperature requires investments both in the distribution grid and on a building-level. Additionally, the operation of a lower temperature distribution grid requires more careful management of temperature levels [53].

Building-level measures can either reduce the energy demand through efficiency improvements or by introducing smart demand side management (DSM). Energy efficiency measures and their impact were assessed in Chapter 2.1. According to Guelpa and Verda, widespread demand response and other DSM techniques could reduce the peak demand district of heating systems by up to 30% and annual costs up to 10% [50]. Cai et al. also report similar annual cost savings (11%) [53], but Salo et al. report only 0.7% cost savings in heat production costs [54]. Part of the cost savings are typically achieved by not only optimizing the temperature, but also reducing it on average. In addition, DSM
systems can lead to higher short-term variability of the district heating load [55].

### 2.2.3 Available resources

High temperature heat sources, such as hot geothermal and heat from industry are cheap and technologically easy sources of heat for district heating. However, these sources are typically too far from major heat sinks, such as large cities. Often a local industrial town can be heated with industry waste heat, but it is too expensive to transfer the excess heat over longer distances.

Iceland can manage their district heating with hot geothermal heat, but that is practically not available in other European district heating countries. Even in Denmark, which has a land area which is approximately 10% that of Sweden or Germany, GIS modelling of heat sources and sinks showed that only 5% of the heat demand could be economically covered from industrial excess heat [53]. Furthermore, Manz et al. identified a large amount of unused waste heat that could help to decarbonize DH, but they concluded that a major share of the heat would still have to be supplied by renewables [56].

Waste incineration units can be built in both smaller and larger cities, which has been a current trend in DH generation [57], but the amount is limited and can replace only a share of fossil fuels. In addition, enhanced recycling and stricter regulations should reduce the amount of waste in the coming decades.

Low temperature excess heat requires a heat pump and is thus a less profitable option than high temperature excess heat. If the heat sources are available throughout the year and sufficiently large, these heat sources are often good investment choices. The publications of this thesis did not study how much or what kind of low temperature excess heat sources are available, but instead used techno-economic modelling to investigate under which conditions DH generation from low temperature sources would be a better investment option than other possible technologies.

The availability of biomass is limited from multiple perspectives. In addition to resource sufficiency, biodiversity and land use emissions are other difficult issues related to bioenergy expansion. Forest land emissions have increased as bioenergy consumption and energy wood production (primary solid biofuels in IEA statistics) have increased in the EU and in Finland (Figure 4). In Finland, the consumption closely followed domestic energy wood production until 2010, since when imports and bioliquid production have increased. In the EU, the consumption of other bioproducts started to significantly increase already in 2000. In the EU, 12% of produced bioproducts were bioliquids and 11% biogas in 2021. EU level net imports have increased from 13 PJ in 2000 to 260 PJ in 2021.

Declining forest carbon sinks were one major reason why the EU Commission proposed a new EU Forest Strategy [58]. The high-level purpose is to restore forest carbon sinks and improve biodiversity. From the energy sector perspective, this can have a significant impact on the defined amount of sustainable bioenergy, practically limiting further investments or making them rely on imported biomass.
2.3 Sector coupling and flexibility

District heating is already very tightly coupled with the power sector through CHP units. CHP units produce electricity and heat either at fixed or adjustable ratios. A fixed ratio CHP is significantly less flexible and can adjust production only through the total power of the unit. On the other hand, CHPs with a flexible power-to-heat ratio have more options as they can adjust their operation depending on market prices and demands. Certain technology types can increase the share of heat, others reduce the share of heat, while some units can do both. In addition, CHP units can participate in ancillary power markets and provide other system services than energy only [59], which is particularly important during the phase out of existing fossil fuel power units [60].

Large heat pumps for district heating will significantly deepen the sector coupling as they consume electricity, can optimize their operations depending on market prices, and provide demand response [61]. Some modelling studies have concluded that power to heat solutions could provide up to 40% of the annual heat demand in wind power dominated systems [62].

Large heat pumps couple district heating tightly to district cooling in cities that have both systems. The greatest benefit is that heat pumps are a highly efficient technology for cogenerating both cooling and heating [63]. In practice, this means collecting excess heat from buildings and reusing it in district heating. For example, 100% of the district cooling in Espoo in Finland was cogenerated with district heating using large heat pumps in 2022 and 67% of all district cooling in Finland was generated by large heat pumps in 2022 [64].

Residential, commercial, and public buildings have traditionally been passive district heating consumers, but DSM technologies and heat sales to the grid have started to slowly change this [65]. Future district heating grids are likely to have more prosumers than current grids, but the actual amounts highly depend on local regulations, pricing mechanisms, and distribution temperatures [66].

Sector coupling with district heating and industry takes place on similar terms to the tertiary sector except that some industries can offer high volumes of excess heat and could provide larger DSM when consuming DH. The issue often
is that large heat sources are far from large heat sinks (large cities with district heating grids) and distances block their integration. For example, Bühler et al. conducted a GIS modelling of heat sources and sinks in Denmark and found that only 5% of Danish DH demand could be supplied by industrial excess heat [67]. In addition, cities must recognize the risks of supply issues e.g. industrial strikes or bankruptcy and have necessary backup capacity [68].

### 2.4 Risks of technology investments

Energy technology investments carry many inherent risks as do any other investments, but energy technologies are often capital-intensive investments, have a long technological life, and operate in a rapidly changing operational environment. Investors should consider multiple short-term and long-term risks. To assist in these considerations, several risk classifications have been developed. After a review of different energy technology risk assessments, Table 4 summarizes energy technology investment risk classifications by the IEA [69], Milford et al. [70], and WMO [71].

**Table 4. Risk classifications for energy technology investments.**

<table>
<thead>
<tr>
<th>Category</th>
<th>Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technological risks</td>
<td>Construction risks</td>
</tr>
<tr>
<td></td>
<td>Operation risks</td>
</tr>
<tr>
<td></td>
<td>Performance risks</td>
</tr>
<tr>
<td>Economic risks</td>
<td>Market risks</td>
</tr>
<tr>
<td></td>
<td>Counterparty credit risks</td>
</tr>
<tr>
<td></td>
<td>Macroeconomic risks</td>
</tr>
<tr>
<td>Political risks</td>
<td>Regulatory risks</td>
</tr>
<tr>
<td></td>
<td>Transfer-of-profit risks</td>
</tr>
<tr>
<td></td>
<td>Expropriation/nationalisation risks</td>
</tr>
<tr>
<td>Legal risks</td>
<td>Documentation/Contract risks</td>
</tr>
<tr>
<td></td>
<td>Jurisdictional risks</td>
</tr>
<tr>
<td>Social risks</td>
<td>Acceptance risks</td>
</tr>
<tr>
<td></td>
<td>Reputation risks</td>
</tr>
<tr>
<td></td>
<td>workforce risks</td>
</tr>
<tr>
<td>Environmental risks</td>
<td>Natural hazard risks</td>
</tr>
<tr>
<td></td>
<td>Climate change risks</td>
</tr>
</tbody>
</table>

Despite the range and variety of risks, observed dramatic short-term uncertainties, and planned long-term transition, most studies in the literature review presented only a few scenarios and drew conclusions without extensive sensitivity analyses. This is most likely due to available personnel resources but can lead to severe misunderstandings of the system dynamics and conclusions applying only to a specific assumption set. This was particularly visible when comparing the estimations of the future district heating share of building heating and the cost savings from building-level DSM technologies.

Bosetti et al. used three integrated assessment models to analyse the technological and economical risks of solar, nuclear, biofuels, and CCS on long-term decarbonization pathways. The results showed very high impacts of cost and efficiency assumptions for nuclear and biofuel leading to very different futures where variable renewable energy (VRE) generated from 5% to 70% of electricity in 2050, nuclear power generated from 5% to 80% of electricity in 2050, and
from 0 to 7 GtCO2 was captured and stored in 2050 [72]. This study demonstrates that large integrated assessment models are typically very flexible and can produce very different future scenarios, and that such models can rule out only certain extreme outcomes.

A recent unfortunate example of economic and political risk is still unfolding due to Russia’s war in Ukraine. The war and sanctions led to increasing energy commodity prices, scarcity of energy commodities, nationalization of companies, etc. Nerlinger and Utz analysed the economic impacts of the war, and based on an early outcome, some energy companies outperformed the stock market especially in Northern America, while some were hard hit by events [73].

Events like wars are extreme cases for risk analyses, but certain commodity prices were highly volatile also before the war. The European CO2 allowance price increased from 8 EUR/tCO2 in Jan 2018 to 100 EUR/tCO2 in Jan 2022 due to the ambitious 2030 plans adopted in the EU. This had a very large impact on the profitability and the merit order of fossil fuel units [74].

Social risks have been particularly present with biomass and nuclear for district heating. For biomass, the acceptance issues have concerned the sustainability of feedstock and the increased traffic near production units [75]. In the case of nuclear district heating, the acceptance risks are similar to those for nuclear power generation or worse if units are planned closer to cities [76].

Long-term uncertainties are associated especially with climate risk for green investments [77] as energy technology investments have a long lifetime. However, this might not be as meaningful for companies that require a much shorter economic payback time for investments.

### 2.5 Acceptability of technologies

Public acceptance is a factor that is sometimes addressed too late while developing new energy systems and can have adverse effects. Perlaviciute et al. argue that engineers, policy makers, and project developers tend to misjudge the complexity and consequences of public resistance [78]. Acceptability problems have stalled and cancelled energy projects.

The acceptability issue is particularly important when regarding nuclear power. The possible distance of a nuclear heat reactor to local habitants depends on public acceptance, legislation, and particularly on the required safety zones. In some countries the opposition to nuclear power is very strong, while in other countries like Finland, the general attitude is more positive. In a recent poll, 82% of respondents wanted more solar power in Finland, 77% more wind power, 55% more hydro power and 54% more nuclear power [79]. Only 11% wanted to reduce the amount of nuclear power.

This thesis acknowledges the acceptability issues and their importance but does not analyse them further and focuses on techno-economic assessments. Actual project developers should address the acceptability issues even for the most favoured technologies.
2.6 Decision making

2.6.1 Taking uncertainty into account

Decision makers need to balance and find compromises between the fast rate of change required by energy and climate policies, existing infrastructure, available and emerging technologies, techno-economic analyses, and socio-political factors. Managing multiple expectations, boundaries, and uncertainties is a critical challenge for both policy makers and companies.

Anadón et al. have tried to incorporate expert elicitations, integrated assessment models, and decision frameworks to support public decision making for the allocation of R&D investments and identify knowledge gaps that remain [80]. They acknowledge that their proposal is complex and requires significant efforts to implement, but they also show that expert knowledge reflecting uncertainties can be integrated with sophisticated modelling.

A modelling exercise should consider a range of uncertainties and sensitivity analyses to provide the necessary information for the decision-making process. Robust decision making is an approach which aims to find solutions that work in a wide range of possible futures, and perhaps more importantly, one which tries to avoid solutions that would be highly unsuccessful in some futures [81]. This approach is based on creating a range for key parameters, modelling a relatively large number of sensitivity analyses, typically several thousands, and drawing statistical conclusions from the results. As a downside, the approach does not make decisions, but it provides information about which conditions favour which investment option.

2.6.2 Overcoming barriers to new investments

Reda et al. have investigated socio-technical challenges related to district heating and found a range of barriers slowing the development towards low carbon solutions [82]. They interviewed companies, organizations, city officials, and academia. Each group saw different barriers, highlighting the difficulties of matching legislation, economic incentives, and timing. Large, centralized units are easier to refurbish or replace as there are fewer stakeholders involved.

Companies can accept different risk levels under uncertainty. Antoeneta et al. carried out a study of U.S. venture capital firms’ investments in clean energy from 1990 to 2008 and found that a firm’s reputation could both increase their risk taking, as companies need to keep performing at an expected level, and it could reduce their risk taking by trying to preserve the gained reputation by avoiding failure [83].

Despite accepted risk levels, investing companies must typically acquire financing for the investment and thus also assure the financing sector. Energy sector investments are typically capital intensive requiring relatively long pay-back times. Economic, political, and regulatory stability significantly reduces the associated risks and can enable cheaper loans for companies [84].
3. Approach and methods

3.1 Energy system modelling

3.1.1 Summary of used models

The publications in this thesis use TIMES-VTT, which is a large integrated assessment model, and three different more specific models that focus on power and heat and work on an hourly level. Table 5 summarizes the models used in the publications, modelled geographical areas, and the scopes of the models.

Table 5. Models used in the publications and a summary of their main properties.

<table>
<thead>
<tr>
<th>Model</th>
<th>Modelled area</th>
<th>Scope</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIMES-VTT</td>
<td>Region: Finland, Sweden, Norway, Russia</td>
<td>All energy use and greenhouse gases of modelled countries. Used to analyse long-term decarbonization pathways.</td>
<td>Covers all energy use and GHG emissions, has very extensive technology library, well known model, and capable to analyse large range of policy targets.</td>
<td>splits year to 24 time slices that are not chronological, models larger regions such as “Western Europe” with some added single countries, also sectoral details are approximated</td>
</tr>
<tr>
<td>City-level DHC model</td>
<td>City: Helsinki (FIN)</td>
<td>Modelling the operation and investments of district heating and cooling production in a single city. Sells and buys electricity from markets. Allows studies from the economic viewpoint of the operating company instead of the larger energy system.</td>
<td>Tailored to be very fast to solve, does not minimize the system costs but instead replicates the costs and income of DH operator, can be very detailed on modelled units</td>
<td>The results are specific to one city only. Many system level investigations and sensitivity analyses e.g. increasing the amount of wind power, are not possible as the system is not modelled.</td>
</tr>
<tr>
<td>Extended Northern European Backbone model</td>
<td>Region: Northern Europe, City: Helsinki</td>
<td>An integrated version of three separate models: a Northern European power and heat model, a more detailed Finnish DH model, and a Finnish biomass supply model. Used to study biomass sufficiency under varying investment scenarios, as well as the benefits and disadvantages of investments for different stakeholders.</td>
<td>Combining a larger area power system model to detailed district heating models and a regional biomass supply model. Hourly modelling. Includes power system reserves.</td>
<td>Significantly slower run time (~2 hours) practically limiting the number of sensitivity analyses, not including other sectors important for sectoral integration, mainly EVs and heat demands in industry and tertiary sectors.</td>
</tr>
<tr>
<td>Baltic Backbone model</td>
<td>Region: Baltic countries Cities: Baltic capitals</td>
<td>Integrated modelling of power and heat, buildings, and transport sectors to study the emissions reductions, renewable integration, sector coupling, flexibility, and power system energy security.</td>
<td>Hourly modelling of sectoral integration model covering electricity, district heating, transport, and buildings. Designed to study policy targets, such as domestic generation, renewable shares, and non-ETS emissions.</td>
<td>Did not include explicit modelling of neighbouring countries. Baltic countries are such small that their larger neighbours heavily impact the Baltic countries energy systems, and we couldn’t run sensitivity analysis on neighbouring countries.</td>
</tr>
</tbody>
</table>
All the used models are linear single objective models that minimize the total costs including operations, investments, taxes, etc. Depending on the case, the models might have mixed integer variables. The complexity of the models varies from 17 generation units in the Helsinki DHC model to thousands of processes in the TIMES-VTT model for each model region. The model complexity has a huge impact on the run time, which ranged from approximately one minute for the city-level DHC model to 4-6 hours for the Extended Northern European Backbone.

### 3.1.2 TIMES-VTT

TIMES models are common tools used to analyse energy systems [85] and TIMES-VTT has added details of Nordic countries compared to the global TIMES model. We have added individual modelling of each Nordic country, and added details for district heating modelling, biorefineries and P2X processes [86]. The model has been used to analyse global emissions reduction pathways [87], the inter-sectoral effects of high renewable shares [88], and in support of national policymaking [89].

Figure 5 shows the schematic structure of the TIMES models and energy flows from the primary energy resources to the energy transformation sector and to energy end use sectors. Available primary energy resources and sectoral end use demands are assumptions as are the technology efficiencies and costs.

![Figure 5](image_url). Schematic illustration of the sectors in each model region in the TIMES-VTT.
3.1.3 City-level DHC model

The city-level DHC model was developed separately for publications 2 and 3 in this Thesis. The purpose was to create a model that is as fast to solve as possible, is easy to run with scripts allowing the automation of very large numbers of model runs, and with a sufficient level of detail to model district heating sector investments.

The working principles and features of this relatively simple model are otherwise very similar to available public models, but we were able to reach solve times of less than a minute for a full year run with mixed integer variables and other operational constraints. This allowed us running a very large amount of sensitivity analysis. In publication 3, we modelled over 8000 scenarios, which totals approximately 130 hours despite the fast run-time.

The model was developed to minimize the city-level costs by optimizing the operation of units in the city and trading electricity with the external power markets, similarly to a DHC system operator (Figure 6). This equals profit maximization from the company perspective if profits from sales remain the same.

The model has chronological time-steps and in these models, we used one-hour time steps according to the current Nordpool electricity markets. The model must maintain the balance of local district heating and district cooling grids by varying the generation and storages to match the demand at an hourly level. Electricity is sold and bought on the Nordic markets. The model is documented and validated in the appendix of the publication 3.

Figure 6 highlights the investment options in publication 2. The model investments were not cost optimized, but instead all the studied options were calculated for each different assumption e.g. prices and heating demand. This often resulted in cases where the investment was not profitable but was necessary to rank the investment options.

The purpose of the study was to gain additional insight into whether company-level profit maximization would produce similar results to large scale cost minimization and to study uncertainties from the investment perspective.

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**Figure 6.** Schematic illustration of the city-level DHC model.
3.1.4 Extended Northern European Backbone

Backbone is an adaptable and configurable energy system modelling framework that allows users to relatively easily create their own smaller or larger models [90]. The Backbone has wide technical options to model variable renewables and their stochastics [91].

The Extended Northern European Backbone combines the previously used Northern European Backbone modelling power and heat model with additional details of hydro power [92] and renewable stochastics [93], biomass supply model [94], and detailed city-level DHC model from previous studies in this thesis.

Figure 7 illustrates how separate district heating models (Module C, Figure 8) are joined to the Northern European power model (Module A, Figure 8). Each DHC area has its own heating and cooling grid and operates on common power markets. In the simpler city-level model the electricity price was an external assumption, but in this configuration the electricity price is modelled within the same model. This allows a much more complicated sensitivity analysis, such as varying the amount of wind power in the power system.

The Finnish biomass supply (Module B, Figure 8) is integrated in the Finnish district heating and cooling model, with local forest residue potentials, maximum allowed transport distances, and transport costs and emissions according to the transport distance. This enables an analysis of how much local biomass certain new biomass investments can use and how much would probably have to be imported.

The purpose is to gain additional insight into the value of the DH investments for the city and energy system, to study the sufficiency of biomass when modelling the demand and supply in higher geographical detail, and to estimate the impact of systemic uncertainties on DH investments.

Figure 7. Schematic illustration of the modelled city-level energy system and its linkages to Nordic power system.
Approach and methods

3.1.5 Baltic Backbone

The Baltic Backbone model simplifies the geographical coverage of the Northern European model but integrates the transport sector and buildings into the same model (Figure 9). This configuration enables more detailed analysis of renewable integration, sectoral coupling, and flexibility. However, it loses details on the impact of neighbouring countries policies and investments.

In addition, the model was designed to follow the split between the EU’s emission trading sector (EU ETS) and the EU’s Effort Sharing Regulation (EU ESR) allowing the analysis of national emission reduction targets for policymakers. The model does not cover industry, which is a major energy consumer and source of emissions.

Figure 8. Schematic illustration of the three modules of the extended Northern European Backbone.
Figure 9. Schematic illustration of the three modules of the Baltic Backbone.

3.2 Comparison to other energy system models

Backbone is a more advanced when compared to most commonly used open-source power system models [95]. When compared to other open-source energy system models, Backbone ranked second in technical features category (Figure 10). Other models well above the average are TIMES, which is used in the Publication 1 of this Thesis, and SpineOpt, which was still under development when the publications of this Thesis were done.

Balmorel is a relatively commonly used model in Nordic countries as it was first released already in 2001 and developed in Denmark [96]. Unlike Balmorel, Backbone includes start-up costs, part-load efficiencies, minimum operation loads of units, can model multiple reserves, N-1 conditions, inertia in the grids, energy diffusion between nodes, emissions as inputs to processes, can run stochastic optimization, and is flexible enough to include multiple sectors e.g. electric vehicles, biomass supply, and buildings, and complex units with multiple inputs and outputs and complex ratios between those. Many of these features are essential when studying future energy systems with high shares of wind and solar, P2X, and sectoral integration.
Approach and methods

Backbone is a very flexible modelling framework allowing large range of modelling scopes from District level to international studies. Compared to other open-source models, these features are considered in the model design and allow multi-stage studies, e.g. running first the investment modelling and then more detailed unit commitment modelling, or myopic investment optimization where the model does not know the whole future immediately. TIMES is more limited by its scope and it performs the best in large-scale studies from country-level to global studies.

**Figure 10.** Laveziana et al. results from the comparison of technical features of energy system models [95].

**Figure 11.** Laveziana et al. results from the comparison of scope of energy system models [95].
3.3 Data sources and open access

Large and unified datasets enable large energy system models. Without large, unified datasets, the amount of required workload of collecting data from multiple different sources would simply be too much. Smaller models, on the other hand, can use very specific data sources and build very detailed features. The availability of general energy systems data and more specific electricity system data has significantly increased during recent years, but district heating data is still difficult to collect from multiple national sources.

The International Energy Agency’s (IEA) energy statistics offer data from all countries and more detailed data from the OECD [97]. Detailed energy balances have been available for decades and have practically enabled large integrated assessment models such as TIMES-VTT. The IEA data has been supplemented with other similar overarching datasets, such as the Danish Energy Agency’s technology data [43], the World Resource Institute’s data on energy resources and emissions [98], and UNFCCC data on greenhouse gas emissions [7].

The global TIMES model and processed input data are available for IEA-ETSAP members [99]. VTT's additions have not been published as open data.

The equations and parameters of the city-level model were published in the annex of publication 3 of this thesis. We did not publish an executable model or the code due to documentation and language reasons as variable names and comments were often written in Finnish. However, we migrated the model to Backbone and published the second version of the model as an open-source model and dataset [100] documented and validated in [101]. The published model is otherwise the same than in publications 2 and 3 of this Thesis, but it is expanded by adding the cities of Espoo and Vantaa, which have their own district heating networks that are connected to Helsinki’s DH grid.

The Northern European model is built on ENTSO-E datasets for electricity demand [102], units and renewable energy time series [103], transmission capacities [104], hydro power data [105], and national DH statistics for Finland [106] and Euroheat & power compiled DH data [13]. Similarly, to the city-level DHC model, the fourth publication of this thesis used the first version of the model, but we have since updated the model and published the model and datasets [107].

The Baltic Backbone model models only three Baltic countries in detail. For those, we collected unit level data and were able to model each Baltic electricity generation unit separately. In addition, we collected building data and EV data from national statistics agencies. The fifth publication of this thesis documents the national data sources and main assumptions. We have published the full model and datasets [108].
3.4 Studied technologies

The publication 1 was modelled with a large energy system model covering all energy sectors and investment options in the technology catalogues. Publications 2, 3, and 4, were modelled on more focused DH models with a need to focus on the most promising options in the modelled case studies from all options to produce fossil-free district heating listed in Table 3. Academia and local district heating companies are conducting regular preliminary studies on the most promising investment options and in general there is reasonably good knowledge on available options. Publication 5 falls somewhere in between, as it covers more sectors and technologies than DH models, but less than TIMES-VTT. Table 6 summarizes technologies selected for more detailed investigation in each publication.

Table 6. Modelled sectors and studied investment options in the publications of this Thesis.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Sectors</th>
<th>DH production Investment options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Publication 1</td>
<td>All energy sectors</td>
<td>Technologies for the decarbonization of all energy sectors. The summary of this Thesis focuses on the results for power and heat sectors.</td>
</tr>
<tr>
<td>Publication 2</td>
<td>DHC</td>
<td>SMR CHP, SMR HOB, biomass HOB, biomass CHP, and large heat pumps.</td>
</tr>
<tr>
<td>Publication 3</td>
<td>DHC</td>
<td>Biomass Chemical Looping Combustion (bio-CLC), biomass HOB, biomass CHP, and large heat pumps.</td>
</tr>
<tr>
<td>Publication 4</td>
<td>Electricity, DH, biomass supply</td>
<td>Biomass HOB, biomass CHP, biorefinery, H2 boosted biorefinery.</td>
</tr>
<tr>
<td>Publication 5</td>
<td>Electricity, DH, transport, buildings</td>
<td>The summary of this Thesis focuses on the results for power and heat sectors.</td>
</tr>
</tbody>
</table>

Biomass is a traditional option to produce fossil free DH and we typically model heat only boilers (HOB) and combined heat and power units (CHP). However, new type of biomass units are in development and publication 3 studies Biomass Chemical Looping Combustion (bio-CLC) and publication 4 studies biorefineries with and without hydrogen boosting.

CLC is a new kind of technology type far carbon capturing [109]. CLC units are composed of two connected fluidized beds, of which the other is an air reactor and the other is a fuel reactor. With specific bed materials, such as ilmenite, CLC unit can carry only oxygen from the air reactor to the fuel reactor where the fuel is burned with pure oxygen. This results to very high CO2 concentration in flue gases compared to combustion with air that includes 79% of nitrogen. CLC technology is under demonstration but could result to significantly smaller energy penalties than post combustion capture.

Publication 4 uses the term biorefinery to describe an industrial unit producing transport fuels from the forest energy e.g., forest chips. According to IEA, most transport bioliquids were made from maize (40%), sugars (23%), palm oil (11%), and soy oil (9%) in 2021 [110]. In this publication, we assume that a technology to produce biodiesel from forest residues would be available on 2030s and study its impacts. Several companies have been planning for this kind of a unit, but currently there are no public investment decision in Finland.
In addition, we studied an alternative version of this kind of a biorefinery where the yield could be increased with hydrogen boosting [111]. By adding hydrogen to refining process, the unit could crack hydrocarbons to smaller chains and increase the ratio of bioliquid vs. biomass feedstock at the cost of increased electricity consumption.

Each of the publications in this Thesis include large heat pumps as those are quite easily scalable options and their utilization depends mostly on the availability and quality of heat sources. None of the publications in this Thesis studied the amount or quality of available heat sources, but instead studied the impacts if such heat sources would be available and the profitability of the investments. More detailed additional studies should be carried out, for example when heat source is depending on outdoor temperature, such as large air source heat pumps.

3.5 Techno-economic impacts

The used models optimize the operations and investments in the modelled energy system by minimizing the total costs. Alternatively, investments can be forced or preselected to also study suboptimal investments. In this case, the model only optimizes the annual operations. This is an important practice in the sensitivity analysis allowing researchers to study why a certain investment would be worse than another and how much worse it would be.

Table 7 summarizes the primary techno-economic results from the model runs. Depending on the study, the impacts are analysed either as a difference to the base year or as a difference between two scenarios. The former approach requires pathway modelling and applies to this thesis only in the case of the TIMES-VTT model. The other models cover only a single year and the impacts are calculated from the differences of two or more scenarios.

<table>
<thead>
<tr>
<th>Category</th>
<th>Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Energy commodity flows</td>
</tr>
<tr>
<td></td>
<td>Unit operations</td>
</tr>
<tr>
<td></td>
<td>Storage levels</td>
</tr>
<tr>
<td></td>
<td>Energy trade</td>
</tr>
<tr>
<td>Economic</td>
<td>Investments</td>
</tr>
<tr>
<td></td>
<td>Operational and fixed costs</td>
</tr>
<tr>
<td></td>
<td>Energy commodity prices (unless assumption)</td>
</tr>
<tr>
<td></td>
<td>CO2 allowance price (unless assumption)</td>
</tr>
<tr>
<td>Emissions</td>
<td>GHG emissions</td>
</tr>
</tbody>
</table>

Both approaches have their strengths and weaknesses. Pathway modelling gives results for multiple years before and after an investment, modelling the development of the energy system instead of a static environment. On the other hand, the data needs, run time, and results processing slow the work significantly and large model studies often have a very limited number of scenarios. In addition, large impact assessment models, such as TIMES-VTT, have highly aggregated timesteps (24 time steps in a year in TIMES-VTT) and they are typically not
chronological. A very limited number of non-chronological time steps makes these models not very well suitable for analysing VRE integration, required storages, and flexibility.

Smaller models, such as the city-level DHC model, can model an energy system chronologically hour-by-hour, have detailed descriptions of the modelled system, and yet run thousands of times for statistical analysis of the results. In their case the results need to be interpreted slightly differently as a single run should not be considered an optimal or correct solution to the problem, but just one outcome of a certain assumption set. In principle, this would be a better approach also for larger models, but the required workload often makes this impractical goal.

Certain results, such as investment profitability, flexibility provision, and storage cycles, are calculated post model run from the primary techno-economic results.

The internal rate of return (IRR) is the main indicator we use for the investment profitability. It is defined as the solution $i^*$ for the equation

$$\sum_{r} \frac{R_t - C_t}{(1 + i^*)^t} = I_0$$

where $t$ is time in years, $R_t$ is revenue at time $t$, $C_t$ is cost at time $t$, and $I_0$ is the initial investment [112].
4. Results

4.1 Decarbonizing DH with sustainable biomass and electrification

4.1.1 Model optimized long-term development up to 2050

Publication 1 analyses the long-term model optimized emission reduction scenarios for Norway, Sweden, Finland, and Russia up to 2050. Under strict GHG reduction targets (-80% from 2005), the TIMES-VTT model results show that decarbonizing electricity and heat is the most cost-efficient way to reduce emissions. In addition, these sectors deliver clean energy to other sectors also helping to decarbonize those sectors.

The Nordic (excl. Denmark) electricity generation was mostly fossil-free already in 2010. In total, 90% of the electricity was generated without fossil fuels. The largest share of fossil-free electricity was from hydro power (200 TWh), nuclear (80 TWh), and biomass (20 TWh). Wind and solar power generated only 6 TWh in Finland, Norway, and Sweden in 2010. Fossil fuels were used to generate 40 TWh of electricity mostly in CHP units in 2010.

In the modelled scenarios, the remaining fossil fuels in electricity and district heat generation were replaced with wind power, solar power, and biomass CHP units, biomass heat only boilers, and heat pumps (Figure 12). TIMES-VTT achieved this by 2030 in Sweden and Norway and between 2030 and 2050 in Finland and Russia. The modelled results lead to a decrease in CHP capacity and generation. In real life this would reduce inertia in the power system, but TIMES-VTT does not capture this as reserves are modelled with a peak capacity margin, typically 20% of the maximum demand of the year.

The model also relies on bioenergy with carbon capture and storage as a long-term solution, which would provide a possible option to avoid mitigating the most difficult emissions sources. In the modelled scenario without CCS the electricity demand and biomass consumption increased. The impacts were relatively small in the Nordic countries, but more significant in Russia and Central Europe.
Figure 12. Electricity generation and demand in the Barents region countries in the modelled scenarios. RCP45 is an IPCC scenario leading to 4.5W radiative forcing ~2.4 degree warming. RCP26 leads to ~1.6 degree warming compared to 1850-1900 levels.

The residential sector did not cause large direct emissions in 2010 but contributed to overall emissions through the consumption of electricity and heat. The energy efficiency of buildings improved in the modelled scenarios reducing the demand, and the direct use of fossil fuels in the building-level heating systems was replaced with electrification and district heating. As a result, the share of district heating increased, but the total amount slightly decreased.

In the modelling results, the electrification of other sectors, such as transport and heating, led to increased electricity demand. The Nordic countries have more land area and less consumption than Central European countries and the model exported increasing amounts of clean electricity to Central Europe, further increasing the produced amounts of electricity. In addition to clean generation, the Nordic countries have an opportunity to provide balancing services with reservoir hydro.

Investments in electricity transmission and demand-side management become important as the amount of dispatchable generation decreases, variable generation increases, and variable demand increases. However, the main weakness of the modelling is that the aggregated timesteps will not see the most difficult hours and periods. The transmission capacity expansion is subject to the costs and acceptability of new interconnectors. In addition, climate change can affect the reliability of electricity grids through increased storm damage.

The model invested in a significant amount of biofuel refining capacity to decarbonize heavy transportation (trucks, ships, aviation). Combined with the increased use of biomass in the power and heat sector, this would increase the
amount of total biomass consumption for these sectors from 160 PJ to 1600 PJ. The largest components of the increase were Russia’s biofuel production (+1100 PJ), biofuel production of the Nordic countries (+250 PJ), and power and heat production in the Nordic countries (+90 PJ). For three modelled Nordic countries, the increase would be 50% from 2005 by 2050 not including the increased consumption in other industries. Such an increase necessitates a critical examination of whether it is possible or not.

4.1.2 Medium-term development accounting policies and investment plans up to 2030

The medium-term development of district heating systems is driven by policies and company-level investment decisions that might lead to similar or quite different developments compared to long-term solutions optimized by energy system models.

Publication 4 of this thesis modelled the development of the Northern European (Germany, Poland, Baltics, and Nordics, see Figure 8) power system up to 2030 according to the ENTSO-E capacity expansion scenarios. These scenarios would lead to roughly doubling of the wind and solar generation in the area and halving the coal-based power generation in the modelled 2030 baseline (Figure 13, left panel). The share of electricity generation from natural gas would remain at 2017 levels.

Finnish legislation demands a phase out of coal in power and heat by 2030 [113], thus slightly increasing the share of natural gas in the Finnish DH sector compared to 2017 (Figure 13, right panel). The results show that the district heating sector would decarbonize significantly more slowly than the power sector and that the new renewables would be from biomass and heat pumps. Increasing biomass demand was covered by the increased use of logging residues, small diameter wood, and imports. The share of heat pumps tripled, but their total share remained at 10%.

![Figure 13. Electricity generation in the Northern European model area (left panel), biomass and peat supply to power and district heating in Finland (middle panel), and district heating generation in Finland (right panel).]
The amount of peat roughly halved in the results, but many units can co-fire peat and biomass, keeping a certain amount of peat use economical in the modelled system (Figure 13, middle panel). However, the reduction of peat use has been faster than modelled after the government decided to phase out peat in 2021 and subsidies are being reduced [114]. Since 2022, the biomass imports from Russia reduced and the decline of peat production has at least slowed, if not increased again [115].

Publication 5 modelled the development of the Baltic energy systems and found that policies and investment plans would lead to a significant shift from fossil-based energy sources to wind power, solar power, and biomass (Figure 14, left panel). According to plans, the share of wind and solar would increase from 11% in 2017 to 60% by 2030. Estonia was planning to phase out shale oil capacity, as it was economically not competitive during the low average electricity prices and high CO2 allowance prices before and during the Covid-19 crisis.

The planned phase-out would have converted Estonia from an electricity net exporter to an electricity net importer. The Baltic region would remain an electricity net importer despite the modelled increase in wind and solar capacity. However, the electricity prices started increasing dramatically after submitting the publication and the domestic generation capacity proved its value as a provider of energy security. This revealed a flaw in the parameter range of modelled scenarios further strengthening the conclusion that modelling studies should include a broader range of sensitivities.

The modelled changes were more subtle in district heating: demand was expected to slightly decrease (10% in Estonia and Latvia, 20% in Lithuania), and shale oil and natural gas to be partly replaced by biomass, biogas, waste, and large heat pumps (Figure 14, right panel). The Baltic district heating system still had a notable share of natural gas in 2030, especially in Latvia where a large share of heat only boilers are fuelled by natural gas. Additionally, in this study the district heating sector decarbonized more slowly than the power sector and natural gas units remained active producers in the system in the 2030s.

Latvian NGCC units saw fewer operation hours in the modelled 2030 reference scenario with an increasing share of wind power (Figure 14, left panel). Reducing utilization rates indicates a possible phase out or moth balling of at least one unit despite being not officially planned. However, this did not significantly reduce the amount of used natural gas as it was burned in heat only boilers instead.
4.2 Main uncertainties: electricity, biomass, natural gas, and policies

4.2.1 System-level uncertainties typically outweigh unit level uncertainties

Publication 3 studied how unit-level and system-level parameters impact the profitability of a bio-CLC investment. Both parameter groups caused significant uncertainty in the profitability of the bio-CLC unit with the studied parameter ranges, but the system-level parameters caused an uncertainty that was an order larger (Figure 15). The figure summarizes the studied uncertainty ranges in the brackets by starting from a value that leads to lower profitability, e.g. higher investment costs or a longer maintenance break duration. The publication did not model statistical distributions, but instead calculated the impact on profitability by varying a single parameter at a time. The units of the parameters are listed in the figure.

The most notable sources of uncertainty were how large subsidies would be received for captured CO2, as well as the biomass and natural gas prices due to indirect impacts on other units in the modelled DHC system. The biomass price directly impacted operation costs, while natural gas prices made the operation of other units in the system cheaper or more expensive, thus indirectly impacting the profitability of the studied bio-CLC investments. Unit-level parameters were a less significant source of uncertainty in the case of a bio-CLC unit.
In Publication 2, Nuclear DH units were less impacted by the studied system parameters than uncertainties of unit level parameters. Nuclear DH units had an IRR of $12\%$ in all modelled sensitivity scenarios. In that sense, the technology seems a more robust choice and less assumption dependent. An additional sensitivity analysis in Publication 2 showed that the modelled nuclear units were the most sensitive to the assumed investment cost. This highlights the importance of successful demonstration projects and technology development so that the targeted level of investment costs can be reached.

4.2.2 Systemic uncertainties can easily change the preferred order of technologies

Publication 2 of this thesis studied how system-level parameters impact the profitability of biomass units, large heat pumps from low temperature excess heat, and nuclear heat reactors (Figure 16). The most significant changes in the modelled sensitivity analysis happen when electricity price, biomass price, or electricity grid fees change. Different assumptions on these parameters change the order of the most profitable units. In most cases, a nuclear heat only reactor and a heat pump with COP 3.5 had the highest profitability. However, at the annual average electricity price of 50 €/MWh, modelled SMRs become more profitable than heat pumps with a COP of 3.5. With an average annual electricity price of 60 €/MWh, modelled biomass CHP units become the most profitable due to the income from the sold electricity.
The increasing price of biomass has a strong negative impact on the profitability of biomass units. The price of imported biomass has been at the level of 30 €/MWh in Southern Finland, but biomass options are significantly more profitable if inland cities have a cheap local source of biomass with costs around 20 €/MWh. Other factors, such as natural gas prices, are very important to the profitability, but do not have a significant impact on the order of technologies.

**Figure 16.** IRR impacts of system-level uncertainties on biomass boilers, biomass CHPs, large heat pumps, nuclear heat only (DHR-400), and nuclear CHP units (NuScale CHP).

Publication 3 of this thesis expanded this method and modelled over 8000 sensitivities on system parameters allowing the statistical analysis of the uncertainty parameters instead of varying only a single parameter at a time. The increased number of scenarios allows drawing parameter areas where a certain technology outperforms others (Figure 17). The studied bio-CLC technology would be the most profitable investment in the case of cheap biomass and high subsidies for captured biogenic CO2. However, heat pumps would be more profitable even with very high CO2 subsidies in the case of cheap electricity and expensive biomass.

A statistical analysis of uncertainties shows that typically technologies have certain parameter areas where they outperform other technologies, e.g. in profitability. However, the borders of these parameter areas are not strict because of a range of the other parameters. Graphical presentations of parameter areas could be helpful for decision makers to both understand the underlying dynamics and to allow faster comparisons of expected future developments, e.g. future prices or long-term contracts with suppliers.
4.2.3 Avoiding the worst choices instead of trying to choose the best one

Previous results show that it is not a reasonable approach to try to choose the best one, as a large array of future parameters lie within preferred ranges of multiple technologies. Accepting this leads to another viewpoint and examining which technology option is the least bad investment.

Publication 3 compared six options: no additional investments, biomass HOB, bio-CHP, bio-CLC, and heat pumps with COP 2.5 / COP 3.5. Based on the statistical scenario results analysis, not replacing any units and keeping combusting fossil fuels was almost always economically the worst option (Figure 18). A heat pump with COP 3.5 was never the worst choice with any of the studied parameter sets. A bio-CLC unit was the best in case of high subsidies for captured biogenic CO2. Without subsidies it was not economical, but still typically better than no investments. A biomass CHP unit was the most profitable in the case of
high electricity market prices, but second worst in the case of low electricity market prices. See Figure 17 for ranges of parameter values.

As an important result, a biomass heat only boiler was typically an average option rarely performing well or poorly. It is also a flexible unit and can have lower investment costs due to the refurbishment of old units or sharing infrastructure with existing units. As a result, biomass HOB seems a safe bet in the decarbonization palette from the technological viewpoint. The biggest risk is the amount of available sustainable biomass as discussed in Chapter 4.2.

**Figure 18.** Rank of studied technologies for each modelled sensitivity case. 1 is the best ranking option and 6 the worst.

4.3 Investments change the system but do not benefit all

4.3.1 Direct impacts are limited to the local DH system

New DH generation investments change the behaviour of the DH system directly by changing the merit order of the units. The direct impacts within a DH system are simulated in Figure 19, which shows the hourly production in Helsinki’s DH grid in the 2030 reference scenario of Publication 2 and the same system with 2x 400 MW nuclear DH reactors. Nuclear units would have lower variable costs than even heat pumps (HPU) and would replace them as baseload units. The maintenance breaks of nuclear heat units were rotated in summer to achieve as many full load hours as possible. Biomass heat only boilers (BioB) were pushed to generate heat on colder winter days operating significantly fewer full load hours after the nuclear heat investment.

In this publication, natural gas combined cycle (NGCC) units produced only several hundred hours per year which most likely would lead to their phase out
and the peak demand would be generated with fossil fuel boilers (FosB). However, decommission decisions were not studied yet in this publication. The district cooling was generated with absorption chillers that effectively can convert district heating to district cooling increasing the utilization rate of nuclear heat units.

Figure 19. Hourly operation of units in Helsinki’s DH grid in two modelling cases: the 2030 reference scenario (top) and 2030 reference scenario with two nuclear heat units, SMRs (bottom). Note: B in unit type abbreviation means heat only boiler. HPU is the sum of heat pumps. NGCC is the sum of NGCC units.

Common to all studied investments in the publications of this thesis was that they pushed natural gas units higher in the merit order and changed their role and behaviour. Biomass units, large heat pumps, and SMRs all operated before existing gas units and transformed them from based load units to heating season units. As a result, natural gas units had relatively high ramp up rates throughout the year, with 40 to 80 operation cycles per year (Figure 20). We modelled the costs for start-ups, but not the costs for ramping up. It is not known if those actual units can operate as flexibly throughout the year without additional maintenance costs.
The studied biomass investments started and shut-down up to 50 times a year, but much less often than remaining NGCCs in the system. Biomass CHP units need to operate more flexibly than biomass HOBs as CHP units must react to both electricity prices and the DH demand.

The model aims to operate biorefineries for as many hours as possible (Figure 20) as their main revenue comes from selling transport fuels. However, if those biorefineries were to be hydrogen boosted, they would become unprofitable during the highest electricity prices. This changes the operation logic, and the model shuts them down up to 15 times per year, depending on electricity market prices. On the other hand, H2 boosted biorefineries could provide flexibility by increasing their electricity use during low prices.

### 4.3.2 Indirect impacts make certain investments more preferred to the bigger system than the city

DH investments can impact the whole of Northern Europe indirectly through system effects, which can be rather complicated. For example, replacing a natural gas CHP unit with a biomass heat only boiler would reduce the produced electricity, which would then need to be produced elsewhere in the system. This indirectly changes the energy flows and consequently impacts electricity and fuel trade, emissions, and so on. A Northern European model is needed to study these impacts.

Publication 4 studied these effects at the system level by varying the amount of wind power in the Northern European power system, CO2 price in historical ranges, and large heat pumps in Helsinki’s DH system. From the city’s perspective, the results strengthen the previous results. Additional VRE made biomass HOBs a more profitable investment and reduced the profitability of bio-CHP units (Figure 21). Additional heat pumps significantly reduced the profitability of biomass units. Higher CO2 prices improved the profitability of both investments.
When studying the system level, both biomass HOB and biomass CHP were more profitable from the Northern European system perspective than from Helsinki’s perspective (Figure 21). Both options reduced district heating generation costs in Helsinki, but also reduced the amount of electricity produced with NGCC units that could be sold to the markets. According to the results, a biomass CHP was not a profitable investment for Helsinki (IRR under 2%) in any of the modelled sensitivity analyses, but it was often profitable for the overall system. This is a significant difference in results between more detailed city-level modelling and system level modelling.

The results of Publication 4 show similar split interests also in emission reductions. In the case of biomass HOB, the emissions reduction was larger in Helsinki than in the system (Figure 22), as the lost electricity generation needed to be produced elsewhere. In the case of bio-CHP, the system-level emissions reductions were typically larger than the emissions accounted for in Helsinki, as the bio-CHP had more hours of operation than NGCCs, resulting in reduced electricity generation emissions also outside Helsinki.

A biorefinery reduced the system emissions significantly more than emissions in Helsinki’s DH system. The impact was mainly due to replacing fossil fuels in Helsinki’s DH system through excess heat recovery and in the transport sector. In the case of an H2 boosted biorefinery, the emissions of the power system increased in most cases, but the amount of produced bioliquids was larger and the transport emissions decreased more. The largest emission reductions were in a scenario where an H2 boosted refinery and additional VRE capacity were built.

The H2 boosted biorefinery was the most complex unit regarding emissions reduction as it increases the electricity consumption. As a result, the H2 boosted refinery increased the consumption of fossil fuels unless built simultaneously with additional VRE capacity. In practice this means increasing electricity prices and emissions in the power system. However, in total it also reduced the fossil fuels when including the avoided emissions in the transport sector.
In general, emissions reductions were much less sensitive to assumptions in the studied scenarios than the investment profitability. Emissions reductions of different technologies are relatively stable across different scenarios except for bio HOBs if large numbers of DH heat pumps are built before bio HOBs, or for the H2 boosted refinery which increased the total system emissions in the case of low CO2 prices as the additional electricity was generated with fossil fuels.

### 4.4 Local conditions create additional constraints on investments

#### 4.4.1 There is not enough domestic bioenergy

Biomass is relatively easy to scale up either with new-built capacity or converting old coal-fired units to biomass units with relatively small costs. However, bioenergy is a limited resource. Current units and investment plans can already consume more than is domestically available (Figure 23). This issue is not visible in larger models, where the Finnish energy wood supply is modelled as a single model area. The results of Publication 4 show that current and already planned investments will consume more biomass than is available at sustainable levels.

Smaller cities have a chance to build and operate more specialized systems based on one or few solutions, such as biomass, due to a lower heat demand density. In contrast, large cities have such a high heat demand in a small geographical area that a single excess heat source or renewable fuel is typically not enough. Fossil fuels offered a solution to this as they were easy to transfer to cities over long distances and burn there.

Biomass does not offer a silver bullet to decarbonize large cities even when looking only from the perspective of available energy. The decarbonization of large district heating systems will likely require a broad range of solutions including heat pumps, utilization of excess heat sources, direct electricity boilers, biomass units, large heat storages, low temperature distribution, and demand side solutions.
4.4.2 DH demand projection impacts the scale of required investments

Nordic and European electricity markets are significantly larger than any of the invested single units, but DH production investments must consider the annual demand within a single DH system over the lifetime of the invested unit. Publication 4 studied the factors impacting on DH demand and found 3 main indicators to forecast the demand: heating degree days, population, and the DH demand per capita. These 3 indicators explained the historical DH demand (2008-2017) of the modelled regions with up to a 99% correlation (Table 8).

Projections up to 2040 show a decreasing number of heating degree days (HDD) in all regions due to global warming, improving energy efficiency (DH/capita), and varying population trends. As a result, the average annual DH demand remains almost the same or slightly increases in the capital region, Tampere, and Oulu (Northern Finland). Other regions have a decreasing trend in the average annual DH demand up to a 25% decrease from 2017 to 2040. In practice, this should be examined in more detail at the municipal level including the projected change in the share of DH customers from the population, if that is likely to change.

Projections of stable average annual DH demands help DH companies significantly to plan their investments, whereas projections of decreasing demands are a significant challenge for companies, as they should replace the existing fossil fuel capacity quickly. This means that the new capacity should be able to
serve current demand volumes, but still pay itself back with decreasing demands over the years.

Table 8. Table 1 – Correlation of the annual DH demand between reconstructed historical values and DH statistics, and projections of major components of DH demand and the resulting DH demands in different heating regions in Finland.

<table>
<thead>
<tr>
<th></th>
<th>Correlation of reconstruction and DH statistics from 2008 to 2017</th>
<th>Change from 2017 to 2030</th>
<th>Change from 2017 to 2040</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HDD</td>
<td>DH/ cap</td>
<td>Pop</td>
</tr>
<tr>
<td>Helsinki</td>
<td>99%</td>
<td>-8%</td>
<td>-9%</td>
</tr>
<tr>
<td>Espoo</td>
<td>98%</td>
<td>-8%</td>
<td>-6%</td>
</tr>
<tr>
<td>Vantaa</td>
<td>99%</td>
<td>-6%</td>
<td>-8%</td>
</tr>
<tr>
<td>Surrounding capital region</td>
<td>97%</td>
<td>-6%</td>
<td>-5%</td>
</tr>
<tr>
<td>Turku region</td>
<td>96%</td>
<td>-6%</td>
<td>-5%</td>
</tr>
<tr>
<td>Tampere region</td>
<td>99%</td>
<td>-6%</td>
<td>-5%</td>
</tr>
<tr>
<td>Lahti region</td>
<td>94%</td>
<td>-5%</td>
<td>-5%</td>
</tr>
<tr>
<td>Western and Central Finland</td>
<td>97%</td>
<td>-6%</td>
<td>-5%</td>
</tr>
<tr>
<td>Eastern Finland</td>
<td>92%</td>
<td>-5%</td>
<td>-5%</td>
</tr>
<tr>
<td>Northern Finland</td>
<td>92%</td>
<td>-5%</td>
<td>-5%</td>
</tr>
</tbody>
</table>

4.4.3 Local heat demand profile defines the annual operation of units

The more that the annual heating degree days increase, the higher the difference in the heat demand between the summer and the winter in DH grids. In Helsinki, the factor between the summer baseload and highest winter peak is typically a factor of 12 (Figure 24).

In the Baltics, the factor is a bit smaller at around 10. In milder climates, the difference can be closer to 7. However, harsh continental climates in Eastern Europe or Alpine regions can have more severe winters than Finland.

Heating season baseload units, such as the NGCCs in Figure 24, operate most of the winter, but only occasionally in the spring and autumn. The reduced operation hours reduce the profits and consequently limits the suitable technologies for this role in the system. Some climates have high day-night variability in spring or autumn, which creates an additional demand that this unit group should be particularly flexible in terms of shutdown and start-up cycles.

Peak load units have only low or very low annual operation hours. In older DH systems, peak load units are typically old units that have already been taken out from regular operation but are maintained as backup capacity. Investing in new peak load units is economically difficult and the best option would be low capital cost units. However, the peak demand hours for DH typically correlate with the peak demand hours for electricity, which practically rules out the least capital-intensive options for peak capacity such as electric boilers. Bioliquids and electrofuels could be a solution in fully fossil-free systems, but their costs are currently much higher than fossil fuels including CO2 costs and energy taxes.

The important take away is that the higher the difference between the base load and the peak load, the fewer running hours an average investment gets.
The baseload investments operate most of the year and thus can cost more and still be profitable. However, a higher difference between winter and summer loads means that based load units can have smaller capacity.

![Figure 24. Hourly dispatch results for a full year in the Helsinki District heating grid in a 2025 reference scenario that assumes coal phase out and additional investments that were known in 2020.](image)

This modelling of Helsinki’s DH system uses 2016 prices and demand time series. It also assumes that coal CHPs are phased out, and heat pump and heat storage investments that were decided by the time of the modelling in Publication 3 are in operation. This could roughly reflect 2025 capacities. We modelled the large NGCC units with mixed integer variables and thus they had to respect realistic minimum loads often leading to shutdown periods seen in the magnified part of the figure. The modelling assumed constant fuel and CO2 prices which maintains the merit order of the units over the year. The model typically charges storages to avoid shutdowns and discharges storages to avoid start-ups, reducing the total operation costs especially in the spring and autumn.

It is important to note that the figure does not capture many real-life constraints such as the heat demand in different parts of the grid, the outdoor temperature dependency of generation units, and the actual business model of trade between the cities. Therefore, the results from a single scenario should always be studied with caution and conclusions should be drawn from the analysis and comparison of many scenarios. A higher heat demand density requires larger or more solutions.
5. Discussion and conclusions

5.1 Large energy system models are too optimistic

Heating and cooling consume half of the final energy use in the EU and only 20% of it is produced from renewable sources. Thus, the EU’s increased ambition for 2030 climate policies puts immense pressure on the heating and cooling sector to start decarbonizing rapidly. Chosen climate targets are based on necessity as explained in the IPCC reports [116] but also on energy system modelling results that indicate how large and fast a change could be possible with acceptable costs.

Despite the efforts, the actual change is lagging more and more notably behind the political targets. In practice, the renewable share of heating and cooling increased from 17% to 23% in the period from 2010 to 2020 [1]. Assuming a linear rate, the sector would be fossil fuel free around the year 2120, which is awfully too late. Similarly, the IEA’s Tracking Clean Energy Progress 2023 report shows that from 47 studied sectors, 3 are on track, 28 need more effort, and 18 are not on track [117]. The IEA does not list district heating as an individual sector but classifies building heating in the “more effort needed” category. The current development shows a clear pitfall in the long-term modelling studies, in which the heating sector is decarbonized with relatively low marginal reduction costs and typically by the 2030s at the latest.

The Nordic and Baltic countries have succeeded at increasing their share of renewable heating and cooling better than the rest of Europe, which might be because over half of the population is served by district heating. This enables additional effective routes to decarbonization and countries can reduce their emissions in large centralized units, smaller distributed DH generation, and with building-level investments. Germany’s renewable share of heating is progressing below the EU average, and this will be likely to have an impact on Germany’s national emission reduction targets under the EU’s Effort Sharing Regulation.

The results of this thesis further strengthen the conclusion by showing that general energy system models, such as TIMES-VTT, give more optimistic results on the decarbonization of DH than more detailed models. More detailed DH models and more detailed biomass supply models create additional constraints based on real life operating environments. Such constraints include, but are not
Discussion and conclusions

limited to the local availability of sustainable biomass, the availability and distance of heat sources, acceptance of new technologies, technological maturity of new solutions, uncertainties and risks related to investments, as well as quickly changing operational environments and legislation due to strict climate targets.

5.2 Models should systematically address uncertainties

Each modelling study should consider a large range of uncertainties or they risk drawing flawed conclusions based on overly narrow sets of modelled cases and assumption ranges. The main sources of uncertainty in the results of this Thesis were related to

- electricity: variability, price
- biomass: availability, price
- natural gas: availability, price
- investment costs of new units
- breakthrough of new technologies
- required phase of emission reductions

In the modelled sensitivity analysis of the publications in the thesis, heat pumps from low quality excess sources were more robust choices than biomass units if the electricity price, grid fees, and electricity taxes remained at a low level. However, these have been particularly turbulent since the release of the publications. Electricity prices hit historical lows during the early phase of the Covid lockdowns in 2020, but they soared to historical highs in 2022. Currently cheap Russian natural gas imports do not seem likely to return but installation rates of solar and wind power have been at historically high levels. All these create a high level of uncertainty concerning future electricity prices. The Finnish government pushed a legislative update through in July 2022 reducing the cost of electricity for heat pumps by approximately 15 EUR/MWh [118], giving large heat pumps a notable edge. The electrification route increases the uncertainty related to CHP units as both VRE capacity and the electrification of DH reduce their hours of operation. Low operation hours might lead to early phase-outs.

The EU is renewing its legislation to limit the use of woody biomass for energy production [119]. The revised directive would extend the no-go areas in old forests, wetlands, and peatlands. The directive also requires national strategies to ensure that woody biomass is used “according to its highest economic and environmental added value.” The final versions are not known but this can potentially have a significant impact on the available amounts of biomass to burn for heating and could increase the prices of remaining biomass resources.

The publications in this Thesis only studied the price sensitivity of natural gas but assumed that there would be no restrictions in availability. Once again, reality showed that even broader ranges of uncertainties should be studied. Russia’s war in Ukraine created a shock in natural gas prices and might limit the availability of Russian natural gas in Europe for decades. This has the potential to alter the modelled development pathways where coal would be replaced by natural gas in the 2030s.
5.3 Biomass is a versatile but limited replacement for fossil fuels

The EU’s use of bioenergy has increased from 2700 TWh/year in 2000 to 6100 TWh/year in 2021. Most of the increase in bioenergy consumption has been from domestic sources (93%), but the growth is nearing its end for two main reasons: land use emissions and biodiversity concerns. Increasing the use of forest wood leads to faster release of carbon stored in wood compared to a situation where it would decay in the forests over the years, which contributes to the EU’s decreasing forest carbon sinks. In addition, biodiversity is at risk and there are legislation incentives to increase the area of protected forests, reducing the amount of bioenergy we can use for energy production. The resulting changes in legislation might lead to resource scarcity and increasing prices.

Finland has the highest forest area as a share of the total land area in the whole EU and OECD [120]. Forests covered 74% of Finland in 2020. This was globally the 11th highest value. Many countries, such as the United States, Germany, Italy, France, and Poland, fall between 30% and 35% forest coverage, while some countries, such as the United Kingdom and Denmark, have much below average values with between 10% to 15% forest coverage. Finland has 5 hectares of forest per capita while Germany has only 0.1 ha/capita. Energy crops can have a 10 times higher energy yield per hectare than forests [121], which balances this, but the overall area per capita in Finland is 15 times higher than in Germany.

Despite all these biomass resources, the results of this thesis show that there is not enough domestic biomass to decarbonize even the Finnish DH sector. The energy demand of large cities is too much for local resources within the economic transport distances. Furthermore, the shortage becomes greater if biomass is used also for bioliquids for heavy transport and other uses, such as material for construction.

When there is sustainable biomass available, it provides several well-rounded options to replace fossil fuels in district heating systems. This is because bioenergy can replace either solid, liquid, or gaseous fossil fuels with relatively small changes to existing equipment, practices, and business models. This provides an easy route to decarbonize smaller DH systems in Finland and create local jobs in harvesting and transportation. Additionally, larger DH systems benefit from this, but cannot fully decarbonize through the biomass route.

Current biomass investments may lead to a lock-in effect, where biomass is combusted for heat even when it could have higher value uses, e.g. for materials or in the chemical industry. On the other hand, bioenergy with carbon capture and storage can become a profitable solution if governments start to subsidise BECCS to avoid higher cost emission reductions in other sectors. Coastal biomass units might have options for retrofitting post-combustion capture equipment if the necessary space and transport connections are available.

New biomass-based processes, such as bioliquid refining for transport, could be built near large cities to allow the utilization of excess heat for district heating. The plan could be economically and technically feasible, but large cities are
likely to have biomass resource scarcity issues already without such new installations.

5.4 **Electrification of DH resonates with current trends in the electricity sector**

Electrification is another scalable route of decarbonization for district heat generation that can be applied to all locations. This technology group includes direct electrification, heat pumps from low temperature excess heat, and heat pumps from ambient heat sources. Typically, these technologies benefit from heat storages in that they can generate heat for storage when electricity prices are low and avoid operating when electricity prices are high. The increasing amount of variable electricity generation is reducing the annual average prices but increasing the likelihood of very cheap and expensive hours. All these favour the electrification of district heating up to a certain share of heat generation.

Direct electric heating is increasing in popularity as it is very cheap to install in heat storages and can utilize low or negative electricity market prices, that already occur regularly. With increasing shares of wind and solar, low-price events should be more regular. District heating is starting to provide a significant balancing capacity by consuming electricity when it is cheap and generating DH and electricity with CHP units when electricity price is high.

Good quality excess heat sources are valuable sources of heat but limited in amount. Some cities might have industries near the city, but this is not often the case. Often the distance between the heat sources and DH grids is a major obstacle. Some cities are tackling this by trying to lure energy consuming industries back into the cities, reversing a long trend where industrial units have been located further from large cities. One example is the Finnish city of Espoo where the city, a local DH operator, and an international IT company signed a contract for a large datacentre [122] that would be built within the city, conflicts with other possible land uses. The excess heat is used in Espoo’s DH grid.

Hydrogen provides a similar possibility where the production and compression of hydrogen generates excess heat that could be used in the DH grid. This could be of mutual benefit also for making the hydrogen investments slightly cheaper.

Some locations have decent sources for ambient heat, such as a deep ocean close to a city. In such cases, the ambient heat could replace the low temperature excess heat and provide a similar investment option. Stockholm invested in large heat pumps (total 180 MWDH) getting their heat from the ocean already in the 1980s [123].

Other ambient heat sources have their problems, such as air-to-DH having poor COP and less solar heat available during cold winter days, but Denmark has still invested in a relatively large capacity of both as the winters are milder at those latitudes than in Sweden and Finland [124]. These technologies were not covered by the publications in this thesis but should be analysed in further studies.
5.5 A faster transition might lead to a different technology mix

Demanding faster emission reductions from DH operators may lead to a different technology mix, because certain technologies are currently under development. Publications 2, 3, and 4 of this thesis studied emerging technologies: nuclear heat only reactors, bioenergy with carbon capture and storage, and hydrogen boosted biorefineries. Nuclear district heating seemed particularly promising from the techno-economic viewpoint with initial unit parameters, but there are other issues to solve, such as technology development to achieve the initial unit parameters used in the modelling, legislation, and public acceptance. If politicians demand a fast change, it probably rules this technology out from the first investment round.

Helsinki hastened the carbon neutrality target for the Helsinki DH operator from 2035 to 2030 [125]. This was justified due to the increased overall targets to reduce GHG emissions by 2030, but it also reduces the remaining years to achieve the target from 12 to 7 years. This is a short time to replace 2 large coal units and 2 large natural gas units. With this kind of decision, local authorities can have a large impact on the technologies that are viable options for DH companies. Currently, it seems likely that the required fast phase of decarbonization excludes nuclear district heating from the first investment round in the 2020s. If mature in the 2030s, it could provide means to replace the remaining fossil fuels and free biomass for other uses.

The same appears to apply also to bio-CCS, as the technology is still in the demonstration phase. However, it is possible to make so called CCS-ready biomass units, by building units on the seashore to allow CO2 transportation to storage facilities and reserving enough space to install post-combustion capture equipment afterwards.

Hydrogen boosted biorefineries could provide the excess heat to cities but would suffer from longer biomass transport distances and probably issues with biomass availability in Southern Finland. Current DH companies in the capital region are studying a similar option where P2X products would be produced near the city and exported to Central Europe. In these cases, the excess heat could be used in the cities’ DH grid. However, Publication 4 identified possible security of the supply issues when local CHP generation is replaced with heat pumps and electricity consuming industrial facilities. This concern is valid also for the P2X installations.
References


Discussion and conclusions


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Heating and cooling, including industrial heat, consume half of the final energy use in the EU, but only 20% of the heating is produced from renewable sources. District heating (DH) could help decarbonizing the heating, but DH sector must replace its own fossil fuels first. In this Thesis, energy system models are applied to study the investments, impacts, and uncertainties of fossil-free DH production.

This Thesis uses an existing long-term energy system model TIMES-VTT and develops new more detailed DH models with Backbone modelling framework that capture additional real-life constraints, such as unit operational limits and local conditions, and have faster solve times allowing extended uncertainty analysis.

This Thesis studies investments to electrification, biomass-based technologies, and few specific new technologies that are currently not commercially available. Each of the studied technologies have strengths and weaknesses highlighting the importance of extensive sensitivity analysis.