TECHNO-ECONOMIC ANALYSIS OF DISTRICT HEATING PRODUCTION CAPACITY REPLACEMENT INVESTMENT ALTERNATIVES

Case Kajaani

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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Techno-economic analysis of district heating production capacity replacement investment alternatives: Case Kajaani

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There is an increasing need to address sustainability in energy production to comply with climate targets and preserve nature and living conditions on Earth. As one of the key energy sub-sector, space and domestic hot water heating plays a vital role in the sustainability development in countries with cold climate like Finland. District heating is the leading heating method in Finland. It heats the homes of over half of the population. Consequently, district heating has a vast potential to provide positive impact on the society from various aspects including, inter alia, sustainability, security of supply and affordability of energy.

District heating production capacity investments are long-term and capital-intensive infrastructure investments. While the investments are usually made for decades, the decisions are made under increasing complexity and changing operational environment. This research studied district heating production capacity renewal investment alternatives in Kajaani, Finland. The research focused on analysing five alternative production portfolios with varying role of combustion and non-combustion-based technologies. The analysis was based on dynamic merit order driven production simulations with an hourly resolution and a forecast period of 25 years. The simulations combined local district heating system characteristics and assumptions on how the system’s operating environment may evolve over the period due to potential changes in climate, commodity prices and emission regulation.

The research showed financial outperformance of a production portfolio that minimised combustion. A hybrid solution combining combustion and non-combustion-based heat sources was also found to be relevant alternative. The results emphasised technological, environmental, and financial potential of electrified district heat production under the assumed future operating environment in Finland. The research also demonstrated feasibility of a tailored long-term merit order modeling in district heat production investment analysis.

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Energiantuotannon kestävyyteen on kiinnitettävä yhä enemmän huomiota ilmastotavoitteiden saavuttamiseksi ja maapallon luonnon sekä elinolosuhteiden turvaamiseksi. Energiasektoreista rakennusten ja käyttöveden lämmityksellä on yksi keskeisimmistä rooleista Suomen kaltaisissa kylmän ilmaston maissa. Suomessa merkittävin lämmitysmuoto on kaukolämpö, jolla lämmitetään koteja yli puolelle maan väestöstä. Kaukolämmöllä onkin valtava potentiaali vaikuttaa positiivisella tavalla yhteiskuntaan esimerkiksi kestävyyden, toimitusvarmuuden ja energian kohtuuhintaisuuden näkökulmista.

Kaukolämmön tuotantokapasiteetti-investoinnit ovat pitkäaikaisia ja pääomavaltaisia infrastruktuuri-investointeja. Samalla kun näiden investointien elinkaari on kymmeniä vuosia, päätökset tehdään yhä monimutkaisemmassa ja muuttuvassa toimintaympäristössä. Tässä tutkimuksessa tutkittiin investointivaihtoehtoja kaukolämmön tuotantokapasiteetin uudistamiseksi Suomen Kajaanissa. Tutkimus keskittyi viiden vaihtoehtoisen tuotantoportfolion analysointiin, joissa polttavien ja ei-polttavien teknologioiden roolit vaihtelivat. Analyysi perustui dynaamisen ajojärjestyksen mukaisiin tuotantosimulaatioihin, jotka tehtiin tuntitarkkuudella 25 vuoden ennustejaksolle. Niissä yhdistettiin paikallisen kaukolämpöjärjestelmän keskeisimmät ominaisuudet ja oletukset siitä, miten järjestelmän toimintaympäristö voi kehittyä ennustejaksolla esimerkiksi ilmastonmuutoksen vuoksi.

Tutkimus osoitti taloudellisesti parhaan tuloksen syntyvän polttamisen minimoimiseen perustuvalla tuotantoportfoliolla. Myös polttavia ja ei-polttavia teknologioita yhdistävä hybridiratkaisu todettiin kilpailukykyiseksi vaihtoehdoksi. Tulokset korostivat sähköistetyn kaukolämmön tuotannon teknologista, ympäristöllistä ja taloudellista potentiaalia oletetussa tulevassa toimintaympäristössä Suomessa. Tutkimus osoitti myös räätälöidyn ajojärjestysmallinnuksen soveltuvuuden kaukolämmön tuotannon investointianalyysiin.

ABBREVIATIONS

AWHP	Air-to-water heat pump
BFB	Bubbling fluidised bed boiler
Capex	Capital expenditure
CFB	Circulating fluidised bed boiler
CHP	Combined heat and power
COP	Coefficient of performance
CPF	Capture price factor
DC	Data centre
DF	Direct firing
DFB	Direct firing boiler
DH	District heating
DHS	District heating system
DHW	Domestic hot water
EB	Electricity balance
EF	Energy efficiency
ETS	EU Emission Trading Scheme
FC	Fixed cost
FCF	Free cash flow
FGC	Glue gas condenser
FLH	Full load hours
FM	Fuel mix
GSHP	Ground-source heat pump
HOB	Heat only boiler

HP	Heat pump
IRR	Internal rate of return
Kavo	Kainuun Voima Oy
KPI	Key performance indicator
LCOE	Levelized cost of energy
LFO	Light fuel oil
LNG	Liquefied natural gas
MC	Marginal cost
MILP	Mixed integer linear programming
MO	Merit order
MOM	Merit order model
NPV	Net present value
Opex	Operating expense
PHR	Power-to-heat ratio
PM	Production mix
PtX	Power-to-X
RDF	Refuse-derived fuel
RES	Renewable energy sources
SMR	Small modular reactor
TC	Total cost
TES	Thermal energy storage
VC	Variable cost
WW	Wastewater
WWHP	Wastewater heat pump

Table of contents

Abstract

Abbreviations

Appendices

1 Introduction

The global average surface temperature on earth is increasing and year 2023 was the warmest ever recorded (NASA 2024). The global 2023 temperature was ca. 1.4 °C higher compared to the average temperatures measured during late 19th century (NASA 2024), while the Paris agreement pursues to limit the increase to 1.5 °C or at least well below 2.0 °C. To address the challenges the European Union has set targets to 1) reduce greenhouse gas emissions by 55 % or more from 1990 level by 2030 and 2) reach climate neutrality by 2050 (Ministry of the Environment 2024). Finland has a national target to be carbon neutral by 2035 (Ministry of Economic Affairs and Employment of Finland 2022).

Globally energy sector is a major source of carbon dioxide emissions, whereas heating forms a significant share of the total final energy consumption. The significance of heating sector is emphasised in countries with cold climate like Finland. Indeed, 27 % of the national final energy consumption was attributable to heating buildings in Finland in 2022 (OSF 2023e). By heating degree days Finland has the second highest demand in Europe (Eurostat 2023b). This heating demand is predominantly met by district heating ("DH"), which is the biggest source of space and domestic hot water heating with ca. 35 % market share (OSF 2023d). Just over half of the population lives in district heated dwellings (Finnish Energy 2023b).

Given DH's role as an essential national infrastructure and its large share in final energy consumption, it also has a key role in Finland's sustainability endeavours. While DH is largely produced from sustainable woody biomasses in Finland, 38 % of the DH fuel mix was still fossil fuels in 2022 (Finnish Energy 2023b). In addition, sustainability of burning biomass for heat production has also been recently questioned to an increasing extent and the EU's RED III directive already includes some regulatory tightening as e.g. woody biomass from old-growth forests will not be treated as sustainable going forward (Ministry of Agriculture and Forestry in Finland 2023). Also, promoting non-combustion-based heating is mentioned as a key focus for heat production by the Ministry of Economic Affairs and Employment of Finland (2022) in the national carbon neutrality by 2035 program.

DH's operating environment is facing changes also from other perspectives. As the sustainability challenges are addressed in other sectors as well, the energy system is becoming more and more integrated and complex both from consumption and production sides. For instance, the increasing share of wind and solar power in the national energy mix is causing commercial volatility while increasing availability of clean and affordable electricity. Simultaneously, energy demand side management has been increasing and global geopolitical situation has its own impact on fuel markets. While the energy system level development is a vast opportunity also for DH it also creates some challenges. Combining this changing operating environment, increasing sustainability pressures and competition from building specific heating solutions, like heat pumps, is a challenging task for the long-term and capital-intensive DH sector that is responsible for the infrastructure, which forms backbone for the national heating. The Finnish DH production is undergoing a major transition phase where the sector has and will invest significant amounts into production capacity renewals to secure sustainable and cost-efficient heating for decades to come.

While the changes in the operational environment are generally same across Finland, DH production capacity renewals are always regional and local solutions considering demand and supply characteristics. On the supply side, especially the availability of sustainable fuels, waste heat and renewable electricity are in the core of the production capacity investment considerations. This research focuses on techno-economic analysis of DH production capacity renewal alternatives in Kajaani, the capital of the Kainuu region in Finland. The research utilises a novel modeling of Kajaani’s district heating system.

1.1 Background of the thesis

This research has been carried out in cooperation with a regional energy utility Loiste Group. Its subsidiary Loiste Lämpö Oy (“Loiste”) owns and operates local DH network in city the of Kajaani in Finland. The network has a length of ca. 130 km with ca. 1 700 customers (Loiste 2022a). Majority of the heat in Kajaani is currently produced in combined heat and power (“CHP”) plant using primarily domestic biofuels and peat (Loiste 2022a, Kavo 2022a). The CHP supplies also steam to third-party customers (Kavo 2022a).

The CHP plant is owned by Kainuun Voima Oy (“Kavo”), and it was originally designed to also cover industrial heat and steam loads of a now closed paper mill. The CHP was built during 1987-1989 (Kavo 2022a) and is reaching end of its techno-economic lifetime over the coming years. Hence, there will be a need for new heat production capacity to satisfy Loiste’s DH demand in sustainable and cost-efficient manner.

1.2 Aim and research questions

This research explores and compares potential solutions to renew the district heat production capacity in Kajaani. The thesis aims to identify relevant production methods through literature and techno-economic analysis to ultimately identify the most techno-economically feasible heat production capacity portfolio for Kajaani while satisfying the below criteria:

- The solution shall be socially, environmentally, and economically sustainable
- The solution shall be based on mature technologies that can operate over long term
- The solution shall prefer non-combusting technologies if possible
- The solution shall be suitable for current operating environment while being flexible to accommodate potential changes in it.

The thesis aims to answer the following research questions:

1) What would be techno-economically the most viable and sustainable district heat production portfolio to replace the current production capacity in Kajaani?
2) How does the investment profitability of alternative heat production portfolio solutions compare if long-term commodity price and other key assumptions are altered?

1.3 Methodology and limitations

The role and development of district heating in Finland is studied through literature and statistics. Current research focus in the field is discussed through recent literature also giving the theoretical context for this thesis. Suitable DH production technologies for Kajaani are identified and studied via literature. Where relevant, recent examples of technological choices and investments in the Finnish DH sector are discussed for practical benchmarking.

The research questions are explored by defining five potential heat production portfolios from the identified potential heat production technologies in Kajaani's context. The five solution alternatives combine technologies with different weighing between electricity and combustion-based heat production with and without combined electricity production. The production portfolio alternatives were set considering local aspects and limitations.

Techno-economic analysis is conducted on portfolio level for each alternative. In addition, the portfolios are financially compared against a reference system that is based on a hypothetical continuum of heat production with similar CHP solution as today in Kajaani. The research analysis is based on a merit order modeling with an hourly resolution and operating period of 25 years. Merit order is not static but is defined for each hour. Historical hourly profiles for e.g. DH demand are used to define intra-year profiles to increase relevance and accuracy. However, changing annual assumptions are applied for the 25-year period. The novel and dynamic model is built on Microsoft Excel by combining on-sheet calculations and VBA coding. The modeling is described in detail in paragraph 6 .

The model simulates the operating period by optimising the variable costs on hourly basis while considering set operational limitations like achievable supply temperature from heat pumps and required ramp-up and down times for fluidised bed boilers. The model outputs for each production portfolio are analysed and compared from operational, environmental and financial perspective to answer the research questions.

The research is limited to the specific energy system in Kajaani and is conducted from the perspective of local DH system. Despite the system level perspective, it is worth to note that any potential industrial steam demand in the area is excluded from the analysis and should be considered separately if regarded relevant. The results are considered relevant, although indicative by nature, for other DH systems in Finland and elsewhere where the climate, building stock, fuel and electricity market conditions are comparable. The results are also reliant on, inter alia, the assumptions of investment costs and future development of the operating environment. No possible capital constraints were considered in the research, although that could set limitations among the alternatives in many companies in practise.

The merit order model results reflect the pre-set capacities, and other assumptions and it is recommended that additional production capacity optimisation analysis is carried out separately. Furthermore, thermal energy storage potential and potential impact on end results should also be considered separately. From modeling perspective, the hourly resolution gives detailed results, but is still limited as for instance intra-hour production ramp-ups and ramp-downs are not explored. Also, potential additional technical limitations should be explored in detail in connection with final technology choices. For instance, coefficient of performance profiles and maximum supply temperatures may have significant differences between heat pump manufacturers.

1.4 Thesis structure

This thesis is structured under four main parts. The first one covers introduction, context and methodology on a high level in paragraph 1 The second part covers the theoretical framework and literature review. The third part focuses on describing the modeling methodology more in detail and discussing the techno-economic analysis and related results. The fourth part covers conclusions, reflections and summary. References are listed at the end. The research report is complemented with additional details included in separate appendices that are not part of the thesis.

The theoretical framework and literature review part spans across the paragraphs **Error! Reference source not found.**-5 . Paragraph 2 discusses the historical and future development of DH and the role of DH in Finland. Paragraph 3 reviews non-combustion-based district heat production technologies and their potential in Kajaani. Similarly, paragraph 4 reviews potential production technologies and related potential in Kajaani, but the section focuses on combustion-based solutions. The paragraph also discusses combustion related key biofuels in Finland and selected flue gas treatment solutions. Paragraph 5 discusses the DH system in Kajaani more in detail and concludes the relevant heat production technologies in the local context.

The modeling and techno-economic analysis part is covered in paragraphs 6 -7 . Paragraph 6 discusses the merit order model approach and its assumptions in detail. It also defines the analysed portfolio alternatives. Paragraph 7 summarizes the operative, environmental and financial analysis. It also covers alternative scenarios through financial investment profitability sensitivity analysis.

Finally, the results are concluded and further discussed in paragraph 8 The section is followed by a summary in paragraph 9 and references.

2 District heating and its development

District heating is an efficient way to produce and distribute thermal energy in densely build areas. DH production and distribution systems have evolved over decades, but the main principles of integrated heat production and thermal energy distribution via pipeline networks apply still today. DH often represents the heating system backbone for building stock in areas where implemented, especially in Finland. This local significance makes individual DH systems essential in driving sustainable development locally and regionally. DH also has potential to make sustainable energy and transitioning towards sustainable decarbonized heating systems more affordable compared to decentralized heating (Kleinertz, Gruber 2022, 122059). As such, DH is an effective platform to introduce more efficient energy use, integration of renewable energy sources and utilisation of waste heat in heating sector (Jodeiri, Goldsworthy, Buffa, Cozzini 2022, 112156).

Despite the acknowledged benefits of DH systems, the sector is also facing challenges as societies are moving towards more sustainable and affordable energy solutions on back of emission reduction and resource efficiency targets. Whilst DH systems have potential to be part of the solutions, they will need to continue improving to defend against emerging alternatives, such as building specific ground-source heat pumps and solar thermal solutions. The improvements will need to happen on all fronts of sustainability (environmental, economic and social) to meet expectations set for future energy systems.

The situation is not new as DH has bright history and development track record. Historical DH development can be divided into four main generations described below in Figure 1. The key differences between the generations are supply and return temperatures, energy efficiency, system flexibility and supply sources and their variety. In recent years also fifth generation DH systems have been discussed in literature. However, the terms do not reflect sequential generations very well but rather describe parallel developments (Lund, Østergaard, Nielsen et al. 2021, 5). Key differences between the 4th and 5th generations are that the 5th assumes heating and cooling in common networks operating in close to ambient temperatures, whilst the 4th generation systems utilise separate heating and cooling networks (Lund et al. 2021, 5).

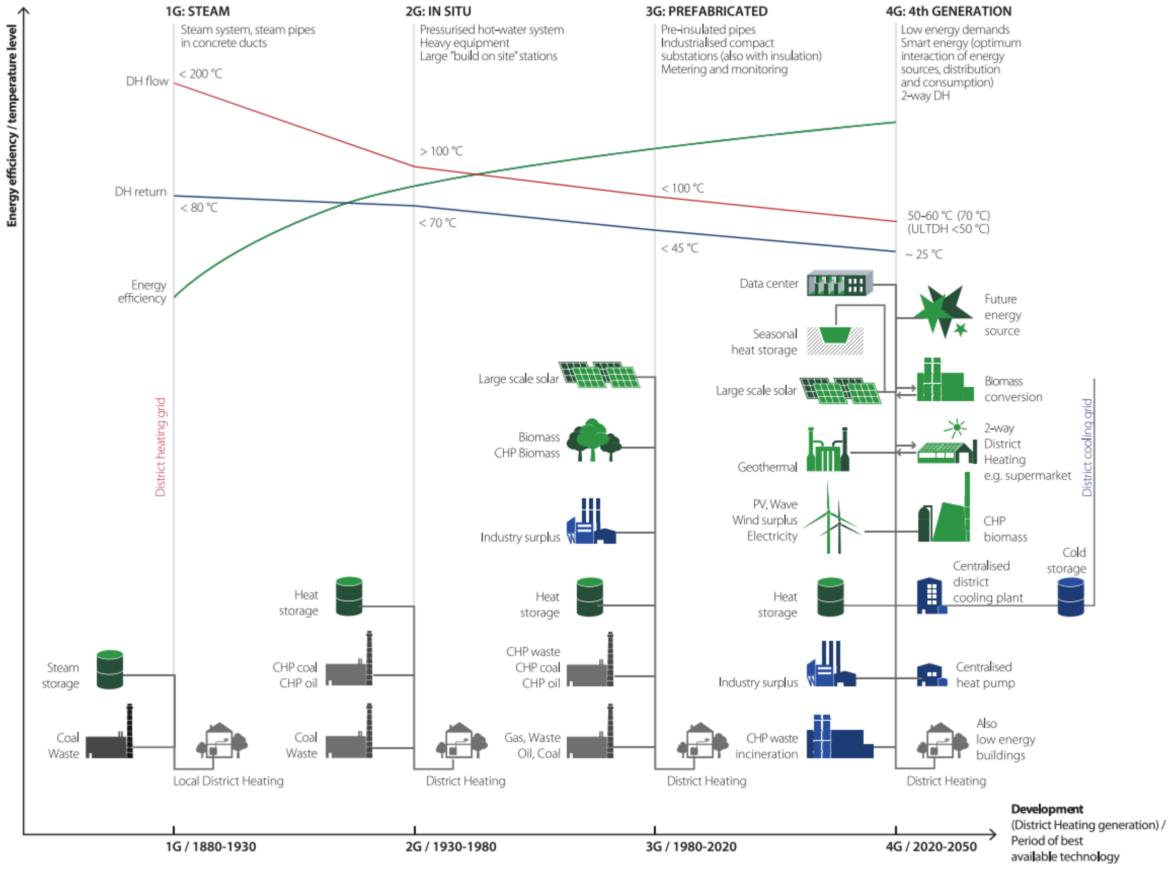

Figure 1. District heating system generations as defined by Lund et al. (2021, 3).

2.1 District heating research and development paths

Recent DH literature has focused on characteristics and factors that are regarded to be essential for the future of sustainable and integrated DH systems. In well recognized research Lund et al. (2021, 1-7) have defined five characteristics that future DH systems shall have in order to fulfil their role as sustainable energy systems: 1) ability to supply the whole building stock with low-temperature heat for space and domestic water heating, 2) ability to distribute heat with high efficiency, 3) ability to utilise low-temperature waste and renewable heat sources, 4) ability to integrate in smart energy systems to contribute in solving the challenges of fluctuating renewable energy sources and proving energy conservation into the system, and 5) ability to secure adequate operational and strategic planning, cost and incentive structures to ensure sustainable energy system transformation.

To meet these characteristics and requirements, four key development areas can be identified: 1) heat production, 2) system integration and optimisation, 3) heat distribution and 4) thermal storages. The below sections briefly describe the recent literature concerning areas 2-4. Heat production technologies are discussed later in main paragraphs 3-4.

2.1.1 System integration and optimisation

Intelligent DH system optimisation and control as integrated part of wider energy systems are considered essential focus areas for future smart DH systems. Novitsky et al. (2020, 1596) define these integrations to cover electricity, gas, heating and cooling energy systems to leverage increased storage capacities and flexibility on both supply and demand sides. Especially electricity system integration is recognized as vital to ensure access to affordable renewable electricity in DH systems (power-to-heat) and on the other hand to provide demand flexibility and storage for intermittent wind and solar power. Correlation between renewable electricity penetration and benefit potential of power-to-heat capacity in DH systems has been studied and shown by e.g. Dorotić et al. (2020, 1-18). Whilst from the electricity sector point of view Sorknæs et al. (2022, 1) point out DH system's relevance in allowing deeper penetration of variable RES trough affordable storage capacity, waste heat utilisation possibilities and flexibility of heat production technologies.

While integrations to other energy systems can be regarded as physical prerequisite, in their study Novitsky et al. (2020, 1598) also underline the need for co-optimisation between the systems and the important role of information and communication technologies and data for real time execution. To overcome challenges between sub-hourly variation of RES electricity production and traditional discrete-time hourly optimisation models, Nourollahi et al. (2023, 119926) propose continuous-time optimisation for integrated DH and electricity systems. The topic has been studied earlier also by e.g. Liu et al. (2022, 124311), who proposed multi-time scale optimisation for integrated electricity and DH system operations.

Besides DH's benefits in RES utilisation, the importance of energy conservation and waste heat utilisation in DH systems is pointed out by e.g. Lund et al. (2021, 1-7). While high temperature waste heat recovery from existing sources close to DH grids is not a new topic, recent literature has focused on low temperature sources from both traditional industries and new sources. Low temperature (or indirect) waste heat generally requires priming to higher temperatures e.g. via heat pumps (Sorknæs et al. 2022, 125215). Cioccolanti et al. (2021, 116851) studied DH potential of low-grade waste heat in pulp and paper industry, whereas

Hiltunen and Syri (2021, 120916) showed the benefit of low temperature waste heat originating from data center in replacing coal fired production in Finland. Also e.g. Huang (2020, 114109) discusses the benefits of data center waste heat in improving energy and resource efficiency in DH systems, while utilising RES in powering data center operations. This represents indirect renewable electricity integration to DH production, which is the case already today in the data center integrated to DHS in Kajaani. Another emerging waste heat source currently under academic focus is power-to-X ("PtX"). For instance, in their study regarding 4th generation DHS in Denmark Sorknæs et al. (2022, 125215) mention PtX as one of three key waste heat sources alongside data centers and existing industrial sources. In PtX most of the recoverable heat stems from electrolysers, but sometimes also from subsequent synthetic fuel production process phases.

Other integration and optimisation related topical DH research areas are prosumers, two-way district heating, grid configurations and district cooling integration. These all relate also to the so-called 5th generation DHS, which have been extensively discussed by e.g. Lund et al. (2021, 120520) and Buffa et al. (2019, 504-522).

2.1.2 Low temperature systems

Decreasing distribution temperatures in DHS has been a trend over the DH generations and this is expected to continue. Key benefits of lower temperatures are lower grid losses, increased production efficiency and wider spectrum of relevant technologies. Lower supply temperatures allow more waste heat sources to directly supply the grid, while very low temperature waste heat sources become more relevant due to decreased priming need and subsequent improvement in COP of heat pumps. Indeed, 4th generation DHS operating with low temperatures is regarded as an integral part of smart renewable energy systems by Haoran and Nord (2018, 496). Also, Li et al. (2022, 123601) have recently studied the topic and mention that lower supply temperatures are key drivers in developing energy efficiency and economic competitiveness of DHS. Haoran and Nord (2018, 483-498) have summarized the benefits of lower grid temperatures as presented in Table 1.

Table 1. Key benefits of lower DH network temperatures (Haoran and Nord. 2018, 484).

Topic	Benefit
Flue gas condensation	25-40% higher production capacity by condensing the fuel moisture in biomass fuels and waste
Medium temperature heat sources	50-100% higher production capacity from 70-100°C sources like industrial waste heat (and geothermal energy in some cases)
Solar energy	Solar heat collectors become more relevant with higher output potential
Conventional CHP plants	Lower temperatures allow higher power-to-heat ratios with the same plant design and heat demand
Heat pumps	Better COP driven by lower temperature and pressure in the condenser
Heat storage	Lower heat losses and increased capacity in water-based storage units
Grid	Better efficiency driven by smaller thermal losses in the pipelines
Grid	Lower thermal stress contributing to lower leakage risks and related costs
Grid	Plastic pipes become relevant in low pressure areas
Grid	Lower risk of steam formation in the pipelines (safety, efficiency, adequate functioning)
Buildings	More suitable vis-à-vis demand of modern buildings
Safety	Reduces / eliminates hot water related risks to people

Shifting the supply temperature curve is a complex task as individual consumption points are adjusted to follow status quo control curve. Lower temperatures may require building heat exchanger and apartment radiator replacements. Also, Legionella bacteria risk in domestic hot water (DHW) is limiting lower end of the curve. While the challenges are well recognized, Østergaard et al. (2022, 123529) underline that lower temperatures could be utilised in many DHSs with existing system set-up and radiators. Their study shows that typically space heating supply temperature below 55 °C, the range being 30-70 °C, is enough to ensure adequate indoor conditions for most of the time (Østergaard et al. 2022, 123529). For DHW the study suggests 50-70 °C supply temperature, and for both heating and DHW return temperatures could be 25-35 °C (Østergaard et al. 2022, 123529).

While Østergaard et al. (2022, 123529) do not find building stock energy renovations as prerequisite for low temperature DHSs, they point out that the renovations should be parallel activity while shifting to lower system temperatures. This has been studied also in the Kajaani DHS, which is planning to utilise 5-10 °C lower grid temperatures during heating season going forward without replacing grid infrastructure (Saviniemi 2023). In Kajaani currently the limiting factor to go much below 70 °C minimum supply temperature in the main pipes is the Legionella risk in grid parts that have low demand and flow resulting in temperature drop (losses) before reaching the consumption points (Saviniemi 2023).

2.1.3 Thermal energy storages

Thermal energy storage (TES) capacity is regarded as a critical element in any future DHS across the recent literature. Storage capacity supports well the required future DHS abilities defined by Lund et al. (2021, 1-7), while Novitsky et al. (2020, 1596) name thermal storages as one of the key energy system integrations for DH.

TES is a wide term, but storage types can be identified under different criteria. There are three different technological types: sensible, latent and chemical TES. Of these, sensible storages are already widely adopted and mature, whereas the other two are more on a research and piloting phase. In terms of storage capacity, TES types are divided into short-term and long-term storages. Short-term TES typically has a duration capacity of 3-24 hours, and they are designed to meet intraday demands. Long-term TES has a duration from weeks to months and they are typically designed to shift seasonally available heat or cold to periods with higher demand. Sensible short-term solutions are widely adopted, whereas long-term solutions are rather limited due to high energy losses and limited technical experience. Long-term TES would be vital for large scale conservation of geothermal, solar and waste heat in DHS. (Guelpa and Verda. 2019, 113474.)

In addition to dedicated TES, DH grid and building stock also represent significant thermal capacity. The potential of the system inertia has also been identified at Loiste (Saviniemi 2023). In addition, customers represent storage-like flexibility via demand side management. For instance, many of the consumption points are not very sensitive to minor temperature fluctuations. To utilise this, adequate incentives are needed for which Novitsky et al. (2020, 1598) propose dynamic heat pricing to promote distributed and efficient flexibility.

While TES provides significant benefits, like increased system flexibility and RES utilisation potential, peak load shaving and load shifting capacity, increased heat production optimisation and waste heat conservation potential, Guelpa and Verda (2019, 113474) underline that it is not possible to identify a unique best TES solution for all systems due to vast range of solutions and system characteristics related to production, distribution and consumption of DH, as well as characteristics of integrated other energy systems and operating environment. Due to this complexity, a lot of recent literature has focused on system optimisation, including TES capacity. The field has been studied recently by e.g. Li et al. (2022, 123601) and Fiorentini et al. (2023, 125464).

2.2 District heating in Finland

District heating is the incumbent heating method in Finland, a country with cold climate and good availability of biofuels. In total ca. 2,9 million Finns, or 52 % of the population, lived in dwellings heated by DH in 2022 (Finnish Energy 2023b). DH was the primary heating method in 51 % of the Finnish households and in 89 % of apartments in blocks of flats in 2022 (OSF 2023b). The difference is explained by DH's relevance in densely populated population centres. DH's share of total residential space and hot water heating energy was 35 % in 2021, which was the biggest share among all heating methods as shown in Figure 2 (OSF 2023d). Within the whole building stock 48 % of the total area was heated by DH in 2022 and the share has increased over time as shown in Figure 3 (OSF 2023c).

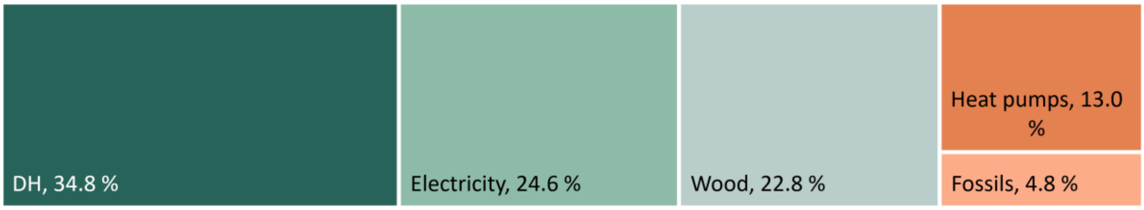

Figure 2. Energy consumption for space and hot water heating in residential buildings by heating method in Finland in 2021. Data: OSF 2023d.

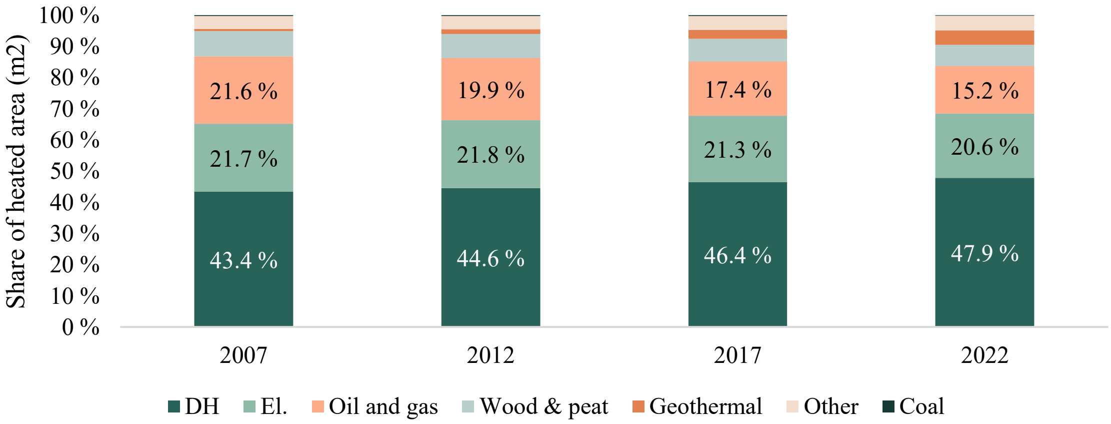

Figure 3. Heating methods in the whole Finnish building stock 2007-2022. Data: OSF 2023c.

On top of the DH's large share also the unit demand is high. Households' space heating energy consumption per capita was 8,4 MWh in Finland in 2021, whereas the EU average of 4,4 MWh was nearly half of that (Eurostat 2023a). Similarly, average heating degree days ("HDD") in 2019-2022 were 5314, which was 82 % more than the EU-27 average (Eurostat 2023b). In Europe the number was higher only in Norway as seen in Figure 4.

Figure 4. Average HDDs in Europe (EU + Norway) in 2019-2022. Data: Eurostat 2023b.

Finland as a large but sparsely populated country has large biomass resources and strong forest, pulp and paper industries. These factors have contributed to efficient biofuel markets and supply chains with generally good availability of sustainable wood-based fuels for DH use. Renewable wood fuels represent over 40 % of total fuels consumed in DH production (see paragraph 2.2.2). National sustainability aspects are underlined by the Act on banning the use of coal for energy generation (416/2019), which forbids coal for electricity and heat production in 2029. In addition to voluntary shift towards sustainable solutions seen already, this legal backstop increases the demand for low-carbon DH in Finland. Electrification and bioenergy utilisation are regarded the two main options to carry out this DH production decarbonisation (Lindroos, Mäki, Koponen, Hannula, Kiviluoma, Raitila 2021, 120779).

2.2.1 Demand

As DH has been able to retain and grow its market share in history, the volume demand has been growing over time. The total DH end customer demand was 33.0 TWh in Finland in 2022 and weather normalized equivalent was 33.9 TWh (Finnish Energy 2023b). While changes in annual temperatures cause demand fluctuation, the normalized (based on HDDs from 1991 to 2020) demand has grown consistently over long term but stabilized in recent years as shown in Figure 5.

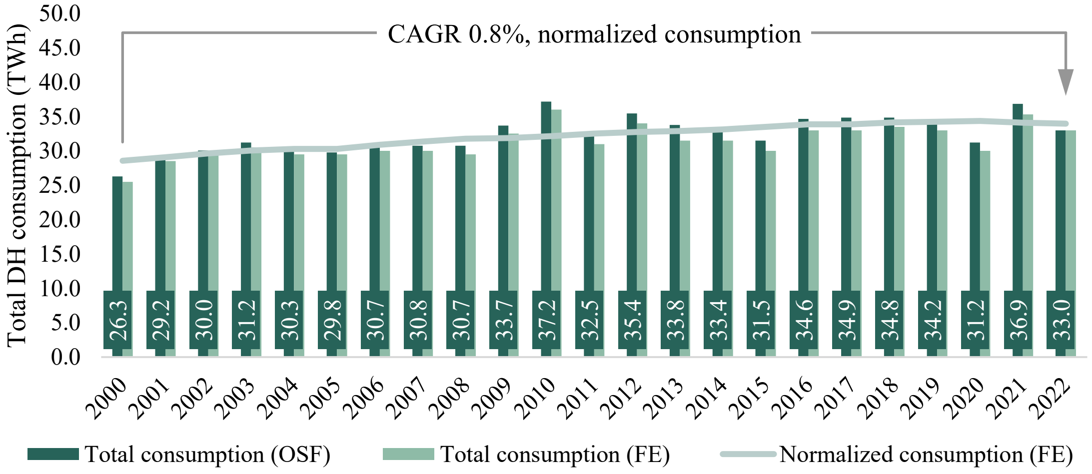

Figure 5. DH consumption development since 2000. The normalization is based on HDDs in 1991-2020. Data: OSF 2023e, Finnish Energy 2023b.

The demand reflects overall building stock composition in densely populated population centers, where the high enough customer density supports DH’s commercial and technical competitiveness. Figure 6 shows that a little more than half of the demand comes from residential sector while industry represents less than a tenth. The remaining ca. 40 % comes from other buildings including offices, stores, and public service buildings among others. Figure 6 also shows that similar magnitudes apply when considering building stock area by building types. In the residential sector block houses’ large share of the total heated area underlines DH’s role as an urban solution, whilst there are often competitive heating alternatives for smaller dwelling units both within and outside the DH network areas.

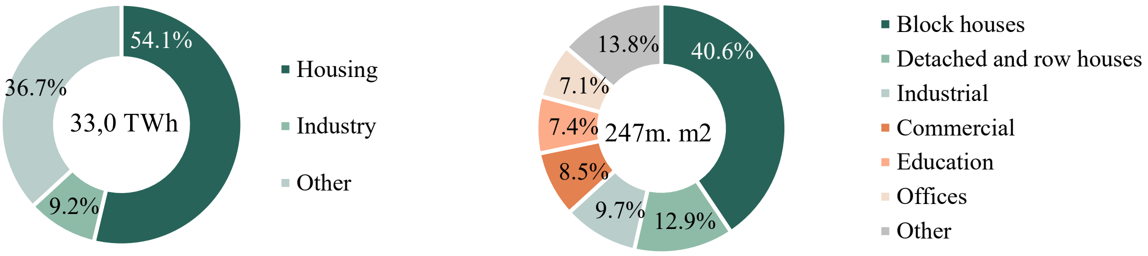

Figure 6. DH consumption by segments (left) and DH heated area by building type (right) in 2022. Data: Finnish Energy 2023b, OSF 2023c.

While DH has been able to grow its share of the total heated areas (Figure 3), also the total area has grown. The total national building stock area increased by 25 % in 15 years 2007-2022 and when considering DH's increased market share the total building stock area heated by DH grew by 37 % during the period (OSF 2023c). However, changes in climate and increased energy efficiency of the buildings have decreased specific energy consumption with a stable negative long term CAGR as illustrated in Figure 7. Although the DH volumes have increased over long term, the specific consumption decline has largely offset the volume impact from larger connected building stock and resulted in relatively small growth, or even stagnation, in recent years. This can also be seen in Figure 5.

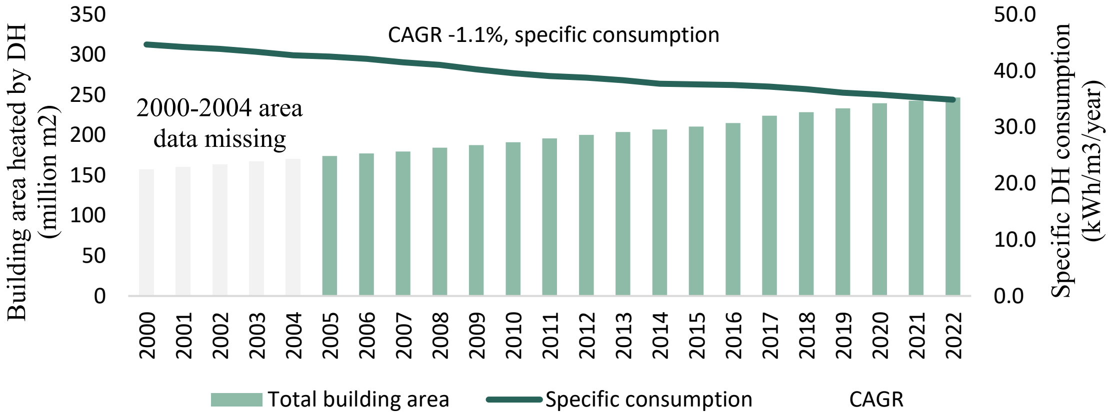

Figure 7. Development of building stock area heated by DH and annual DH consumption per building volume in Finland. Data: OSF 2023c, Finnish Energy 2023b.

Although DH has the largest market share heated area and population, in terms of number of buildings DH provided heat to only 13 % in 2022 (OSF 2023c). This can be explained by large share of relatively small buildings, like detached houses and second homes, being outside DH network areas. Direct electric heating provided heat to 39 % of all buildings, being the most common heat source in 2022 (OSF 2023c).

According to Finnish Energy (2023b) there were ca. 160 000 DH connections, i.e. customers, and based on OSF (2023c) these customers equaled to 209 000 DH connected buildings in 2022. The buildings have a total volume of ca. one billion cubic meters (Finnish Energy 2023b). The total committed thermal power towards the customers was ca. 19 GW in 2022 up from 16 GW in 2007 and 14 GW in 2000 (Finnish Energy 2023b), also underlining the long-term demand growth despite the stabilized delivery volumes.

2.2.2 Supply

District heat is supplied by DH utilities who often own the distribution networks. Generally, the utilities also produce most of the delivered heat by themselves, but third-party wholesale heat producers and waste heat suppliers are also common in Finland. As part of the changes in the Finnish energy sector, the share of DH that has been produced in CHP plants has been declining as demonstrated in Figure 8. Total DH production capacity was ca. 25 GW in Finland in 2022 (Finnish Energy 2023b).

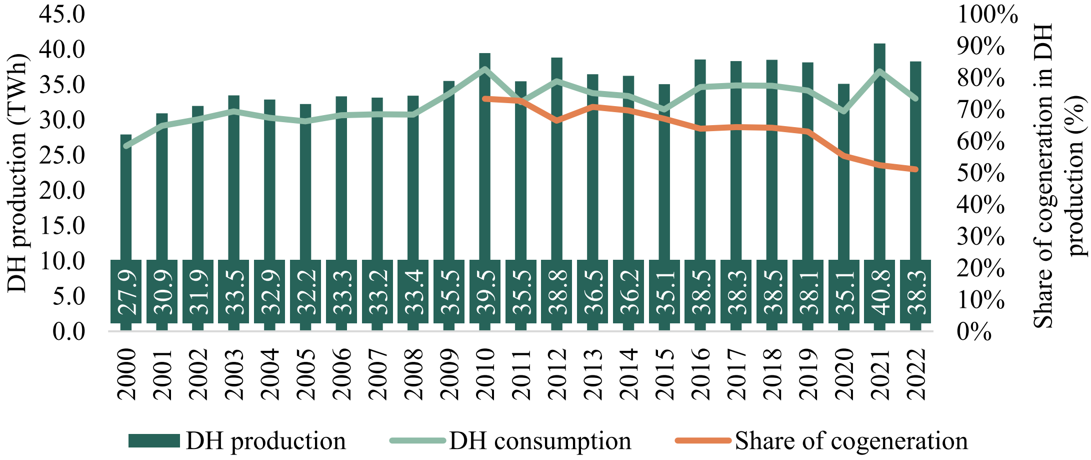

Figure 8. Development of DH production and share of cogeneration. Data: OSF 2023e-f.

CHP production has a significant role in the Finnish energy system still today. However, as shown in the Figure 8 share of cogeneration in DH production has been declining on back of declined competitiveness of combustion-based electricity against RES. Large CHP units have also often been fossil fuel fired. Strive towards sustainable energy production, emission regulation and its costs also explain the decline. As such, fossil fired CHP capacity has been replaced by biomass fired heat only boilers over the past years in many areas. This was the case for instance in the city of Lahti (Lahti Energia Oy 2023). This development, together with potentially increasing DH production electrification is increasing the sector coupling and the DH sector may shift from electricity net producer to net consumer in near future.

In an international heating context Finnish DH is relatively sustainable and the sector has successfully increased the share of renewable sources in its fuel mix (Figure 9). Still 38 % of the used fuels were fossil-based in 2022, whilst the majority was covered by renewable biofuels and heat recovery, including flue gas condensing. The share of wood fuels has increased from 11 % in 2000 to 44 % in 2022 (OSF 2023f). The most significant wood fuel fractions are wood and forest residue chips, bark and sawdust. Further details of the biofuel fractions are discussed in section 4.1 .

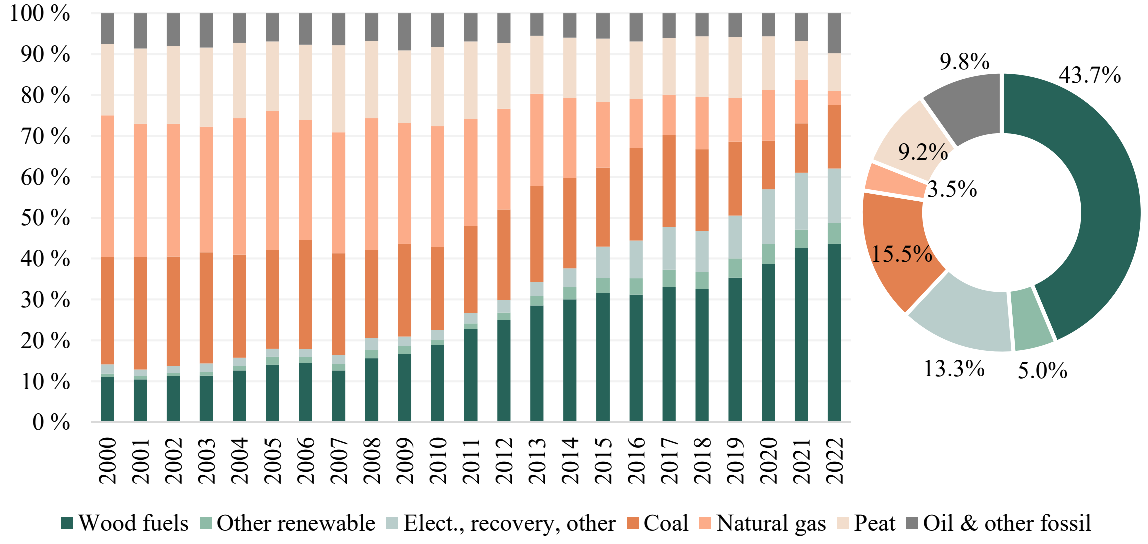

Figure 9. Development and 2022 split of DH fuel mix in Finland. Waste fuels (8 % in 2022) are allocated to renewable and fossil parts according to their composition (54 % and 46 % respectively). Data: OSF 2023f, Finnish Energy 2023b.

The realised DH production sustainability improvements are visible also in Figure 10 showing the consistent increase in share of renewable fuels from one tenth in early 2000s to 62 % in 2022. Simultaneously the carbon dioxide emission per produced DH energy unit has decreased by 51 % (Figure 10). Increased utilisation of heat recovery and heat pumps (e.g. flue gas condensing and wastewater) is included in the renewables share. These sources have increased from less than 1 TWh to around 5 TWh over the past 15 years representing a 13 % share in 2022 (Figure 9) (OSF 2023f, Finnish Energy 2023b). Despite the good track, the DH sector has a long way to reach net zero carbon emissions, especially if key biomass fractions are not regulated as CO2 neutral fuels over long term as they are today.

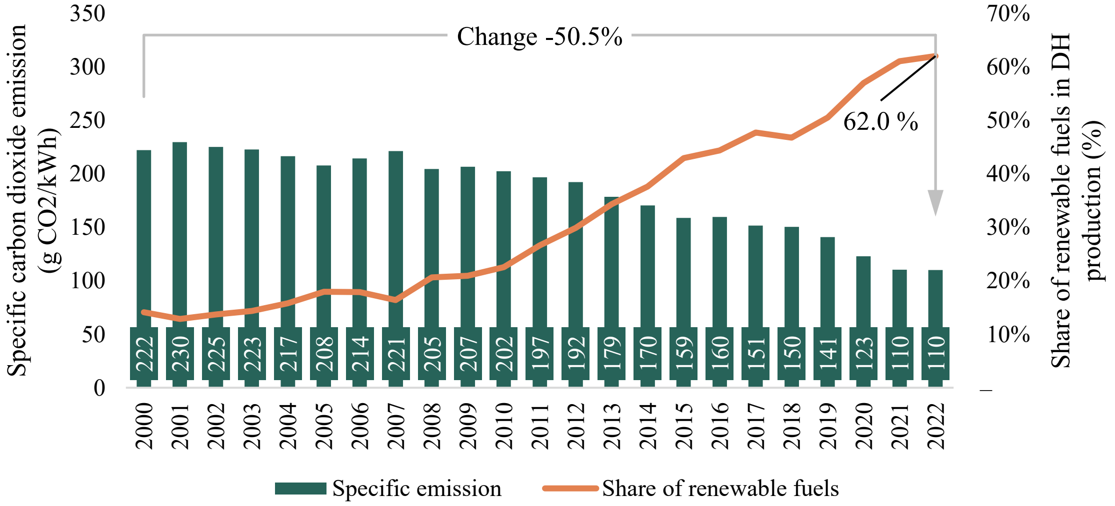

Figure 10. Development of specific emissions and share of renewable fuels (incl. waste heat and electricity) in Finland. Data: OSF 2023f, Finnish Energy 2023b.

To supply the heat, Finnish DH networks use insulated underground pipes. These are either single pipe 2Mpuk or double pipe Mpuk (i.e. supply and return pipes are in the same insulated structure) systems. Total length of the networks was 16 200 km in 2022 (Finnish Energy 2023b). This means that there were ca. 10 customers, and 2.0 MWh was consumed per kilometre on average during the year. Network losses have remained rather stable at around 10 % in recent years (OSF 2023e-f). Annual average supply and return temperatures are typically around 85-90 °C and 45-50 °C, respectively (Finnish Energy 2019).

2.2.3 Market characteristics

The Finnish DH market is fragmented and there were 109 utilities delivering DH to their end customers in ca. 200 network locations across Finland in 2022. Due to the fragmentation the average sourced and used (sold plus losses) DH volume among the utilities was 347 GWh. In the capital region the average was 3.7 TWh for three major companies and elsewhere 251 GWh per company in 2022. The companies' sizes vary a lot (Figure 11) from less than 10 GWh to ~7 TWh annual volumes. Most of the DH companies are at least partly publicly owned by cities and municipalities. (Volume data: Finnish Energy 2023b.)

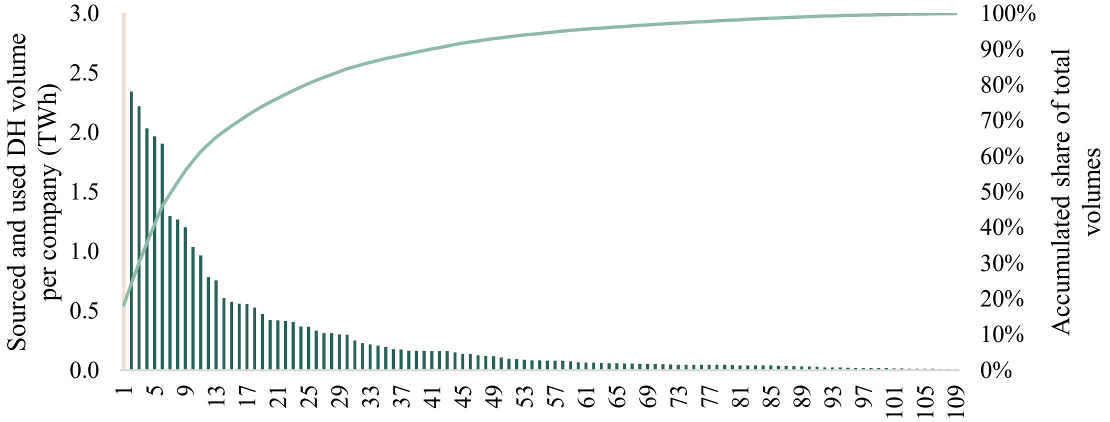

Figure 11. Volumes of the 109 Finnish DH utilities and accumulated share of total in 2022. Y-axis is limited, the largest company had 6.9 TWh volume. Data: Finnish Energy 2023b.

Customers in Finland are free to choose their heating method, and due to this competitive market environment pricing of heating is not regulated (Finnish Energy 2023c). This applies to DH as well, although DH companies may have a so-called dominant market position in certain areas. In such a case competition legislation sets general boundaries for reasonable pricing and terms. In practice, alternative heating methods represent true competition to DH among most customer groups, ensuring competitive pricing and services. Volume weighted national average DH price, including all price components and taxes was, 91 €/MWh ranging from around 50 €/MWh to 120 €/MWh in 2022 (Finnish Energy 2023c).

2.2.4 Emission and environmental regulation

DH is included in the EU emission trading scheme ("ETS"). The ETS is the key CO2 regulation and steering mechanism in the Finnish DH sector. The Finnish ETS authority is Energy Authority, who also approves emission permits and emission monitoring plans (EA 2023b). The ETS currently covers all combustion plants with over 20 MW thermal power and smaller units operating in the same DH network having at least 20 MW aggregated power (EA 2023b). Until 2030 DH sector is entitled to free emission allowances that equal to 30 % of the sector's calculated total amount (EA 2023a). CO2 emissions exceeding the free allowances shall be covered by purchasing allowances from markets. Loiste received 108 tCO2 and Kavo 17 043 tCO2 of free allowances for heat production in 2022 (EA 2023a).

Another binding emission regulation mechanism in Finland is plant specific environmental permit granted by regional state administrative agency. Energy production is obliged to apply for the permit as it may cause environmental pollution or endanger it (Syke 2023). The permits are holistic, covering e.g. air and water emissions, noise and waste management. The permit may set requirements for scope of operations, emissions and their reduction (Syke 2023). Generally, the permit's air emission limits cover other than CO2 given the ETS.

Combustion fuels have CO2 emission coefficients used e.g. in ETS calculations (OSF 2023a). Biomasses' coefficient under the ETS has been zero meaning that biomass is treated as CO2 neutral renewable energy. This has driven the emission intensity decrease in Figure 10. However, EU's RED III directive includes some tightening to the principle as e.g. wood biomass from old-growth forests will not be treated as sustainable anymore (MAF 2023).

Multiple DH related activities are covered also by the 2020 released EU taxonomy, which classifies environmentally sustainable economic activities with an aim to steer capital to sustainable investments (EC 2023c). The EU (EC 2023c) describes such activities "as those which make a substantial contribution to at least one of the EU's climate and environmental objectives, while at the same time not significantly harming any of these objectives and meeting minimum safeguards". DH related taxonomy eligible activities are e.g. DH distribution, heat production from bioenergy and operation of electric heat pumps (EC 2023c). The EU taxonomy sets technical criteria for each activity and alignment against those is case specific. However, it is likely that many domestic DH systems would reach high alignment and would be viewed as environmentally sustainable economic activity.

3 Non-combustion-based district heat production

While biomass combustion in DH production has increased its role in Finland over the past years, non-combusting technologies are regarded increasingly important. To reach carbon neutrality in Finland by 2035 promoting non-combustion-based heating is mentioned as a key focus for heat production by the Ministry of Economic Affairs and Employment of Finland (2022). Indeed, environmental factors are key drivers in making non-combustion-based technologies increasingly preferred alternatives to conventional combustion-based solutions. Tightening emission regulations, increasing emission costs and increasing availability of affordable renewable electricity as well as efficient heat pump technologies are making non-combustion-based solutions more and more competitive. They are also generally regarded future proof while addressing security of supply issues by eliminating fuel availability risks and promoting more diversified and distributed heat production.

Carbon neutral non-combusting-based heat production can be based on direct heat production or direct or indirect heat recovery. Examples of direct heat production are electric boilers and small modular nuclear reactors. Direct heat recovery, i.e. thermal energy of the source is fed into the DH grid without increasing temperature, can be applied in connection to various high-temperature heat sources, like waste heat from selected industrial processes, deep geothermal energy, and solar radiation with selected collector types. Indirect heat recovery covers a wide range of environmental and waste heat sources like nature and waste waters, air and ground surface, industrial processes, real-estate air conditioning and cooling solutions. Due to lower temperature heat sources, indirect heat recovery in DH production utilises heat pumps to prime the temperature higher to meet the requirements of the DHS.

3.1 Heat pumps

Heat pump (“HP”) is a machine that utilises two thermal sources to transfer thermal energy between the sources by means of external energy input. HP can be used for heating and cooling. HP’s performance is characterized by a coefficient of performance (“COP”). COP is defined as the ratio of heat amount exchanged with the target source (whether heated or cooled) compared to the energy input required by the machine. HPs can be classified into compression and absorption heat pumps according to which thermodynamic cycle they apply. (Grassi, 2018, 1-6, 73-76).

Modern heat pumps can generally reach COP values of 2-6 and temperature lift of 60-100 K. Final supply temperatures of DH HPs are typically below 80 °C, but high temperature HPs can reach 120 °C, some even higher. COP decreases with higher temperature rise. (Barco-Burgos, Bruno, Eicker, Saldaña-Robles and Alcántar-Camarena, 2022, 122378.)

Heat pump is an efficient and effective heat production solution (Grassi. 2018, 1-6, 73-76). HPs allow heat recovery from relatively low temperature waste and ambient heat sources while requiring significantly less energy than produced heat (within its design operating circumstances). HP technologies have been adopted widely and they have environmental and performance benefits in district heating systems (Barco-Burgos et al. 2022, 1-15). The supply temperatures in today’s DH grids are relatively high representing a challenge for HPs.

3.1.1 Compression heat pumps

Compression heat pumps use pressure difference to cause refrigerant phase changes for the heat exchange process. The pressure difference is made by a compressor powered by electric motor or engine and the underlying thermodynamic cycle is an inverse Carnot cycle (Grassi. 2018, 2-6). Basic scheme and thermodynamic reference cycles are shown in Figure 12. The scheme also defines the key HP components, which are compressor, condenser, expansion valve and evaporator (Grassi. 2018, 15).

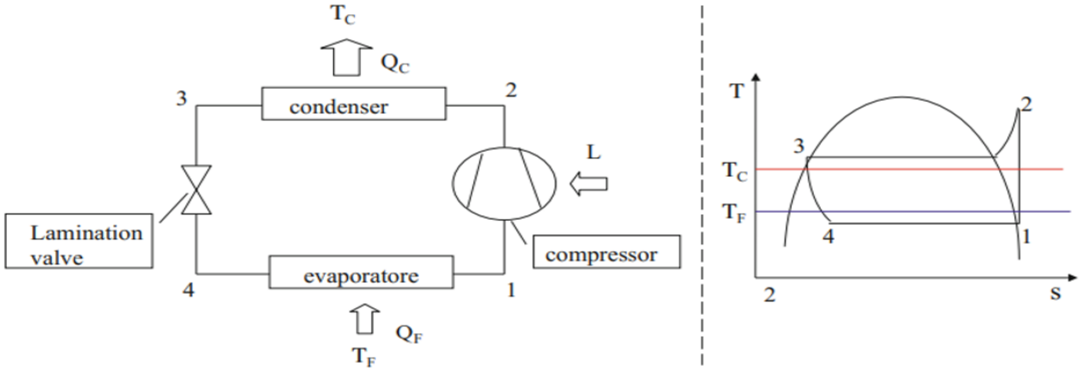

Figure 12. Compression HP’s basic scheme and thermodynamic reference cycles in temperature and entropy plane including, pressure and enthalpy plane (Grassi, 2018, 5).

The operating cycle starts from the compressor, which increases pressure of gaseous refrigerant causing temperature increase. The compressor uses mechanical work being the biggest energy consumption point in a HP. The hot refrigerant is then flowing to the condenser, where the refrigerant condenses after releasing heat. The high-pressure liquid refrigerant is then released through the expansion valve causing sudden decrease of pressure and subsequent evaporation. In the evaporator the refrigerant absorbs heat from the second heat source during the evaporation at low temperature, after which the cycle starts again.

From the plane in Figure 12 we can see that the bigger the temperature difference between the two heat sources is, the more pressure increase is required from the compressor. Hence, the smaller the temperature difference is, the better the HP's efficiency is (Grassi. 2018, 10). This, as well as e.g. limitations of used refrigerant, may limit compression HP's applicability in DHS, which often require high supply temperatures during colder periods, when also many ambient heat sources are at low temperature. Nevertheless, electric or mechanical power powered compression HPs are the most adopted HP types (Xu et al. 2022, 121804).

3.1.2 Absorption heat pumps

Absorption HP does not use a compressor, but uses mix of two fluids, of which one has higher vapor pressure (solute) and the other one has lower (solvent). Common mixtures are water with ammonia or lithium-bromide. The working principle is based on separating the fluids by evaporating the solute with an additional heat source. Figure 13 shows basic scheme and components of ammonia(solute)-water(solvent) HP. (Grassi, 2018, 73.)

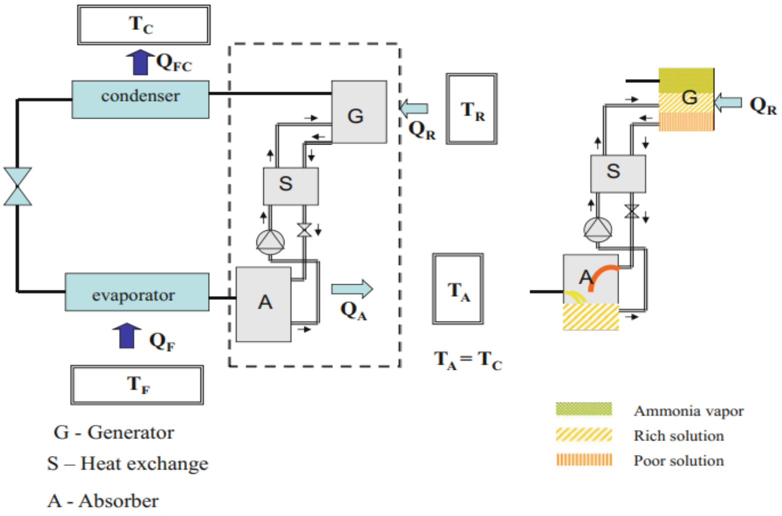

Figure 13. Basic scheme of an absorption HP (Grassi. 2018, 74).

The process starts from a generator, where rich fluid mixture is fed. Distillation happens when the mixture is exposed to additional heat in the generator. Solute is then flowing to a condenser releasing heat, while the now poor mixture is flowing to absorber. Solute is then flowing through a valve to an evaporator capturing heat from the other heat source. After the evaporator, the solute is fed to an absorber where it mixes with the solvent under exothermal reaction and forms rich solution again. The rich solution is pumped back to the generator though heat exchanger absorbing heat from the hot poor solution. (Grassi. 2018, 73-74.)

Compared to compression HPs, absorption HPs typically have lower COP. Due to the COP temperature difference sensitivity of compression HPs, compression machines are more effective with small temperature lifts, whereas absorption HPs become more effective at high temperature differences compared to compression HPs. (Xu et al. 2022, 121804).

3.2 Ambient heat sources

Solar energy is absorbed by air, surface waters and earth crust close to the surface. This stored thermal energy is creating ambient heat sources for DH production. Heat pumps are often used in connection with the sources as they are typically in relatively low temperature.

3.2.1 Solar heat

Solar irradiation can be utilised in DH production via solar collectors heating circulating fluid. The production potential depends on irradiation amount and intensity and temperatures of ambient air and DH grid. As such, the feasibility is highly dependent on location that is also driving DHS temperatures and loads. In Finland, annual irradiation is relatively low and in Kajaani it is on average 834 kWh/m2 for horizontal surface, whereas in Southern Europe the values reach nearly 2000 kWh/m2 and around 2200 kWh/m2 with optimal angles (data: EC 2023a). Monthly irradiation values plotted against DH load index in Kajaani are presented in Figure 14, showing a timing mismatch between availability and demand. The mismatch is largely present in Europe and to overcome this, seasonal storages are expected to play a key role in the success of solar-assisted DH systems (Jodeiri, Goldsworthy, Buffa and Cozzini. 2022, 112156). Generally, of the total DHS demand, solar heat can cover up to 20 % without and even 50+ % with seasonal storage in Europe (Jodeiri et al. 2022, 112156).

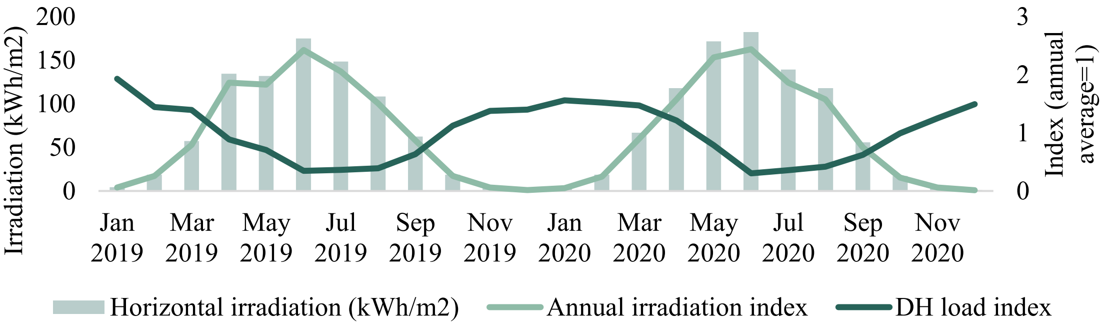

Figure 14. Monthly solar irradiation and DH load index in Kajaani 2019-2020 (data: EC 2023a, Loiste 2023b).

There are multiple types of collectors converting solar irradiation to thermal energy. By type they are either concentrating solar irradiation or not. Target temperature is the most significant factor in choosing the collector type. In domestic heating applications, non-concentrating ones are typically used, whereas concentrating ones reaching higher temperatures are more often used in solar power plants (Evangelisti, De Lieto Vollaro, Asdrubali, 2019, 109318). Depending on the collectors, heat can be utilised in DHS directly either on supply side or as pre-heating on return side. In lower temperatures, HPs can be used to increase temperature for DHS. Flat plate collectors are typical non-concentrating ones, and parabolic through collectors typical concentrating ones in DH use (Jodeiri et al. 2022, 112156). Both can reach temperatures for direct DH utilisation in sufficient conditions (Jodeiri et al. 2022, 112156). In DH applications, the collectors' operating temperatures range typically from 40 °C to 95 °C and efficiencies from 60% to 70% (Jodeiri et al. 2022, 112156). Collectors' efficiencies are the higher the lower the target temperature is.

Solar heat technology in DH applications is mature, but collector field optimisation and types are still under active research (Jodeiri et al. 2022, 112156). Despite growth in recent years, only 1% of all solar thermal system capacity was feeding DH grids globally in 2020 (Jodeiri et al. 2022, 112156). In Finland, the largest solar heat system in 2023 located in Eastern Finland in Mikkeli and the DH connected system has a flat plate collector field of 415 m2 with nominal thermal power of 360 kW (Meriaura Group, 2023).

3.2.2 Surface waters

Surface waters, like lakes, rivers and sea, can work as a significant thermal source for DH. As the water temperatures are relatively low, heat pumps are used in connection with them. Low water temperature during a heating season is a challenge, while the risk of icing during colder periods of an operating season is also limiting how much thermal energy can be obtained. Hence, the ambient waters should be supplemented with other sources and seasonal thermal storage if possible. (Lund and Persson 2016, 134.)

Surface water HP systems are divided into three types: open-loop, closed-loop and pumping-well systems. In an open-loop systems water is pumped through a filter to a heat exchanger and returned to the water area. Pumping and heat exchanger system design have a crucial role in open-loop systems to ensure efficiency, antifouling, corrosion prevention and balance with the ecosystem. In contrast, in a closed-loop the heat exchanger is immersed directly in the water body, and water glycol mix is circulating in the exchanger as a working fluid to harvest thermal energy. As nature waters are not pumped out from the water body, closed-loop systems do not require filtering and are more robust compared to open-loop. The heat exchanger can also be buried in bottom sediments to obtain heat from both the sediments and the water body. Closed-loop systems are commonly adapted and in use today. (Jung, Oh, Han and Lee 2022, 112124.)

Pumping well systems are pumping water from wells through heat pumps back to initial water body. Land between the wells and the water body is porous allowing water to flow through it because of hydraulic head created by pumping. As the soil generally has higher temperature than ambient water, the flow captures heat from the soil providing a higher temperature heat source compared to open and closed-loop systems. This improves efficiency and stability. Respectively, the system can work under colder water temperatures. The systems are primarily used in seashore. (Jung et al. 2022, 112124.)

The amount of efficiently recoverable heat depends on ambient water temperature and flow. These also drive the icing risk and are underlined in lakes and sea where flow is lacking or is smaller compared to rivers (Lund et al., 2016, 134). Despite this, large masses and water's high specific heat capacity provide sizeable heat source in many places. Due to more stable temperatures compared to ambient air, surface waters also provide better availability and predictability for DH production.

Available surface water temperatures and water flow reference points in the Kajaani river are presented in Figure 15. Due to an ice cover, the water temperature is at zero from mid-November to mid-May. The water flows are fluctuating heavily as this is controlled by hydropower plant in the river (Saviniemi 2023). The river is flowing through the city and is the most suitable water area for ambient heat recovery. However, the long winter period increases the icing risk and limits time when the system can provide meaningful contribution to the local DHS and as such is challenging the feasibility in Kajaani.

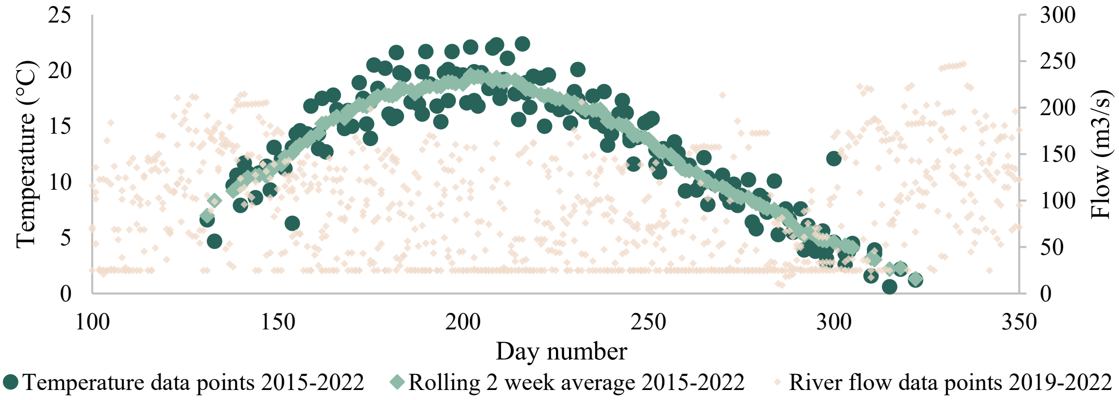

Figure 15. Surface water temperature and water flow in Kajaani river (data: vesi.fi 2023, Järvi-Meri Wiki 2023). X Axis represents a day number within any given year.

Sea water provides virtually unlimited heat source, and the lower freezing point of salty water provides greater operating temperature range. Large scale DH connected sea water heat pump systems are in use for instance in Stockholm (Grassi 2018, 147). Also, in Helsinki a local utility is planning a large-scale sea water HPs for its DH production (Helen 2023a).

3.2.3 Ambient air

Ambient air is available easily and in high quantities for heat recovery. This also enables scalability. Modern air-to-liquid heat pump systems can be used throughout the year also in northern European cold climate, although COP varies significantly, and ambient temperatures may result in temporary unavailability during very cold periods. High air temperature variation and cold periods are challenges and air-based heat pump solutions are exposed to icing like the surface water systems (Østergaard and Andersen, 2018, 924). Wide operating temperature range requires coolant that works within the range.

Ice generally starts to form in evaporator surfaces in temperatures below 7 °C, and when closing -20 °C temperatures icing becomes significant and temperature difference from source to sink often raises too high, limiting HP's operation (Østergaard and Andersen, 2018, 924). Decreased heat exchange rate due to the ice formation can be mitigated by heating the evaporator (melting ice), but this auxiliary energy consumption rises the more the lower the air temperature is (Østergaard and Andersen, 2018, 924). Respectively, COP decreases.

Furthermore, when air temperature decreases temperature rise requirement generally increases as DH demand and supply temperature increase in colder weather. This can be mitigated by feeding the HP output to DH grid’s return side that has a lower temperature.

Hourly air temperatures in Kajaani for 2019-2022 are presented in Figure 16, showing suitable operating temperatures most of the time. During the four years, 1.2 % of all hours (406 h) had temperatures below -20.0 °C. Temperatures were less than -15.0 °C during 1302 hours, representing 3.7% of all hours. The average temperature for the period was 4.4 °C with a minimum of -29.1 °C and a maximum of 30.9 °C. (Data: Loiste 2023b.)

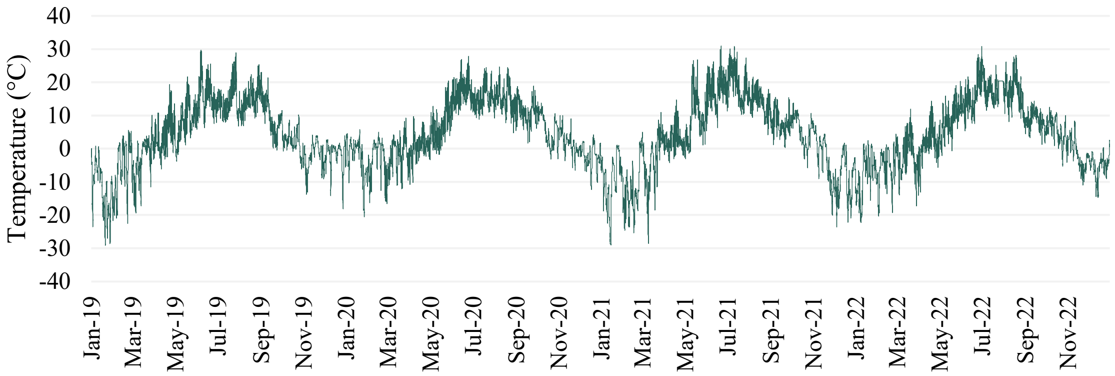

Figure 16. Hourly temperatures in Kajaani 2019-2022 (data: Loiste 2023b).

DH HP systems based on ambient air are gaining momentum. In Finland for instance in Espoo a utility scale system has been installed. The plant uses 12 HP units, has total nominal thermal output of 11 MW and also provides district cooling (Fortum Oyj 2023). In Helsinki, Helen is investing in a system with 14 MW heat and 8 MW cooling output (Helen 2023b).

3.2.4 Ground source heat

Ground source heat in this section refers to heat extracted from earth crust and ground water from shallow depths, typically down to 300 meters. In shallow depths, the Finnish ground is in low temperature requiring the use of heat pumps. Heat extracted from deeper is discussed later in geothermal heat section. Shallow ground source heat pumps are commonly used in building specific heating solutions and GSHPs have increased their market share in Finland.

In 2012, GSHPs were the primary heat source for 3 % of the households in Finland, whereas in 2022 the share was already 9 % (OSF 2023b). Building specific GSHP can be regarded as the primary competitor for DH in many areas in Finland, while no large scale GSHP solutions have been installed for DH production in the country by early 2024.

Ground source heat up to 15-20 meters depth is primarily originating from solar irradiation absorbed to the earth crust, hence having seasonal temperature variation (Clausen, From, Hofmeister, Paaske and Flørning 2014, 21). In greater depths, the temperature is more stable, and it is decreasing down to 100-150 meters, after which it starts to increase due to heat flux driven by heat originating from inside the earth. Temperatures in depths down to 100-150 meters are impacted by a heat front driven by heat flux from buildings (urban areas) and climate change (GTK 2022). After the 100-150 meters, the temperature raises with stable heat gradient of 1.2-1.6 K / 100 m (GTK 2022). As a benchmark for Finland, in Denmark in 100-200 m depths the temperature is 8-9 °C (Clausen et al. 2015, 21), and somewhat similar results have been measured in Stockhom in Sweden as illustrated in Figure 17.

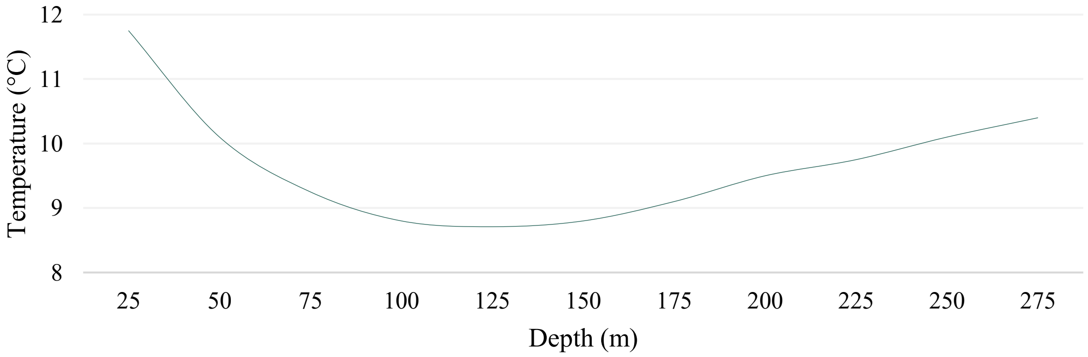

Figure 17. Measured ground temperature by depth in Stockholm, Sweden (data: Gehlin, Spitler and Hellström 2016, 5).

Heat can be extracted from both dry soil and soils that have water in it. There are two key types of heat ground source heat exchangers: horizontal and vertical borehole. In vertical applications, boreholes are typically drilled down to 200 m and closed loop piping (e.g. U tube) is installed in it to circulate working fluid that is extracting heat from the surrounding earth and water. In horizontal cases the piping in different shapes is laid on ground, typically in depths of 0.7-2 m. (Grassi 2018, 145-148.)

Horizontal ones require large areas and are thus regarded irrelevant for DH use (Østergaard and Andersen 2018, 925). In urban DH areas, there are two options to utilise ground source heat in DH: 1) drilling a high number of 200-400 m deep wells and 2) use much deeper wells (GTK 2022). In Kajaani around 80 kWh of heat per borehole meter can be assumed as sustainable heat yield per year (Gebewell Oy 2023). By assuming the 80 kWh/m yield, 300 m deep boreholes (effective depth), 15 m minimum distance between the boreholes and a target to cover 60 GWh, or around 20% of Kajaani’s annual DH demand, required area for a vertical borehole field would be 54 hectares with 2500 boreholes. This illustrative calculation underlines the challenge also for vertical borehole GSHP systems for DH use.

3.3 Waste heat recovery

Waste heat recovery represents significant potential for heating sector decarbonization. The share of waste heat recovery in total DH production in Finland in 2020 was already 11% (Afry 2021). Like most ambient heat sources, many waste heat sources come with low temperatures requiring heat pumps in DH applications. This section discusses selected potential and well recognized yet underutilised waste heat streams for DH systems.

3.3.1 Wastewater

Compared to ambient waters, wastewater (WW) represents more stable temperatures and continuous flow throughout the year for DH production. WW here is defined as domestic sewage wastewater and urban runoff waters steered to a common wastewater treatment system in a certain area. This waste heat source has extensive potential but has not been utilised to its full potential in many European cities (Ziemele, Volkova, Latõšov, Murauskaitė and Džiuvė 2023, 128132).

Heat can be recovered from WW by indirect and direct systems. In the indirect systems WW heat is recovered to intermediate fluid circulation in plate or shell-and-tube heat exchangers. In the direct systems heat is transferring directly to HP refrigerant in flooded or dry-expansion evaporators. The heat exchangers may be equipped with defouling brushes to clean the surfaces from WW impurities, if the heat is extracted before purification process. While WW is increasing its popularity as an urban heat source, key challenges in the systems have been seasonal temperature differences and WW impurities having impact on heat exchange. (Durdevic, Balic and Frankovic 2019, 209.)

In Finland, the largest DH connected heat pump systems are using sewage wastewater as a heat source (Kontu, Rinne, Junnila, 2019, 862). Such heat pump systems for DH production have been implemented e.g. in Helsinki, Espoo and Turku. These systems extract heat from purified WW and the largest one is in Helsinki (Katri Vala HP) with DH capacity of 126 MW (Energiateollisuus ry 2023). For Loiste limited but MW scale (seasonal variation) DH capacity potential from WW has been estimated (Saviniemi 2023). WW temperature development and monthly averages of daily flows in Kajaani are shown in Figure 18.

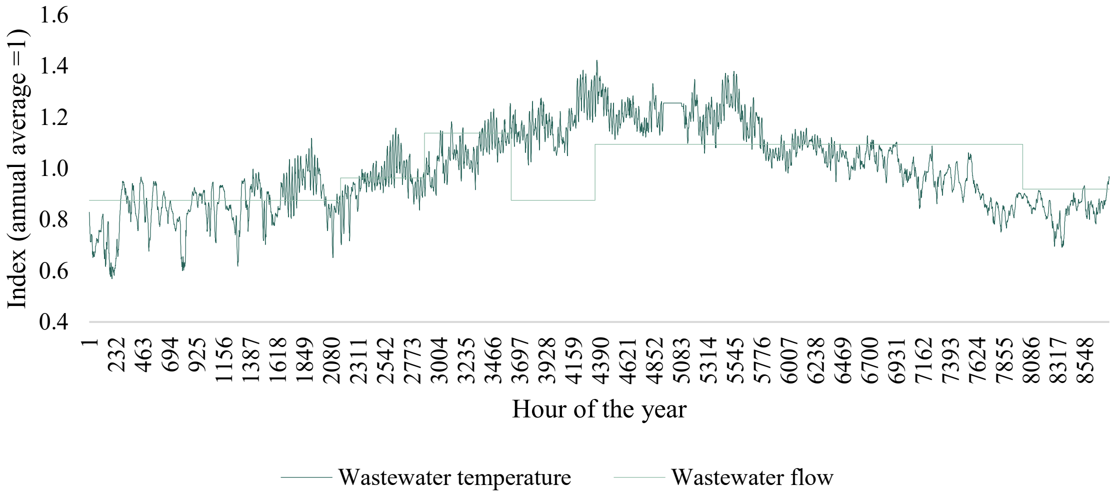

Figure 18. Indexed wastewater temperature and average daily flow in monthly average values in Kajaani in 2022 (data: Loiste 2023b).

Although the potential capacity is relatively small for Loiste, it could provide a valuable addition from the annual energy perspective and since it can sustain some production also during colder periods. However, the technical and environmental feasibility and suitable location should be considered together with the local water utility. The water treatment plant is located ca. 1 km away from the current CHP plant.

3.3.2 Data centers

Driven by the digitalisation of our societies across the sectors, data storage and computation capacity demand in data centers ("DC") is increasing. DCs consume great amount of electricity, of which vast majority is converting into heat. Cooling is needed to maintain stable conditions inside. The cooling provides excellent waste heat stream and Huang et al. (2020, 114109) find DH as a promising way to connect DCs and energy systems especially in the Nordic countries that have high share of RES in the energy mix. The DC waste heat recovery potential is underutilised in Europe today and the issue is facing increasing regulatory pressure due to its sustainability improvement potential (Ramboll 2023). For instance, European Commission (EC 2023b) has stated that the DCs' waste heat should be reused in the heating sector in the EU. There are also national incentives and in Finland energy efficient DCs utilising heat recovery are granted with lower electricity tax.

There are two main ways to remove excess heat from the DC equipment: 1) liquid cooling and 2) air cooling. Historically, air cooling has been the dominant one, but the popularity of liquid cooling is increasing due to increasing DC power loads (Huang et al. 2020, 114109). Liquid cooling provides more effective heat transfer due to convective heat transfer coefficient, high specific heat capacity of coolants and direct contact with heat emitting components (Huang et al. 2020, 114109). In both systems waste heat can be utilised for DH.

The liquid cooled systems typically provide waste heat at temperatures of 50-60 °C, and the air-cooled ones at 25-35 °C. These are often below the DH networks temperatures and temperature upgrading is needed. Alternatively, the waste heat can be fed to the DH return side, where temperature remains generally below 50 °C. While the temperatures set some constraints on recyclability of the waste heat, research has shown that as much as 97 % of DCs' electricity consumption can be recovered as heat. (Hiltunen and Syri 2021, 120916.)

In addition to the two main types, two-phase cooling has been developed to provide even higher cooling efficiency in very high power density DCs (>1000 W/cm2). Here nearly saturated coolant is pumped into the cooling circuit where it boils and evaporates efficiently cooling the equipment racks while storing latent heat. Two-phase cooling can provide as high as 80 °C waste heat temperature. (Huang et al. 2020, 114109.)

Finland has successfully adapted DC waste heat recovery and there are several DH grids utilising it. For instance, DH grid in Mäntsälä has covered more the 50 % of its demand in recent years by DC waste heat that has maximum capacity of 7 MW (Energiateollisuus ry 2023). In Kajaani, Loiste has connected DC that is built into an old paper mill with target to cover 20 % of the DH demand (Saviniemi 2023). The DC in Kajaani has liquid cooling and its heat pumps provide DH production capacity of ca. 8 MW (Granlund 2021). Nationally the largest initiative is in Espoo, where waste heat from a new 100 MW DC is expected to cover majority of the annual DH demand (Hiltunen and Syri 2021, 120916).

3.3.3 Industrial processes

Various industrial processes have great potential to act as a waste heat source. Primary option for effective utilisation is to recycle the heat within the source processes and facilities. This is not always possible and surplus, often low-temperature, waste heat is discharged to the environment typically in the form of water or air (Motiva 2019, 7). This heat can be utilised in DH either directly or via heat pumps depending on the temperature.

It has been estimated that on EU level there is 300 TWh of annual industrial waste heat dissipation and that one third of this is in temperatures below 200 °C (Xu, Wang and Chun 2019, 1038). Technical potential of surplus waste heat was estimated at around 19-23 TWh in early 2010s in Finland, and 21-26 % of it was estimated to be relevant for DH utilisation (Motiva 2019, 13). The largest Finnish industrial sectors producing waste heat are pulp and paper, oil refining and coke production, metal refining, food and beverages, mechanical forest industry and chemical industry (Motiva 2019, 13). Typical industrial waste heat sources and temperatures are summarized in Table 2.

Table 2. Industrial waste heat temperatures and potential sources (Motiva 2019, 18).

Temperature	Waste heat source (generally in the context of Finland)
< 50 °C	Process cooling waters Condensate energy of mechanical cooling Process exhaust air flows
50-100 °C	Process cooling waters, leaks and breaths Cooling of oil-lubricated compressed air compressors
> 100 °C	Flue gases Process exhaust gases (e.g. furnaces)

Electrification of industrial processes is increasing sector integration, introducing new ways and sources for waste heat utilisation. Emerging but potentially significant waste heat sector is power-to-X. Significant part of electricity used in electrolysers in hydrogen production converts to waste heat (Motiva 2023, 8). Due to availability of RES, biogenic CO2 from DH production and DH grids' potential to utilise waste heat, Finland is regarded highly attractive location for the PtX sector. Indeed, most of the PtX projects in Finland are planned to be connected to DH production facilities as of 2023 (Mäntylä 2023).

Biomass combustion heavy DH production in Finland is utilising flue gas scrubbers providing large share of the DH sector's waste heat recovery utilisation today. In this thesis, this is not regarded as an industrial process, but is discussed more in paragraph 4 as part of fuel combustion processes. However, in addition to the discussed wastewater and data center integrations, there are also industrial processes connected to the DH production in Finland. For instance, in Kokkola waste heat from cobalt and battery material factory's process wastewater is utilised by heat pumps to produce DH (Motiva 2023, 17). Another relevant example, although not directly DH connected, is an ethanol factory in Ilmajoki, which is priming heat from 35 °C process water to 90 °C through heat pumps, after which the heat is reused in the factory's production processes (Motiva 2023, 9). Outside actual heat production waste heat can benefit DH e.g. in drying biofuels to increase burning efficiency.

In addition to the existing DC, there are no other identified material long-term industrial waste heat sources that could be utilised (Saviniemi 2023). However, a separate study is recommended to map the regional potential especially in the old paper mill area.

3.3.4 Cooling systems

Large scale cooling and air conditioning systems are attractive waste heat sources as the cooling often occurs in places where also heat is needed or in facilities that are connected to DH grid. District cooling heat pumps' condenser side is also often used for DH production simultaneously when the evaporator side produces cooling. This is the case for instance in Helsinki (Helen 2023b). In Turku in pharmaceutical factory waste heat is recovered from process cooling and primed by heat pumps to 70-80 °C after which it is circulated to areal heating grid heating the factory (Motiva 2023, 9). An additional common example is energy intensive cooling equipment in grocery stores, although the waste heat volumes are typically not enough for external DH recovery but are recycled within the building.

3.4 Electric boilers

Electric boilers convert electric energy directly to heat and can contribute significantly to sector coupling and balance varying electricity production from wind and solar. By using renewable electricity, electric boilers can operate with very low carbon footprint. Indeed, flexibility, RES integration and emission reductions compared to fuel combustion are key benefits of electric boilers (Golmohamadi, Larsen, Jensen, Hasrat, 2022, 112200). However, electric boilers are exposed to varying electricity prices while their profitability can be improved by storage capacity (Golmohamadi et al. 2022, 112200). Electric boilers come with relatively low investment and O&M costs (other than electricity). They are also silent, safe, and reliable given technical simplicity and absence of fuel handling. They can ramp-up to maximum power in 30 seconds and produce both hot water and steam from residential scale to dozens of megawatts in one unit (Parat 2023).

There are two main types of electric boilers: 1) resistive boilers and 2) electrode boilers. The conventional boilers have resistive electric heating elements immersed in water which absorbs the thermal energy generated in the elements. Resistive boilers are commonly used, but they often have higher losses from the boiler surfaces and may experience overheating in the resistive elements. The electrode boilers on the other hand are based on water itself being the resistive element. In the electrode boilers, ions (salt) is added to the boiler water to enable electric current flow directly through the water. The electric energy is converted into heat when the accelerating and moving ions are colliding in the water. The power of electrode boilers is regulated by electrode exposure area, conductivity of the water and applied voltage. Electrode boilers can have very high energy efficiency (ca. 99.9%). They can reach high powers and are applied in industries requiring high responsiveness and scalability making them suitable for DH. Illustration of an electrode boiler is in Figure 19. (Manni, Nicolini and Cotana, 2022, 112569.)

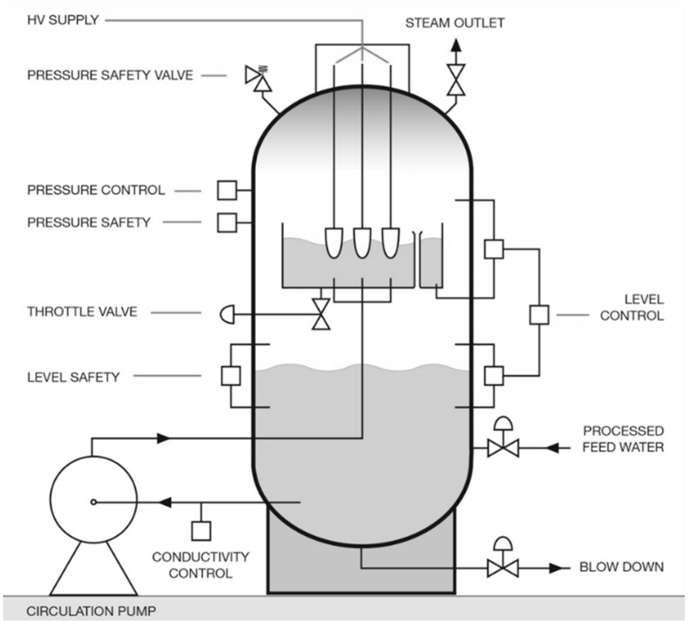

Figure 19. Illustration of Parat high voltage electrode boiler with steam output up to 85 bar and 60 MW per unit (Parat 2023).

Electric boilers in DH use have gained momentum in Finland recently. The development has been driven especially by biofuel market scarcity and increasing RES and CO2 neutral electricity production capacity that have lowered overall electricity prices while increasing volatility. For instance, 40 MW electrode boiler capacity has been added to two DH systems in Seinäjoki and Vaasa during 2021-2022 (Sevo 2023, EPV 2021). Both units are also connected to thermal storage capacity (Sevo 2023, EPV 2021). Finland is also supporting electrification of DH production and like DH heat pumps DH connected electric boilers are eligible to lower electricity tax that in 2023 means 0,63 €/MWh in total (Verohallinto 2023).

Excellent production flexibility, relatively low investment and O&M costs, technical robustness, high output temperatures and option to produce industrial steam make electric boiler attractive alternative for the DHS in Kajaani especially to ensure sufficient capacity during colder periods. The low investment costs, which are discussed more in detail later in this thesis, are partly offset by uncertainty and risks related to electricity prices, which may have an impact on DH competitiveness in high power price scenarios.

3.5 Geothermal energy

In addition to the shallow ground source HP solutions discussed in paragraph 3.2.4 , the Earth crust's thermal energy can be utilised in DH production by utilising heat and high temperatures available deeper either directly or via heat pumps. The deeper solutions represent vast sustainable energy source and effective heat production solution, although they currently come with significant uncertainties and risks.

There are no commonly accepted definitions for shallow, medium and deep geothermal energy (Romanov and Leiss 2022, 112727), but in this thesis geothermal energy refers to heat extracted from depths beyond 350 meters. Traditionally, geothermal energy in wider context refers to electricity or combined heat and electricity production in areas with suitable geological conditions usually near outlines of tectonic plates, providing high temperatures near surface (Romanov and Leiss 2022, 112727). Such areas are not available in Finland.

Romanov and Leiss (2022, 112727) discuss medium deep systems in connection with depths of 350-2500 meters, while 3-5 km depths are mentioned in connection to deep geothermal energy. By assuming similar thermal gradient (1,2-1,6 K / 100 m) as in section 3.2.4 , temperature in 2500 meters should be ca. 40-50 °C, and in 5000 meters 70-90 °C. In 6 km the temperature should reach at least 80-105 °C. As such, the deep solutions could be used for DH without additional temperature increase, while medium deep solutions would require heat pumps in most cases as also classified by Romanov and Leiss (2022, 112727). In medium deep solutions typically U-tube or coaxial heat exchangers are used, whereas in deep solutions the working fluid, like water or CO2, is often fed directly into the wells (Romanov and Less 2022, 112727). In such direct deep systems enhanced geothermal system set-up is often used, meaning that two boreholes are connected in the depths by creating new or widening old fractures in the rock through which the fluid can travel from feeding to production borehole (Romanov and Less 2022, 112727). Different geothermal heat depths and heating solutions are summarised in Figure 20.

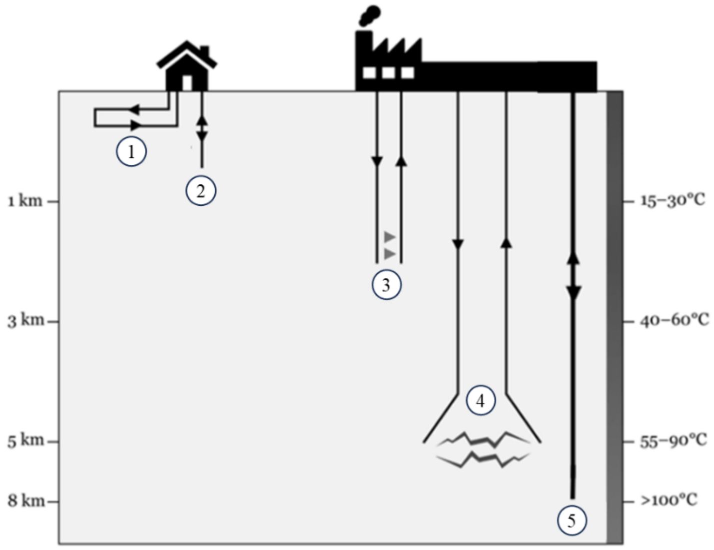

Figure 20. Geothermal heat in different depths. 1. Horizontal ground source heat, 2. vertical borehole ground source heat, 3. medium deep geotthermal heat with two boreholes and a HP, 4. deep enhanced geothermal heat system, 5. deep single borehole system. Modified figure, original source: Seismologian instituutti n.d.

In medium deep and deep heat wells drilling is the key challenge and key limiting factor in scaling up the technological penetration (Romanov and Less 2022, 112727). Indeed, practically all Finnish pilot projects with more than 1 km depths have faced considerable difficulties (GTK 2022). In addition, the cost of drilling may represent majority of the total costs. Based on benchmarking by Romanov and Leiss (2021, 349) the cost of drilling was 2-2,3 €m/km in early 2020s, whereas LCOE from deep reference system in Germany came with wide range of hundreds of euros being beyond (>>100 €/MWh) typical DH tariffs in Finland. The large cost range is underlined by uncertainties in production capacity and annual energy yield after completion (Romanov and Leiss 2021, 349). Medium and deep geothermal heat projects come with significant risks as at the time of drilling there is no certainty that the wells are suitable for heat production. In addition to the drilling challenges, costs and production uncertainties, the deeper systems have also long, typically 5-7 years, development periods (Romanov and Leiss 2021, 349).

In Finland in Espoo two 6,4 km deep wells have been drilled with the purpose to utilise the enhanced geothermal system set-up for DH use (GTK 2022). The temperature at the bottom is 120 °C, but the energy yield remained too small for commercially viable DH use as too little amount of water was flowing through the fractions between the wells (St1 2023). Another deep exploration was made in Tampere, where 15 energy companies tried to drill one 7 km well, but drilling difficulties forced to stop at 2,2 km (Mansikka 2023).

In addition, there are some medium deep solutions and companies offering medium deep (1-2 km) solutions with coaxial heat exchangers and heat pumps for additional temperature increase (QHeat 2023a). There are several such systems in Finland, but these are primarily not DH production units. One reference is a regional low temperature heating grid connecting six block houses with 14 000 sqm and 250 apartments that have 0.5 MW heat load and 1.9 GWh annual heat consumption (QHeat 2023b). There are three medium deep wells and a heat pump facility covering the whole heating need (QHeat 2023b). One well represents net energy of ca. 650 MWh p.a. incl. HP electricity. This represents ca. 27 times the heat available from one 300 m well discussed in section 3.2.4 .

Similarly, in Kajaani's context to cover 20 % of the annual DH demand, the estimated borehole amount would be 93 and the total drilling amount 186 km (2 km per well). The amounts with 300 m wells would be 2500 and 750 km. This underlines much better feasibility and potential of medium and deep geothermal heat for DH, should the technical and commercial uncertainties be solved. However, from Loiste's perspective the deep solutions are regarded too immature (no commercially viable solution in Finland yet). Also, the medium deep solutions are regarded to have a too high technical and commercial risk level, in addition to high investment cost (>100 €m to cover 20% of demand).

3.6 Small modular nuclear reactors

Small modular reactors ("SMR") are defined by the International Atomic Energy Agency (2023) as "advanced reactors that produce electricity of up to 300 MW(e) per module, have advanced engineering features, are deployable either as a single or multi-module plant, and are designed to be built in factories and shipped to utilities for installation as demand arises". Since electricity in nuclear plants is produced in turbines driven by thermal energy that is released in the nuclear reaction, SMR's could also be used directly for CO2-free heat production.

Compared to conventional large nuclear power plants, the key benefits of SMRs' are production flexibility, passive safety systems providing enhanced safety, lower upfront investment and suitability to non-electric and cogeneration applications like DH (IAEA 2023). Pursiheimo, Lindroos, Sundell, Rämä and Tulkki (2022, 80-91) studied SMRs in the context of district heating in the capital region of Finland, and their analysis support SMRs' theoretical relevance and competitiveness in a modern DHS. Nevertheless, Pursiheimo et al. (2023, 91) underline that SMR technologies are not mature yet.

Indeed, despite promising fundamentals SMRs are under technical development, and there are currently only a few pilot plants existing in the world, whilst around 80 technical designs and concepts have been proposed (IAEA 2023). The nuclear industry is heavily regulated, but the SMR specific regulation is still under its way in most jurisdictions, like in Finland where current legislation does not allow heat use of nuclear energy (Pursiheimo et al. 2022, 91). Heat use would require a location close to population. Even on a global scale, there is no modern SMR licensing framework or experience as such (Pursiheimo et al. 2022, 91). Due to the technological maturity, juridical status, uncertain costs and timeline to commercialisation, SMRs are currently not regarded relevant for DHS in Kajaani.

4 Combustion-based heat production

Over the history of Finnish district heating, combustion of solid, liquid and gaseous fuels has covered vast majority of the heat production. Coal, peat, oil and natural gas have had their roles and times also in Finland, but their use has been declining and the main use in DH is expected to be limited to peak production already during 2020s. On the other hand, biofuel's role has been increasing and DH operators have made sizeable renewal investments to new biofuel boilers over the past 10-15 years. This has been enabled by the large Finnish forest industry sector that acts as a primary source of biomass fuels nationally.

Another strong combustion related characteristic in the Finnish DH context is the relatively extensive CHP production. This has coupled heat and electricity sectors especially in larger cities in Finland already in the past. The nature of this coupling is now changing as DH is shifting from electricity producer to consumer on back of the technologies discussed in previous paragraphs. Increasing share of RES electricity production has made new CHP investments difficult, while existing capacity has been diminishing. Uncertainties on availability of sustainable biomass and potential biomass emission regulation are decreasing attractiveness of both CHP and heat only solutions, while the development of electrified solutions has gone to opposite direction. Nevertheless, as seen in paragraph 2.2 combustion-based production still has a strong role in the Finnish DH in early 2020s.

Given the development towards sustainable energy systems, including DHS in Kajaani, this section focuses on biomass-based combustion. Focus is kept on production technologies, but also key biofuel fractions and flue gas treatment concepts are briefly discussed.

4.1 Key biofuels in Finland

Combustion of biofuels covers a significant share of DH demand in Finland. Wood fuels represent nearly 100 % of the used biofuels (Figure 21) and, as discussed in section 2.2.2 wood fuels covered 44 % of the total DH production in 2022. Due to Finland's large woody areas, the nation's efficient forest industry and proximity of Russian biomass resources, availability of wood fuels has been generally good across the country. However, increased consumption and current geopolitical situation has tightened the market as the imports from

Russia ended in 2022. The scarcity, among other factors, has raised concerns of true sustainability and availability biofuels. For instance, Jodeiri et al. (2022, 112156) concluded that combusting biomass-based fuels should not be regarded as a long-term solution for heating when also considering alternative uses for sectors that are more hard-to-abate.

Standard SFS-EN ISO 17225-1 divides wood fuels into primary, secondary and tertiary fractions (Alakangas, Hurskainen, Laatikainen-Luntama and Korhonen 2016, 66). Primary fractions cover biomass extracted directly from the nature, secondary refers to side streams and residues from wood processing industries, and tertiary refers to wood that has been discarded from use (e.g. recycled and scrapped) (Alakangas et al. 2016, 66). As can be derived from Figure 21, most of the use in DH belong to primary and secondary factions. Key properties of domestic main DH fuels are summarized in Table 3.

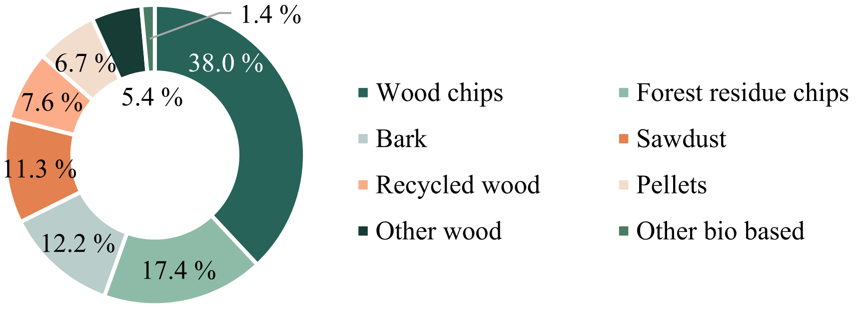

Figure 21. Split of consumed DH biofuels, including CHP production, in Finland in 2021. Black liquor is included in “other bio based” (data: Finnish Energy 2023a.)

Table 3. Key properties of selected domestic fuels used in DH production (data: Alakangas et al. 2016 and Motiva 2021).

	Lower calorific value (dry), MJ/kg	**Arrival state lower calorific value, MJ/kg**	**Humidity, m-%**	**Ash, m-%**	**Lower calorific v., MWh/m3**
Wood chips	18.5–20.0	~7–11	25–45	0.5–1.2	0.7–0.9
Forest residues	18.5–20.0	~6–9	25–65	1.3–6.0	0.6–1.0
Conifer bark	18.5–20.0	~5–9	40–70	1.7–3.4	1.2–1.3
Sawdust	18.9–19.2	~6–10	50–55	0.1–1.1	0.4–0.7
Recycled wood	18.6–20.7	n.a.	4.7–21.9	0.3–10.6	n.a.
Pellets	18.7–19.0	16.7–17.9	5.2–9.7	0.2–0.4	2.6–3.4
Milled peat	20.6–20.9	9.6–9.8	45.9–48.5	5.1–6.3	0.8–0.9
RDF	~17–37	~15–21	5–30	1–16	0.8–1.7

All the woody key fractions are loose fuels with varying piece size and properties namely depending on which part of the wood they are extracted from. Their calorific values for both dry mass and at humid arrival state are typically close to each other, although the arrival state varies relatively much due to varying humidity. Wood pellets are an exception. As compressed and dried fuel they come with higher calorific value at arrival state and standardized mechanical properties. From woody fuels pellets have exceptionally high energy density per volume enabling longer transportation distances. In general, dispatchability of biomass fuels are limited by logistical challenges like the distance and limited storing time (e.g. Jodeiri et al. 2022, 112156).

In addition to solid biofuels, biogas and bio-oils are used in small amounts in DH production. In DH production, including CHP production, use of these fuels amounted to 92 GWh (0,4 % of all biofuels) in 2021 (Finnish Energy 2023a). Within solid fractions use of other than wood-based biofuels are very limited in DH space. For instance, 66 GWh of herbal fuels were combusted in Finland in 2021 (Finnish Energy 2023a).

Although not biofuels, domestic peat and refuse derived fuels ("RDF") are often combusted in the same boilers. When combusted among biofuels, sulphur-rich peat helps to avoid boiler hot corrosion, whereas energy dense RDF is often cost-efficient addition to the fuel mix. Waste-to-energy is also commonly used for community waste in Finland. There is a waste-to-energy facility relatively close in Oulu and in Varkaus, where Kajaani's municipal waste is delivered and burnt (Riikinvoima Oy 2023).

Considering the above and local fuel market conditions in Kajaani, woody solid fuels are considered as primary sustainable options for potential combustion alternatives. All primary, secondary and tertiary fractions have already been used in Kavo earlier. (Saviniemi 2023.)

4.2 Biofuel combustion technologies

There are several combustion technologies for biofuels in gaseous, liquid and solid forms. Solid biomasses represent vast majority of the biofuel consumption in the Finnish DH context as discussed above. Compared to biogases and bioliquids, they represent availability and costs competitiveness in Kajaani's context. Hence, this section focuses on solid biomass combustion, for which key technologies include fixed bed grate furnaces, fluidised bed boilers and direct firing boilers for pulverised fuels (Vakkilainen 2017, Saidur, Abdelaziz, Demirbas, Hossain and Mekhilef 2011). While there are many utility scale designs, fluidised bed boilers have become the standard from 50 MWth upwards (Vakkilainen 2017, 212). This is largely driven by efficiency and fuel flexibility compared to the grate and direct firing boilers. Different fuel characteristics for the key technologies are summarized in Table 4. The key technologies will be discussed more in detail in the next chapters.

Table 4. Key characteristics of biofuels in a context of selected combustion technologies. Modified from Vakkilainen 2017, 21.

Biofuel characteristics	Grate	Fluidised bed	Direct firing
Fuel design flexibility	Low, designed for certain fuel	High, can burn several also simultaneously	Low, designed for certain fuel
Calorific value	>5 MJ/kg	Wide range	>15 MJ/kg
Moisture	30-55%, ~constant	0-70%, flexible	Almost dry, ~constant
Ash content	Low content required	Can cope with high ash content, but sensitive to low ash melting temperatures	Low, higher ash content can be sustained with larger furnace size
Volatiles	Not sensitive but designed for a certain range	Not sensitive but may impact number of fuel insertion points	Not sensitive
Particle size	>10 mm	1-100 mm	<1 mm

Burning solid biomass is a challenging combustion process. Biofuels often come with high moisture content but low ash content. However, the ash from biomass sources generally includes sodium, potassium and chlorine that form highly corrosive salts in the boiler and the corrosive effect is amplified as the ash typically has relatively low melting temperatures (Vakkilainen 2017, 212, Kwong and Marek 2021, 16319). Chlorine in biofuels form alkali chlorides (the salts) that stick to heat transfer surfaces in the boilers causing fouling that consequently amplifies hot corrosion and decreases heat transfer efficiency. Biofuels generally have low sulfur but high nitrogen content, and this causes some challenges in controlling NOx emissions (Vakkilainen 2017, 212). However, the low sulfur content increases risks related to the corrosion caused by the alkali salts as sulfur neutralizes the salts and causes the chlorine to flow away in the flue gases as hydrochloric acid (Alakangas et al. 2016, 201). To mitigate corrosion, agglomeration and fouling, sulfur injections or sulfur heavy fuel fractions (like peat) are often added to the biomass combustion process.

4.2.1 Grate boilers

Grate combustion is the oldest utility scale firing type and grate boilers are commonly in use also today. Solid biomass fired grate boilers in DH use are generally below 10 MWth, whereas larger units have been replaced by more efficient and flexible fluidised bed boilers since 1980s. (Vakkilainen 2017, 203.)

There are various grate boiler types, but in all variants, combustion occurs at the bottom of the furnace in fuel bed, under which the primary air is supplied from (Vakkilainen 2017, 203). Secondary and tertiary air is fed above the fuel bed (Vakkilainen 2017, 208). During the burning process the fuel travels through the grate, where it is fed, dried by the heat from burning fuel down the grate, combusted and finally ash is removed from the other end of the grate. Illustration of a mechanical inclined grate boiler structure is shown in Figure 22.

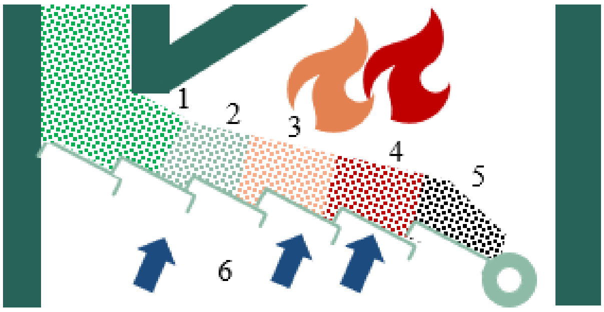

Figure 22. Biomass combustion in an inclined mechnical grate. Phases: 1) biomass feeding, 2) drying, 3) devolatilization (burning of volatile combounds), 4) char combustion, 5) residual ash removal, 6) feeding of primary air. Modified from Vakkilainen 2017 (209).

Grate boilers benefits from relatively simple and cost-efficient structures that allow burning various fuel types including low quality biomass fractions and peat (Vakkilainen 2017, 204). The key disadvantages include slow change in output power, low burning rate that requires large grate area, fuel specific grate design with relatively limited fuel flexibility after construction and high sensitivity to fuel quality variation as the burning process is sequential (Vakkilainen 2017, 203-209). Also, for instance Saidur et al. (2011, 2277) concluded that efficiency and techno-economic viability of biomass firing in grate boilers is limited compared to fluidised bed combustion.

4.2.2 Fluidised bed boilers

The working principle of fluidised bed boilers relies on a hot bed formed by inert medium (typically sand) through which air is blown. By increasing the air velocity, the bed's characteristics begin to correspond fluids. The fluidisation is further enhanced when the gas velocities increase along with higher temperatures due to the combustion. The fuel is fed on the hot bed, and the constant contact with hot solids causes the fuel to ignite and combust. Constant fluidised movement ensures enhanced fuel mixing, effective combustion, heat distribution and transfer. Biofuel particle's mass is typically in the range of 1-5% of the total solid bed mass. As such, the bed forms vast thermal capacity ensuring quick drying of the fuel and relatively constant combustion temperature. In addition to the primary air fed through the bed, secondary and tertiary air are fed above the bed (freeboard space) to ensure complete combustion. (Kwong and Marek 2021, 16303-16305, Vakkilainen 2017, 211-214.)

There are two main types for fluidised bed boilers: bubbling ("BFB") and circulating ("CFB"). In BFB the primary air fluidises the sand and forms bubbles in the bed, which remains at the bottom of the boiler with clear division level between the bed and the freeboard (Vakkilainen 2017, 215). Whereas in the CFB higher air and gas velocities cause the bed to hover and partly flow from the primary furnace to cyclone that separates the solid particles from flue gases allowing circulation back to the main furnace. Heat exchangers' order and placement in the boiler vary depending on the furnace design driven by targeted fuel mix and hot water or steam output temperature and pressure (Vakkilainen 2017, 212). Illustration of main boiler structures of BFB and CFB boiler types are shown in Figure 23.

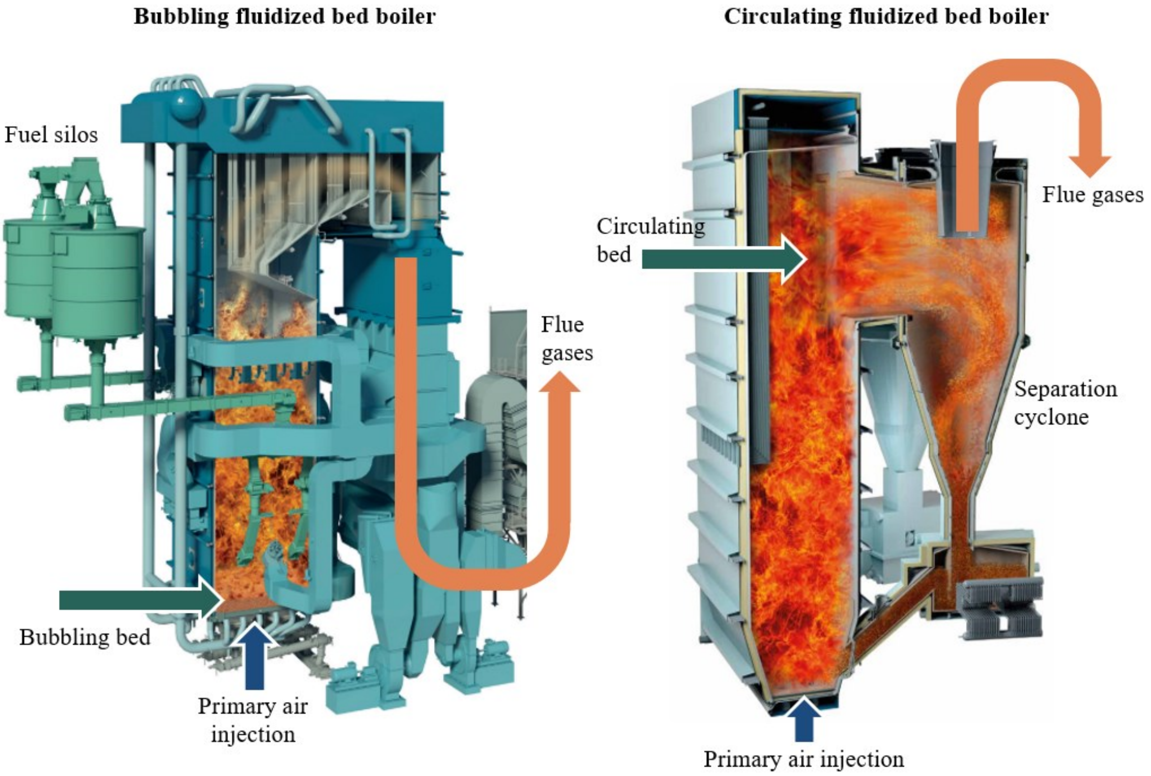

Figure 23. Illustration of BFB and CFB boiler types. Modified from Valmet Oyj 2023a-b.

From the two types CFB has larger process energy consumption, and it is generally applied in larger installations than BFBs. BFBs generally have better unit cost efficiency in the range of 20-300 MW (Vakkilainen 2017, 212). For instance, a Finnish boiler manufacturer Valmet markets BFBs in the range of 20-400 MWth and CFBs from 30 MWth to 1200 MWth (Valmet Oyj 2023a-b). While both types have around 90 % boiler efficiency (e.g. Valmet Oyj 2023a), CFBs have generally better combustion efficiency due to enhanced combustion air and bed circulation (Kwong and Marek 2021, 16305). For reactive fuels like most biomass fractions also BFBs provide highly efficient combustion (Kwong and Marek 2021, 16305). Due to this and lower unit investment costs compared to CFBs, BFB is often the preferred choice for biomass firing especially when only heat is produced in a moderate scale (Kwong and Marek 2021, 16305).

Key benefits of fluidised beds are possibility to burn different fuel fractions simultaneously, flexibility to burn low grade and moist fuels, high energy efficiency, effective sulphur removal and low NOx emissions (Vakkilainen 2017, 212, Kwong and Marek 2021, 16303). Heat capacity and steady temperatures of the fluidised beds also mitigate the challenges related to the corrosion and ash melting caused by the sulfur poor but chlorine rich fuels (Vakkilainen 2017, 212). However, Kwong and Marek (2021, 16319) note that the chemical composition of biofuels still cause challenges due to the bed agglomeration that may lead to hot spots and defluidisation. Other downsides include high investment and operating costs, particle emissions and ash accumulation (Kwong and Marek 2021, 16304). Nevertheless, due to the benefits fluidised bed boilers are well fitted for biomass combustion and they have been largely adopted to use in the energy industry for decades already.

In the Kajaani context, fluidised bed boilers represent potential combustion-based technologies due to the scale of the production capacity need and availability of local biofuels, for instance. However, this would mean in practise renewal of the current combustion-based production portfolio at least partly without mitigating risks related to the biomass costs and availability, future emission treatments and lower cost efficiency improvement potential. Hence, although the DH load is currently largely covered by the existing CFB CHP, a production portfolio primarily based on a large, fluidised bed boiler is not identified as a primary option for the future DHS in Kajaani. Nevertheless, several Finnish utilities have invested in such in recent years. For instance, a new 190 MWth CFB was constructed in Lahti in 2020 (Lahti Energia Oy 2023), an investment to a 150 MWth coal to wood pellet BFB conversion in Helsinki was announced in 2023 (Helen 2023c) and a new 220 MWth biomass fired CFB was commissioned in Helsinki in late 2022 (Helen 2023d). Both CFBs in Lahti and Helsinki are producing only heat but have readiness for a steam turbine for CHP production (Lahti Energia Oy 2023, Helen 2023d).

4.2.3 Direct firing of pulverised fuels

Direct firing of biomass can be applied when dry fuel is fed in small enough particle size (<1 mm). In biomass context this is applicable namely to pellets that can be pulverised in a hammer mill and injected as dust to direct flame for combustion in a boiler. Direct fired pellets represent cost efficient replacement alternative to direct fired fossil fuel boilers, and the technology has been tested in various boiler variants up to 60 MW. Illustrative set-up of a direct biomass firing plant is shown in Figure 24. (Vakkilainen 2017, 203.)

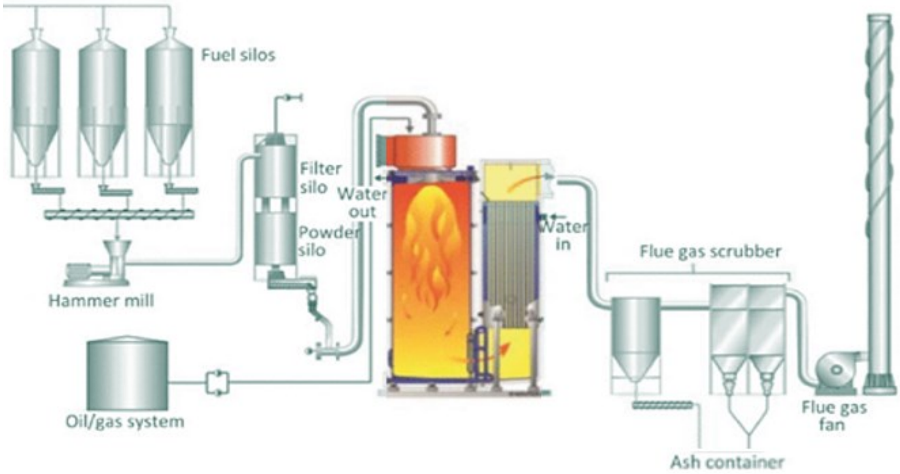

Figure 24. Pellet direct firing plant with burner(s) on top of the furnace. The burners could locate also on the sides of lower half of the furnace. Modified from Vakkilainen 2017 (204).

The benefits of direct pellet firing are high and fast controllability, quick startup, low investment costs, easy remote controlling and hot flame with efficient combustion due to dry fuel with high calorific value (Vakkilainen 2017, 204). Challenges relate namely to fuel availability, fouling and ash handling. For instance, Pronobis, Wejkowski, Kalisz and Ciukaj (2023, 125442) concluded recently that conversion of pulverised coal to biomass boiler may cause operational challenges due to fouling and resulting accelerated corrosion. Pulverised fuel boilers are designed for a certain fuel with low flexibility.

Regardless of the potential challenges direct pellet firing, especially in conversion applications, is regarded an efficient well-functioning solution, and based on Vakkilainen (2017, 204) they have started to gain popularity as peak and backup capacity in connection with larger (CHP) boilers. Loiste has currently considerable 76 MW fuel oil boiler capacity in four units in its peak and backup plant Palokangas (Finnish Energy 2023a). These units are potential for pellet conversion. Due to pellet price premium compared to other wood fuels and availability uncertainty in Kajaani, the pellet conversions are primarily considered competitive solutions for peak and mid-load capacity.

4.3 Flue gas treatment

Removing hazardous pollutants and recovering heat from the flue gases is an integral part of any combustion plant investment today. Flue gas treatment process is designed as part of the whole boiler plant design and carried out in various phases of the combustion process. Generally, the flue gases are treated to remove particles, acid gases and ammonia, whilst CO2 capturing has also started to emerge. From flue gas treatment technologies flue gas condensers ("FGC") are widely adapted and suitable for variety of plant, process and fuel designs. Although not removing CO2 from the flue gases, they are effective for their original purification purposes while unlocking significant waste heat recovery potential.

4.3.1 Flue gas condensing

Flue gas scrubber or condenser is used to 1) decrease the amount of acid gases like SOx and NOx, ammonia, heavy metals and particulates in the flue gases and 2) recover energy (Valmet Oyj 2023c). When entering the FGC, the flue gases are typically at a temperature of around 150 °C, sometimes even more (Terhan and Comakli 2016, 1007). While energy can be recovered by decreasing the gas temperature, the hot flue gases also include significant amounts of water vapor that can be condensed. The vapor is resulting from the burning and fuel moisture. Capturing this sensible and latent heat can increase the overall energy efficiency significantly as generally up to 30 % more heat can be obtained from the same fuel amount with flue gas condensing (Valmet Oyj 2023c, Lepiksaar, Volkova, Ruseljuk and Siirde 2020, 26). This means that the plant efficiency with FGC can be above 100 % when calculated from the fuel inputs' lower calorific values.

While there are several FGC designs, FGC can also be set only for heat recovery. The process is commonly wet, in which the flue gases are sprayed with a mixture of water and chemicals depending on the flue gas cleaning needs. With direct contact to the mixture the flue gas temperature decreases eventually reaching the dew point and resulting in condensation simultaneously as the unwanted impurities are dissolved and neutralized. In DH applications the DH return water is used as a heat sink and the flue gas exit temperature is close to the return temperature (Lepiksaar et al. 2020, 30). Heat pumps can be used to further decrease the temperature as is the case in the new biofuel CFB in Helsinki where the exit temperature can reach as low as 11 °C (Helen 2023d). For this specific plant a total fuel efficiency of 122 % and final vapor content of <1 %-m are mentioned (Helen 2023d).

Due to the condensation driven principle, FGC's energy efficiency benefits can be realised the best with moist fuels like wood chips and other biofuels (Lepiksaar et al. 2020, 26). In the biofuel heavy Finnish DH sector, FGCs already have significant role. According to Finnish Energy (2023b) heat recovery and heat pumps' output represented 10 % of the total fuel volume in DH and DH related CHP production in 2022. Direct heat exchanger recovery covered 71 % (3.5 TWh) of it and FGCs cover majority of the stake (Finnish Energy 2023). Also, for the DHS in Kajaani FGC represents attractive technology from operational, environmental and financial perspective if the future production portfolio includes biofuel boiler capacity targeted for base load use. The existing CHP does not currently have a FGC.

4.3.2 Carbon capturing

Despite large emissions at the time of burning, biomass combustion is currently treated as CO2-free in the EU as discussed in paragraph 2.2.4 Tightening emission regulations, EU taxonomy and genuine concern on emissions has created momentum for a carbon capture and permanent storage ("CCS") and a carbon capture and use ("CCU") in connection to fuel combustion. These technologies could provide a route to retain conventional combustion-based production while reaching sustainable emission levels regardless of used fuel and its regulatory emission treatment. For instance, there are plans to build a large CCS facility to the DHS in Oslo, Norway (the City of Oslo 2022). The facility would remove 17 % of the city's emissions by removing 400 000 tonnes of CO2 annually from the flue gases of a local waste-to-energy plant (the City of Oslo 2022). In Finland, CCU is elemental for most of the planned PtX projects as they are based on capturing biogenic CO2 from DH production facilities as discussed in section 3.3.3 CCS and CCU are not covered more in detail in this research as they fall beyond the scope of DH production renewal investment in Kajaani. Should the local DH operator decide to invest in a large-scale combustion boiler, CCS and CCU could create further opportunities, e.g. in PtX, and the topic should be revisited.

5 District heating system in Kajaani

DH is the incumbent heating method in urban areas of Kajaani. DH supply started in Kajaani in 1974 (Finnish Energy 2023a). In 2022 the total DH production was 310 GWh (Saviniemi 2023). Loiste delivers DH to ca. 1 700 customers (Loiste 2022a). Residents heated by DH covered 69 % of the population in Kajaani in 2021 (Finnish Energy 2023a). In addition to DH, the Kavo CHP produces also steam for industrial customers in the area (Kavo 2022a).

5.1 Current production capacity

Majority of the heat in Kajaani is produced in the Kavo CHP plant burning domestic biofuels and peat (Loiste 2022a, Kavo 2022a). Coal and oils can be used as spare fuels (Kavo 2022a). The boiler is circulating fluidised bed boiler (Kavo 2022a). The plant's total output capacity is 203 MW, of which 40 MW can be taken as electricity and the rest as heat and steam (Finnish Energy 2023b). The plant's design is sized beyond the current use due to the paper mill closure in 2008. The CHP was built during 1987-1989 (Kavo 2022a) and hence is now reaching the end of its techno-economic lifetime.

In addition, Kavo owns a light fuel oil ("LFO") fuelled 120 MW spare boiler as well as a heat accumulator. Loiste itself owns seven LFO fuelled peak boilers with a total capacity of 76 MW. These are all built in 1970s-1990s. The DHS has also access to primed waste heat from a third-party owned data centre from which maximum DH output is 8 MW. In 2022 Loiste produced 0.5 % of the DH in its own LFO boilers, while the rest was purchased from Kavo and other third-parties. (Loiste 2023a, Kavo 2022a, Finnish Energy 2023b)

5.2 Network characteristics

Loiste owns and operates the local DH network in Kajaani, and it covers all key areas in the city centre (Saviniemi 2023). The network has a length of ca. 130 km (Loiste 2022a). Network losses represent ca. 11 % of the total DH production (Finnish Energy 2023), and that is used as an assumption in this research. To decrease the losses and increase potential to utilise waste heat sources and production efficiency, Loiste has studied a possibility to decrease DH supply temperatures. With the current network and customer base Loiste has estimated that it can decrease the temperatures by ca. 5-10 °C when the outside temperature is below +5 °C (Saviniemi 2023). Summertime temperature (73 °C) cannot be decreased due to a risk of legionella bacteria (Saviniemi 2023). Temperature control curves are presented in Figure 25. This research applies the lower curve.

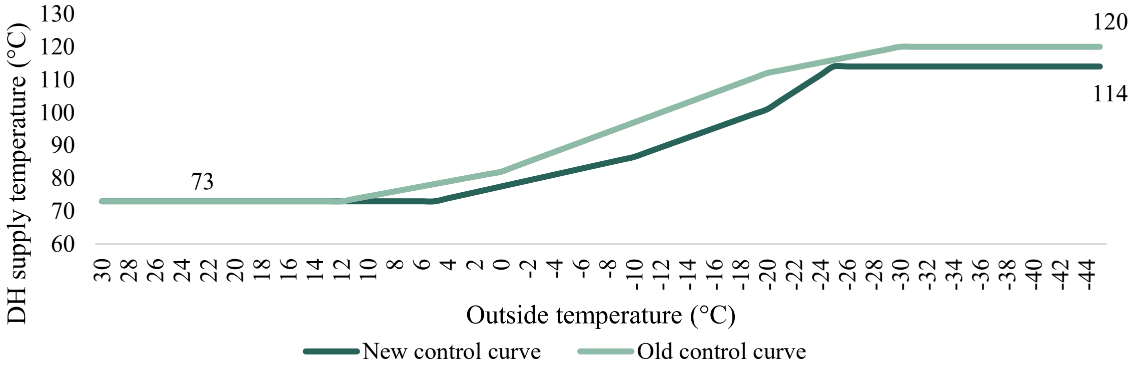

Figure 25. Old and new DH supply temperature control curves in Kajaani.

5.3 District heat demand

Weather normalized DH volumes have increased in history in Kajaani, but actual DH volumes have stabilised in recent years driven by increasing average outside temperatures, increase in building stock’s energy efficiency and customer base development (Saviniemi 2023). These have been assumed as DH demand drivers. The related detailed long-term assumptions are summarised in Appendix 1. The drivers result in overall DH demand CAGR of -0.6% for the 25-year modeling period. However, it was elemental that any chosen portfolio alternative would stand also slightly increasing volumes.

For this research weather normalized DH demand has been assumed to be 319 GWh for 2023 being the first year for demand projection. Historical DH volumes in Kajaani are shown in Figure 26. Annual hourly profile for the first operational year as an example is shown in Figure 27, whereas additional further demand driver details are shown in Appendix 1 and 2.

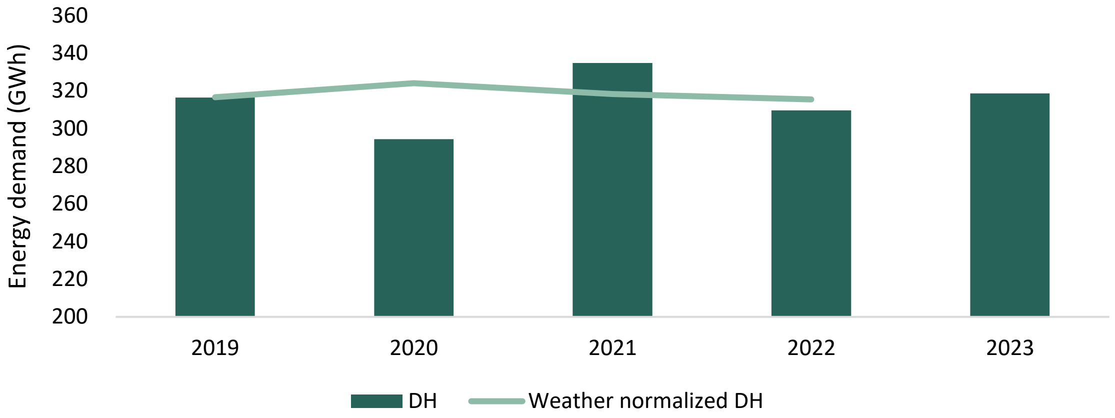

Figure 26. Actual 2019-2022 and projected 2023 DH demand in Kajaani including network losses. DH normalization is made against average heating degree days 2008-2022. Historical data source: Loiste 2023b, Finnish Energy 2023a-b.

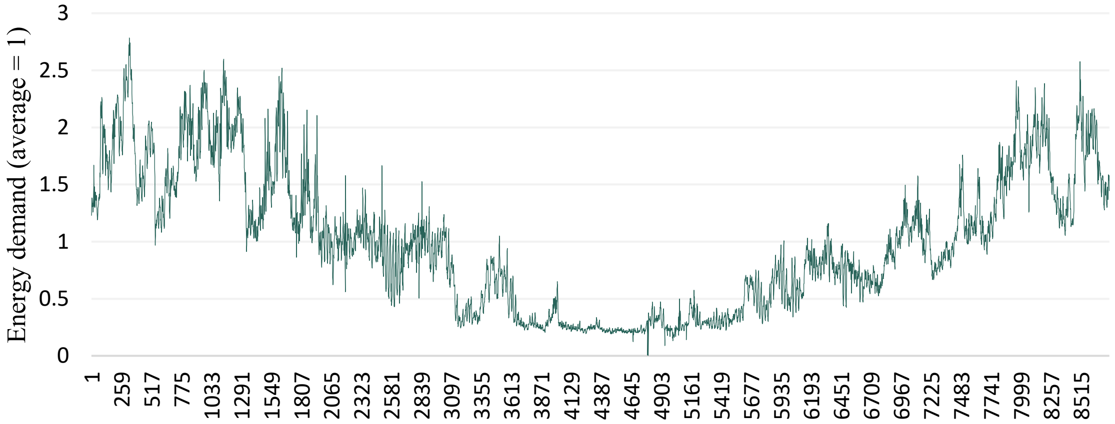

Figure 27. Projected hourly DH demand profile in Kajaani during the first simulated operational year. The profile is based on 2021 realisation (Loiste 2023b), but annual volumes are projected independently. Values are relative where annual average is one.

5.4 Potential production methods

Based on the technology descriptions and preliminary qualitative feasibility assessments made in sections 3 and 4 the most potential production methods for Loiste were identified. These include biomass fired boilers with turbine (CHP) or without (HOB), pellet direct firing boiler ("DFB"), data centre waste heat, electric boiler and heat pumps utilising ambient air ("AWHP") and wastewater ("WWHP") as heat source. Due to varying and large temperature differences compression heat pump is considered the most relevant type for AWHP, whereas more stable heat source wastewater would benefit from an absorption HP. Nevertheless, HP technology choice should be reconsidered in a more detailed design phase. For the bio boilers BFB and CFB are both considered relevant depending on the size in each scenario. On top of the new production capacity, existing LFO fired peak boilers were considered relevant peak and spare capacity especially if bio-oils are used. Also, Loiste has identified a suitable LFO to pellet HOB conversion opportunity among the existing boilers and the conversion is considered as the primary choice for a pellet solution (Loiste 2023b).

Of the discussed technologies medium deep and deep geothermal energy and nuclear based solutions were not considered to meet the required technology maturity level, cost and timeline horizon suitable for Loiste. GSHP was excluded due to limited suitability for DH use (e.g. capacity compared to required borehole amount). The potential for solar heat and surface waters was well recognized but their production is highly seasonal. In Loiste's context this means that those capacities are not largely available during a high demand season and, on the other hand, during the most potential months there is limited need for additional production on top of the DC waste heat given the low summertime load. This materially limits the potential for solar and ambient water heat in Kajaani. Finally, waste heat recovery potential in Kajaani relates namely to the DC and wastewater, whereas no other major sources had been identified by Loiste. As such, all these heat sources are excluded from further analysis.

All technologies have their limitations and for instance in Kajaani some limitations relate to the possibility to produce high enough temperatures for the DH network. These limitations are considered in connection with hourly DH water supply temperatures in the modeling that is discussed in paragraph 6 . To keep investment costs moderate and efficiency of heat pumps high, 85°C is considered as the maximum heat pumps' supply temperature. This applies also to the DC waste heat. It is assumed that HPs can contribute to the production mix also in times with higher DH water supply temperature by feeding heat to the DH return pipes in which temperature is relatively low and constant (40-50°C) throughout the year. However, in such case it is also assumed that sufficient thermal power is needed from technologies that can produce the remaining temperature increase need to reach adequate DH supply temperature. Characteristics and selected modeling assumptions of the selected production technologies are summarised in Table 5.

Table 5. Selected characteristics and applied assumptions for the heat production methods chosen for further analysis. Direct emissions represent emissions regardless regulatory treatment and are based on fuel classification by Official Statistics Finland (2023a). HOB and CHP assume FGC installation justifying the 100% fuel efficiency (per lower calorific value).

Technology	**DH availability**	**Steam availability (if ever needed)**	**Fuel efficiency assumption**	**New investments needed (“no” means exiting asset)**	**Direct CO_2 emissions per fuel input**	**Life-time, years**	**Weather dependent**
Bio HOB	Yes	Yes	100%	Yes	112.0 t/TJ	30	No
Bio CHP	Yes	Yes	100%	Yes	112.0 t/TJ	30	No
Pellet DFB	Yes	No	90%	Yes	112.0 t/TJ	30	No
Data centre (existing)	Yes (up to 85°C)	No	100% (purchased heat)	No	0	Not limited	No
Electric Boiler	Yes	Yes	100%	Yes	0	35	No
AWHP	Yes (up to 85°C)	No	60% of theoretical max. COP in each hour	Yes	0	25	Yes
WWHP				Yes	0	25	Yes
LFO HOBs (existing)	Yes	Only from Kavo HOB	90%	No	70.2 t/TJ	Not limited	No

6 Modeling of production alternatives

This section describes the utilised modeling approach to compare and assess the potential production portfolio alternatives, which were combined from the selected technologies considering the criteria and preferences listed in paragraph 1.2 .

6.1 Modeling approach

To address the research questions a modelling tool was created to investigate the portfolio alternatives. Given the long review period of 25 years and respective uncertainties in the development of, inter alia, fuel and commodity prices, emission regulation and DH demand, modelling flexibility and fast calculation times were set as prerequisites.

Optimising DH production is a complex problem and solving it requires accuracy and efficient computation. Latest academic research in the field has been focused on a mixed integer linear programming (MILP), which has also been adopted in the DH industry. MILP is accurate but regarded as a resource incentive and time consuming with long calculation times. Another largely used approach, especially in electricity generation, is a merit order calculation method (MO). MO is regarded as relatively simple with significantly faster calculation, but slightly less accurate compared to MILP. Both MILP and MO aim to define optimal production dispatch while minimising costs and considering various constraints. (Gonzalez-Salazar, Klossek, Dubucq, Punde 2023, 1262779-1262780.)

Due to the set modelling prerequisites, expected high number of different scenarios and sensitivities, MO modeling was chosen for this research. It is worth noting that research by Gonzalez-Salazar et al. (2023, 1262779) indicates that inaccuracy of MO is not significant in the context. To enhance the user experience and calculation transparency Mircosoft Excel was chosen as modelling platform. The created model as tailored for the specific problem is referred as merit order model (MOM) in this research. For appropriate granularity the MOM applies hourly resolution with annual inputs for 25 years using historical hourly profiles from 2019-2022 applied sequentially during the period. The historical hourly multipliers are applied to the annual average assumptions to derive inputs for each calculation hour. The MOM uses hourly profiles for outside temperature, DH load and electricity wholesale prices.

6.2 Merit order model

The MO approach is based on marginal costs (MC) of production assets at a given time. Based on ascending order of the MCs the assets are dispatched to meet the simulated demand at any time. The MC is defined as an additional cost of producing an additional unit of end-product, and it can be formulated as in formulas 1-3 (Gonzalez-Salazar et al. 2023, 1262781).

$$MC(Q) = \frac{d(VC)}{dQ} = \frac{d(C_{Input} + C_{CO2} + C_{O\&M} - r_{Electricity})}{dQ} \tag{1}$$

$$MC(Q) = \frac{d(p_{Input} \times F_{Input})}{dQ} + \frac{d(p_{CO2} \times k_{Input} \times F_{Input})}{dQ} + \frac{d(C_{O\&M})}{dQ} - \frac{d(p_{electricity} \times E)}{dQ} \tag{2}$$

$$MC(Q) = \frac{p_{Input}}{\eta_{th}} + \frac{p_{CO2} \times k_{Input}}{\eta_{th}} + SC_{O\&M} - p_{Electricity} \times \lambda \tag{3}$$

Where Q is heat production [MWh], VC is variable cost [€], C_{Input} are fuel or other energy input costs [€], C_{CO2} is carbon dioxide emission allowance costs [€], $C_{O\&M}$ is variable operations and maintenance costs [€], $r_{Electricity}$ is electricity revenue [€], P_{Input} is fuel or other energy input price [€/MWh], F_{Input} is respective energy input [MWh], p_{CO2} is emission allowance price [€/ton CO$_2$], k_{Input} is a specific CO$_2$ emission factor [ton CO$_2$/MWh], $p_{Electricity}$ is electricity price [€/MWh], E is electricity generation [MWh], η_{th} is thermal efficiency of the underlying asset, $SC_{O\&M}$ is specific variable O&M cost [€/MWh], λ is power-to-heat ratio for CHP assets.

In the MOM MC is calculated separately for each hour for each asset to determine the merit order and respective dispatch volumes. Dispatching is sized based on simulated hourly demand for DH including distribution losses. The formula 4 forms the economic dispatching task used in the MOM. It defines production volume for each asset in any given hour.

$$\min_{VC_h} \sum_{i=1}^{n} (MC_i \times Q_i),\ subject\ to\ \sum_{i=1}^{n} Q_i = \text{total DH demand} \tag{4}$$

Where VC_h is variable cost for each hour h, MC_i marginal cost for production method i and Q_i is production volume for production method i.

In addition to the MCs, certain operative constraints like annual maintenance breaks are considered. Constraints are further detailed in paragraph 0. Finally, the hourly dispatch volumes are used to calculate variable net costs (including electricity production revenue if any) for each year. Yearly variable net costs are then added to annual fixed costs and maintenance investments. Also, corporate income tax shield based on the annual costs and depreciations is considered to determine annual free-cash-flow, which is used as a basis for financial comparison. Annual total cost (TC) and free-cash-flow (FCF) formulas 5 and 6 are shown below. The free-cash-flow here refers only to production related cash flows excluding any revenue other than CHP electricity generation. The revenue is assumed to be same regardless of chosen production portfolio. Schematic summary of the modelling approach is shown in Figure 28.

$$TC_y = \sum_{i=1}^{n} \sum_{h=1}^{8760} (MC_{ih} \times Q_{ih}) + FC_y \tag{5}$$

$$FCF_y = -TC_y - MI_y - \Delta NWC + \left(TC_y + D\&A\right) \times CIT \tag{6}$$

Where subscript y refers to year, i and h refer to production method i and hour h respectively, FC is total fixed costs, MI is maintenance investments, NWC is net working capital, D&A are depreciations amortizations, and CIT is corporate income tax rate (20%).

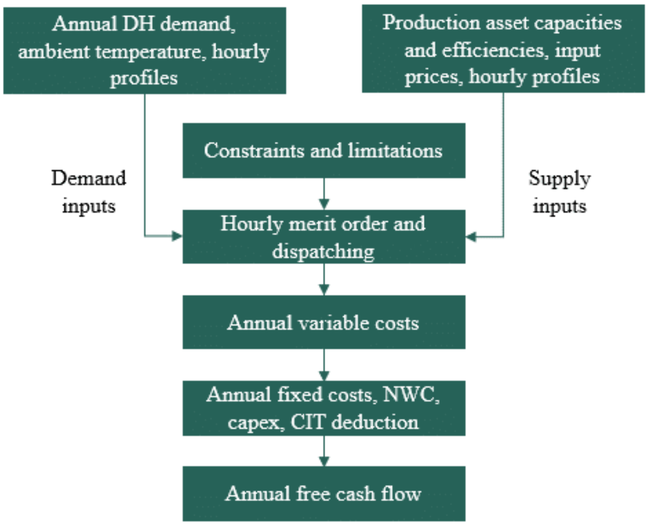

Figure 28. Schematic illustration of the MOM calculation flow.

6.3 Production portfolio alternatives

From the potential production methods five portfolio alternatives were compiled for detailed analysis. The alternatives were divided into combustion, hybrid, and electrified scenarios to provide broad comparison with different levels of non-combustion-based production. Combustion and hybrid scenarios were further divided into HOB and CHP based.

6.3.1 Production capacity sizing

Non-weather dependent new capacity was sized to cover 95 % of the DH demand hours in 2019-2022 persistence curve. 100 % was not chosen to avoid over investing given the existing peak boiler and heat accumulator capacity, as well as potential to use DH network as a short-term heat storage, although this was not included in the MOM. Investing less than 95 % coverage was regarded as a security of supply and emission risk during colder periods.

Capacity limitations were identified for pellet boiler, WWHP and DC. The pellet boiler investment would be a conversion from existing LFO fuelled peak HOB and the existing site and equipment sets 20 MW capacity requirement for the new pellet boiler (Loiste 2023a). The pellet conversion is a cost-efficient solution meeting also most other criteria, so it is included in all alternatives. WWHP relies on local wastewater flows and temperatures and 5 MW output from WWHP was identified and calculated as a relevant maximum as per paragraph 3.3.1 . The DC is an existing asset with DH capacity of 8 MW.

To limit electricity price risk and overinvesting, electric boiler’s size was limited so that it would not alone cover more than 30 % of the historical DH persistence curve in portfolios with HOB or CHP capacity. In portfolios with no HOB (other than pellet) or CHP capacity this limitation was not applied. AWHP is fully scalable and modeling iterations were used to find financially feasible sizing. Both AWHP and WWHP are sized based on maximum output with 4.0 COP, meaning that modelled maximum HP compressor power is 25% of the maximum output. COP is rarely at maximum, so the simulated DH output typically falls below the maximum output.

Finally, biomass fired HOB and CHP capacities, and electric boiler in case of the two technologies were not included in the portfolio alternative, were defined to cover the remaining thermal power compared to the 95 % persistence curve coverage. The selected production methods and respective capacities for each portfolio alternative are summarized in Table 6. The table also shows total investment costs for each scenario in relative values.

Table 6. Summary of selected production capacities and investment amounts in analysed portfolio alternatives. In addition to below, the MOM assumes that the existing LFO peak HOBs are kept in place to the extent not converted to pellet boiler capacity.

Capacities (MW)	**1.Combustion HOB**	**2.Combustion CHP**	**3.Hybrid HOB**	**4.Hybrid CHP**	**5.Minimum combustion**
Data centre	8.0	8.0	8.0	8.0	8.0
Pellet DF boiler	20.0	20.0	20.0	20.0	20.0
Bio HOB	44.7	-	24.5	-	-
Bio CHP, DH	-	44.7	-	24.5	-
Electric boiler	-	-	20.2	20.2	44.7
AWHP	-	-	15.0	15.0	27.3
WWHP	-	-	5.0	5.0	5.0
Total (DH)	**72.7**	**72.7**	**92.7**	**92.7**	**105.0**
Total non-weather dependent (DH)	**72.7**	**72.7**	**72.7**	**72.7**	**72.7**
El. generation capacity	-	11.2	-	6.1	-
Relative capex	**1.2**	**2.2**	**1.2**	**1.6**	**1.0**

CHP’s electricity generation capacity was sized with fixed 25 % power-to-heat ratio. The ratio was set relatively low to limit capex in operating environment where profitability of CHPs’ back-pressure electricity generation has generally declined in recent years while availability of wind and solar power has increased. Nevertheless, the 2022 burst energy crisis and high electricity prices underline the relevance of also analysing CHP alternatives more in detail. Power-to-heat ratio (PHR) is defined in formula 7.

$$PHR = \frac{P_{el}}{P_{th}} \qquad (7)$$

Where P_{el} is electric output power of CHP unit and Pth is DH output power of CHP unit.

6.3.2 Applied operative assumptions and limitations

Technology specific operative limitations are considered in the MOM to increase reliability and relevance of the results. The limitations were set based on the technology characteristics discussed earlier. Also, annual maintenance breaks were scheduled to ensure the demand can be satisfied also during those. The operative limitations and production breaks are summarized in Table 7. If no fixed service window is defined, the assets are assumed to be maintained during down-time periods resulting from the merit order.

Table 7. Summary of operative constraints applied in the MOM.

Constraint	**Bio HOB**	**Bio CHP**	**Pellet DFB**	**DC**	**El. boiler**	**AWHP**	**WWHP**	**LFO HOBs**
Annual maintenance	August, 2 weeks	July, 3 weeks	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic
Min. down time	72 hours	120 hours	0 hours	0 hours	0 hours	0 hours	0 hours	0 hours
Min. up time	24 hours	48 hours	0 hours	0 hours	0 hours	0 hours	0 hours	0 hours
Min. capacity	20 % of max.	20 % of max.	>0 MW	>0 MW	>0 MW	>0 MW	>0 MW	>0 MW
Max. DH supply *T*	>120 °C	>120 °C	>120 °C	85 °C	>120 °C	85 °C	85 °C	>120 °C
Min. *T* sink-source difference	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	5 °C	3 °C	Not applicable
Outside *T* operation limit	No limit	No limit	No limit	No limit	No limit	-20 °C	No limit	No limit

There are certain limitations for production based on combustion (excluding pellet conversion) to reflect lower flexibility of larger boilers compared to electrified and peak boiler capacity. The inflexibility comes from required firing time and time required to ramp down and cool the boiler before firing again. The minimum down time limitation refers to hours the facility needs to remain unused if there is a ramp down and vice versa for minimum up time. The MOM determines HOB and CHP ramp down and up timings based on a forward-looking average marginal cost compared to volume weighted average production cost of other capacities available considering merit orders. For instance, the model shuts HOB for 72 hours if at any hour and during the following 72 hours weighted average production cost is lower if the energy was produced by other units available. Similarly, it is fired again should the total cost be lower with HOB during any hour and the following 24 hours. This prevents showing calculation benefits from unrealistic combustion-based production alteration. Larger boilers also have capacity limitations as they have minimum load below which they cannot go. This research assumes high flexibility by assuming minimum load of 20 % of the maximum output for HOB and CHP. If the load was below the minimum capacity, the MOM would assume excess production to be lost (auxiliary cooling) while including the costs.

To avoid combusting LFO in peak boilers to the extent technically possible, the merit order for them is set to be the last one. While this has small cost implications (LFO may be cheaper than electricity in certain hours), this reflects the ambition to utilise as sustainable heat production methods as possible.

For HP solutions the limitations refer namely to temperatures. In addition to the maximum output temperature of 85 °C, also temperature differences between HP and heat source and sink have been required. This means that the MOM assumes temperature difference between HP's evaporator and heat source and similarly between condenser and heat sink. These are due to heat transfer inefficiencies. For AWHP minimum outside operating temperature of -20 °C is applied due to the increasing need of melting the evaporator and large temperature difference between the heat source and sink resulting in low performance. Table 5 mentions that for HP solutions maximum COP of 60 % of theoretical maximum is applied for each hour. The 60 % was chosen based on expectation of not reaching annual volume weighted average COP beyond 3.0 (iterated in the MOM). COP for each hour is calculated as in equation 8 below.

$$COP_h = \frac{T_H}{T_H - T_C} \times 0.6 \tag{8}$$

Where COP_h is applied heat pump COP in hour h, T_H is temperature of heat sink and T_C is temperature of heat source.

6.3.3 Financial assumptions

The MOM applies a set of financial assumptions first to determine the merit order and variable costs for each hour and finally to derive annual free cash flows and profitability metrics to enable comparison between the alternative portfolios. Key assumptions are summarized in Table 8. The assumptions and their logic are elaborated below.

Determining the MO is based on variable costs that namely relate to fuel and commodity prices. Indexed (2023=1) development of key commodity price assumptions are shown in Figure 29. Biomass refers to other than wood pellets and is considered as a blended mix of woody biomass fractions that are expected to be utilised. These are largely chipped and crushed forest residues, recycled wood and small diameter energy wood. This has also been considered in the price assumptions together with the DH company.

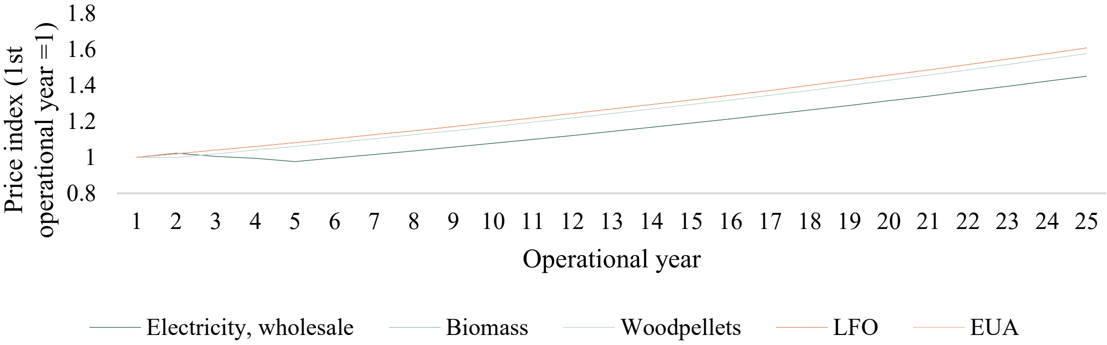

Figure 29. Indexed key commodity price assumptions. Biomass, LFO (including excise tax and emission costs) and EUA are inflation driven and the chart lines are one on the other. Electricity price is annual arithmetic average but the MOM applies also the hourly profiles.

In addition to the fuel price, risk of change in regulatory treatment of biomasses is considered in the modelling through emission costs. The share of mixed biomass subject to EU emission allowances is assumed to increase linearly from zero in 2029 to 50 % in 2050. For generated and consumed electricity transmission fees and taxes have also been considered in addition to the wholesale price. Heat pumps and electric boilers for DH production are assumed to remain in lower electricity taxation class as in 2023. Electricity taxes, grid and balance responsibility fees are assumed to be in total 2.31 €/MWh for electricity generation (CHP) and 3.25 €/MWh for electricity-based DH production assets in 2023 (data sources: Fingrid Oyj 2023, Verohallinto 2023). DH network pumping and other process electricity is not modelled as no material differences between the alternatives are expected. CHP electricity generation income is deducted from the costs in the FCF calculation. Furthermore, the MOM assumes that purchased waste heat from the DC is priced based on alternative costs (MC of other heat sources) so that it is utilised as much as possible. Nevertheless, a minimum price is applied e.g. not to result in negative pricing during hours with negative electricity prices.

On top of these hourly costs annual fixed cash costs are added. The fixed costs include maintenance costs and resources and services needed to operate the production facilities. Fixed costs for each scenario were estimated with Loiste and have been benchmarked against industry wide performance indicators as published by the Finnish Energy (2019). The fixed costs are summarized in Table 8 and for each scenario in Table 9.

To calculate the FCF, corporate income tax shield is calculated based on the total net costs and depreciations. For the implied tax shield depreciations are assumed to be in line with book depreciations. No changes in net working capital are assumed.

The initial investment is assumed to be paid 100 % at the end of the year prevailing the first operational year. Loiste has been granted an investment aid of 5.4 million euros and this has been deducted from the assumed total investment costs for portfolio alternatives 3-5 as they are considered to fulfil the investment aid requirements (Loiste 2023b).

Finally, as some of the assets are assumed to have technical lifetime beyond the 25-year period, terminal value has been applied. It is calculated as a sum of remaining technical values for each asset at the end of the last modeling year. The technical value is determined as a share of the remaining lifetime at year 25 times the inflated initial investment cost.

To account for time value of money, a discount factor based on a weighted average cost of capital (“WACC”) is used for determining net present values (“NPV”) of the total cash flows over the 25-year period for each alternative. WACC parameters are based on the author’s experience and database maintained by professor Damodaran (2023). The WACC inputs are set to represent expected stable long-term market conditions and risk profile for utilities like Loiste, although they do not necessarily represent Loiste’s actual financing cost at any given time or overall capital market conditions at the time of writing. In the MOM a nominal post-tax WACC is applied. Details of the WACC factors are available in Appendix 4.

Table 8. Summary of key financial assumptions applied in the MOM.

Item	Assumption	Comment
Investment period	25 years after the commissioning	1st operational year 2026
Discount factor	Nominal post-tax WACC	See Appendix 4. Parameters based on public market data
Capex	Based on preliminary supplier offers including engineering (8% of fixed asset capex) and 5% contingencies	See Table 6 for relative total sums
Investment aid	5.4 million euros	Applied only to alternatives 3-5
Terminal value	Remaining technical lifetime at the end of year 25	Capex inflated to year 25 times (1-(25 / lifetime)), see Table 5
Inflation	2.0 %, all values and inputs inflated annually	Long-term assumption in line with European Central Bank's target
Corporate income tax	20 %	Current tax rate in Finland
Tax depreciations	15 years, straight line	Assumed to be same as book depr.
Variable costs	Annual cost derived from the hourly MOM dispatch results	Dynamic based on fuel and commodity price assumptions
Fuel and commodity prices	Driven by inflation over long-term	Details in Appendix 5
Electricity supply and balancing costs, taxes	Grid, balance responsibility and electricity taxes applied. Grid connection assumed to national transmission network	Costs in real terms as per the Finnish transmission system operator's price list and electricity taxation rules in 2023
Biomass emission costs	Share of biomass subject to EUA assumed to increase from 0 % to 50 % between years 5 and 25	Emission factors for biomass combustion as in Table 5
Fixed maintenance costs	1.0 % p.a. of initial investment	Inflation added annually
Other fixed production costs	Costs based on estimated need of insourced and outsourced resources and services	Fixed costs estimated for each scenario separately. See Table 9

Table 9. Total fixed cost assumptions including maintenance for each analysed alternative.

Relative fixed costs	1.Combustion HOB	2.Combustion CHP	3.Hybrid HOB	4.Hybrid CHP	10.Minimum combustion
Total (highest = 1)	0.4	1.0	0.4	0.9	0.3

7 Comparison of production portfolio alternatives

Operational, environmental, and financial performance of the portfolio alternatives were studied and compared after the modeling. The analysis was carried out over the whole 25-year modeling period, whereas also hourly level analysis and redundancy checking was done to ensure that e.g. the DH demand is satisfied, and the control curve defined supply water temperatures are reached at any given time. The portfolio performances were analysed based on selected key performance indicators ("KPI") as elaborated below. In the results the portfolio alternatives are numbered with a reference to the Table 6 (1. Combustion HOB, 2. Combustion CHP, 3. Hybrid HOB, 4. Hybrid CHP, 5. Minimum combustion).

7.1 Operative analysis

The operational KPIs aim to describe the key operational and risk profile characteristics of each alternative. To study these from system level perspective the following six KPIs were chosen: production mix ("PM"), fuel mix ("FM"), full load hours ("FLH"), energy efficiency ("EF"), electricity balance ("EB") and electricity capture price factors ("CPF"). The production and fuel mix KPIs are calculated on an annual level simply by fetching the share of energy production covered by each asset and fuel type. Electricity balance shows annual sum of consumed and produced electricity for each alternative. Full load hours, fuel efficiency and electricity capture price factors are calculated as shown in formulas 9-11, respectively. The capture price factors are calculated only for alternatives with CHP or electricity-based DH production. Environmental aspects are considering CO2 emission intensity and are discussed more thoroughly in paragraph 7.1.2

$$FLH\ [h] = \frac{Q}{P} \tag{9}$$

Where Q is DH production p.a. [MWh] and P is installed DH production capacity [MW].

$$FE\ [\%] = \frac{Q+E}{F} \tag{10}$$

Where Q is DH [MWh] and E is electricity production [MWh], F is total fuel consumption (in lower heating value) including electricity and waste heat [MWh]. Values are annual.

$$\mathrm{CPF} = \frac{p_{electricity,WA}}{p_{electricity}} \tag{11}$$

Where $p_{\text{electricity,WA}}$ is consumption or production volume weighted average electricity price and $p_{\text{electricity}}$ is annual arithmetic average price on annual level. Electricity prices for CPF cover only wholesale energy cost and not grid fees or taxes for instance.

Since the MOM calculates the dispatching on an hourly level, the operational KPIs' are largely driven by hourly DH demand profiles and the alternatives' capability to meet that efficiently. The biggest driver in hourly dispatching is the outside temperature that drives the overall DH load and DH water temperatures. In Kajaani the temperatures varied between -29.1 °C and 30.9 °C during 2019-2022, while the new DHS control curve defines supply temperature range of 73–114 °C (see Figure 25). DH return temperature varies relatively little compared to supply and outside temperatures as shown in Figure 30. Return temperatures are calculated by using linear regression model derived from historical supply and return temperature data.

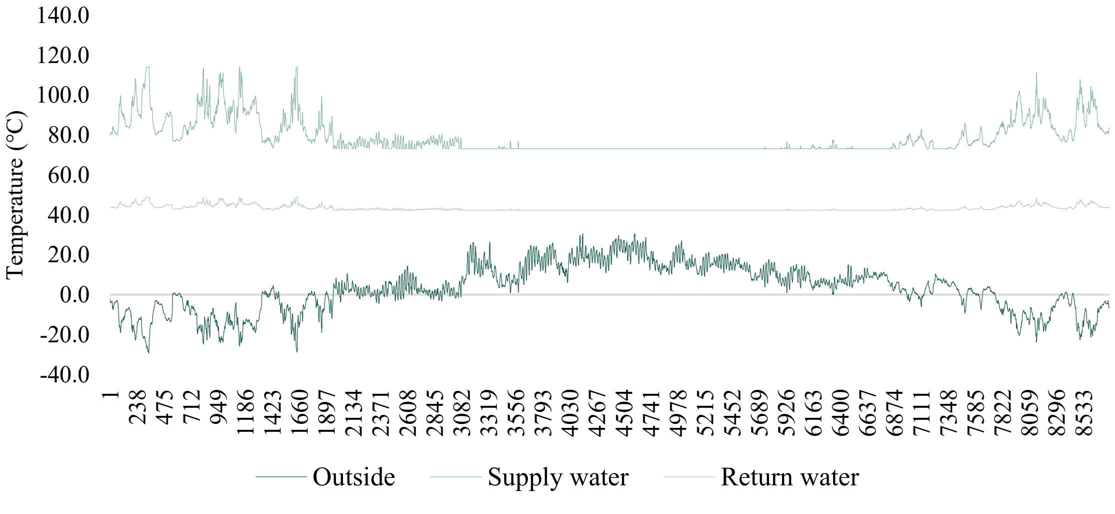

Figure 30. Simulated hourly outside temperature and DHS supply and return water temperatures during the first operational modeling year.

As the outside temperatures are assumed to increase over time impacting DH demand (among other assumed demand factors) and as the commodity price assumptions are not flat in nominal terms and e.g. the biomass emission costs are introduced 2030 onwards, the KPI outputs evolve during the 25-year period. Hence, many of the KPIs are illustrated separately for the first and last operational modeling year in the following sections. The first and last year are comparable as they are both based on actual reference hourly profiles from 2021.

7.1.1 Operative performance indicators

The portfolio alternatives have varying capacity emphasis between combustion and electricity-based production capacities. Expectedly this is clearly visibly also in the production mix outputs shown in Figure 31. In the combustion heavy alternatives (#1-#2) ca. 75-80 % of the DH demand is annually covered by combustion-based production. For hybrid alternatives (#3-#4) the shares vary between 14-38 % per annum. For the minimum combustion alternative (#5), the share of combustion production is only 1-8 % annually. Generally, there are only limited production mix differences between the HOB and CHP configurations. With higher turbine flexibility (constant heat to electricity ratio assumed) the differences could be somewhat higher though.

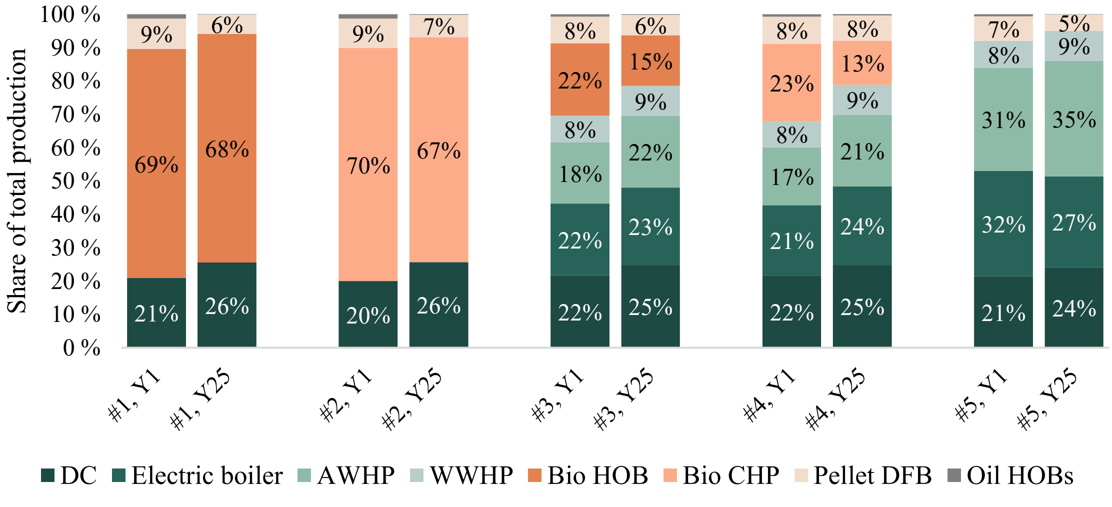

Figure 31. DH production mix for each portfolio in modeling years one and 25.

The PM values also emphasize differences in production decentralization and dependency on individual primary energy inputs. While the hybrid scenarios have highly diversified PM, the combustion-based alternatives have very high dependency on single assets. The minimum combustion alternative is in between, but with high dependency on electricity availability and prices. Diversified capacity mix increases flexibility and mitigates risks related to availability and pricing of different energy inputs.

On the other hand, Figure 31 shows that there are also similarities. These are namely a similar share of DC waste heat, pellet DFB and limited use of LFO fired peak boilers. The DC covers relatively stable 20-30 % of the demand across the alternatives over the whole period. This is natural given the high competitiveness of otherwise curtailed heat. The share of pellet DFB varies generally between 5 % and 10 % emphasizing its role as an intermediate and peak production with relatively costly fuel. The oil HOBs have very limited role, as they should, with a share of ca. 1 % or less in all alternatives. This is also aligned with historical share (0.5 % in 2022). This and the low but still existent oil peak boilers' share across the alternatives indicates no significant capacity under- or oversizing in any of portfolios.

In all alternatives there is some PM variation between the years due to the different hourly profiles and evolving inputs over time. The alterations are limited and the most present in the hybrid alternatives having more flexible asset base. An example is shown in Figure 32.

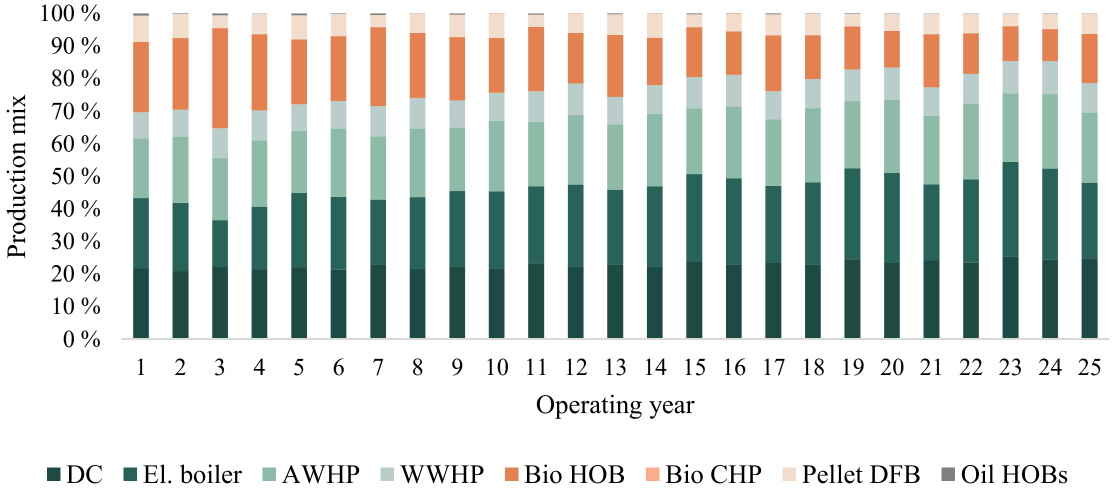

Figure 32. DH production mix development over the 25 years modeling period for portfolio three (hybrid HOB).

PM translates directly into fuel mix and the output conclusions are fairly similar. Hower, it is worth to note that alternatives with CHP (#2 and #4) here also include electricity generation and related fuel consumption, whereas PM considers only DH production. Figure 33 shows FM for each alternative further emphasizing the biomass availability and price risks in the combustion-based alternatives, and respective electricity risks in the minimum combustion alternative. The hybrid scenarios show again higher diversification and potential to mitigate related energy input risks, but also unavailability of individual production assets.

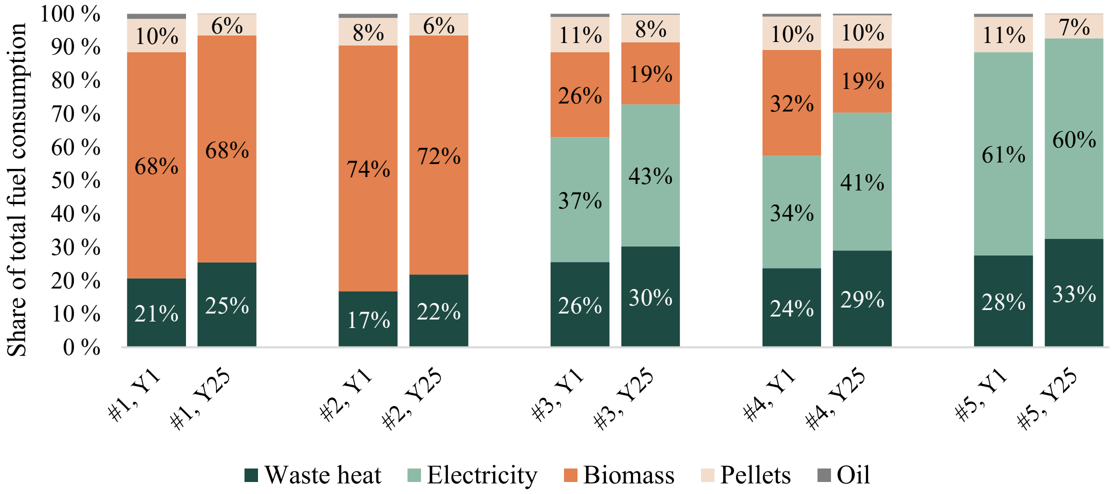

Figure 33. Fuel mix for each portfolio in the first and last modeling years.

When comparing the production asset output capacities with the PM and FM outputs it is clear not all assets are utilised to the same extent relative to their size. This is natural given the merit order modeling and varying cost competitiveness of each asset. Rate of capacity utilisations in terms of FLH are illustrated in the Figure 34. The figure confirms the previously mentioned relatively stable role of the DC waste heat given the 8 MW capacity is utilised in all alternatives nearly or above 8000 hours. Theoretical maximum is 8760 h (24 h x 365 d). As such, waste heat is considered as an important base load production in all alternatives. It also shows the high potential of even small waste heat streams in DH systems.

Also, heat pumps are highly utilised during the heating season in the relevant portfolio alternatives. However, this is not fully visible in the Figure 34. The annual HP FLHs are limited due to 1) HPs not being able to reach full output in colder weather and 2) DH demand being relatively low during warmer times when the HP output availability would be the highest. Regardless of the somewhat limited FLHs, HPs' are regarded as base load production during the heating season, while it is worth to note that due to their limitations, simulated AWHP and WWHP outputs are often supplemented by additional electric boiler or combustion-based production to ensure high enough supply water temperatures.

Bio HOB and CHP capacities are highly utilised in the first two alternatives and the FLHs reach nearly 5000 in both cases during the first operational year. This is aligned with expectations given the assets cover most of the new production capacity in these alternatives and such plants also typically cover base load. On the other hand, in the hybrid alternatives the base load HOB and CHP have a significantly smaller role and FLHs. As such assets are generally relatively large investments, the low FLHs indicate disadvantages in financial performance as elaborated in paragraph 7.2.1 . In the case of electric boiler, the somewhat low FLHs are not as significant as the investment per installed MW is relatively small.

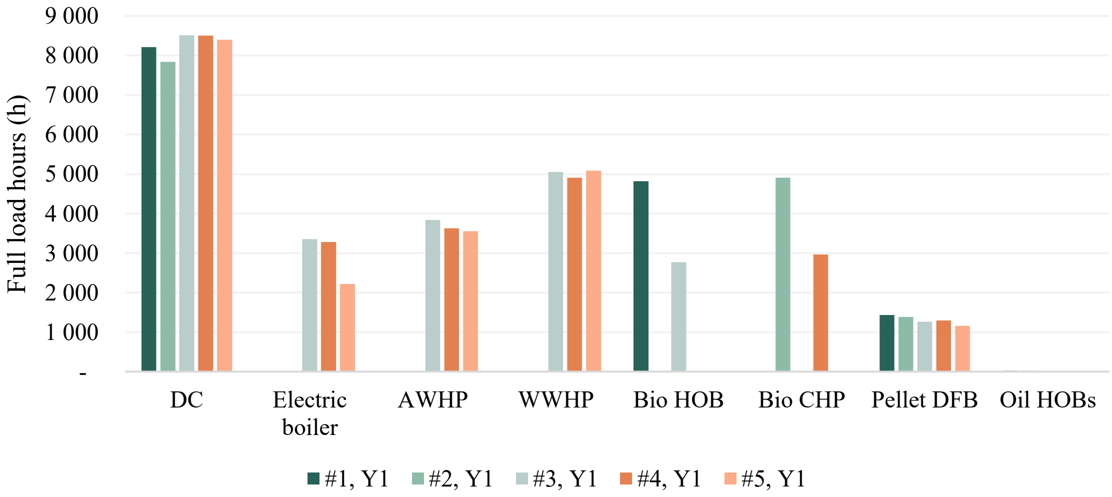

Figure 34. Full load hours in during the first operating year. HP full load hours are calculated based on the installed capacity, which is available only in warm weather conditions.

By calculating FLHs for the combined production capacity in each alternative it can be shown that the portfolio level FLHs and production capacity utilisations (FLHs of maximum, %) are rather similar across the alternatives. This is illustrated in Figure 35, which also shows that the portfolio level FLHs are rather high around 4200-4400 during the first operational year (excluding oil peak boilers) and as such the capacities are regarded to be in efficient use in all alternatives. Ca. 50 % capacity utilisation rate is high also in the light of highly varying DH demand during the year. Nevertheless, the numbers are expected to decline regardless of the production portfolio due to the expected declining long-term demand. The simulated decline on a portfolio level FLHs is ca. 15-17 % in all alternatives over the 25-year period.

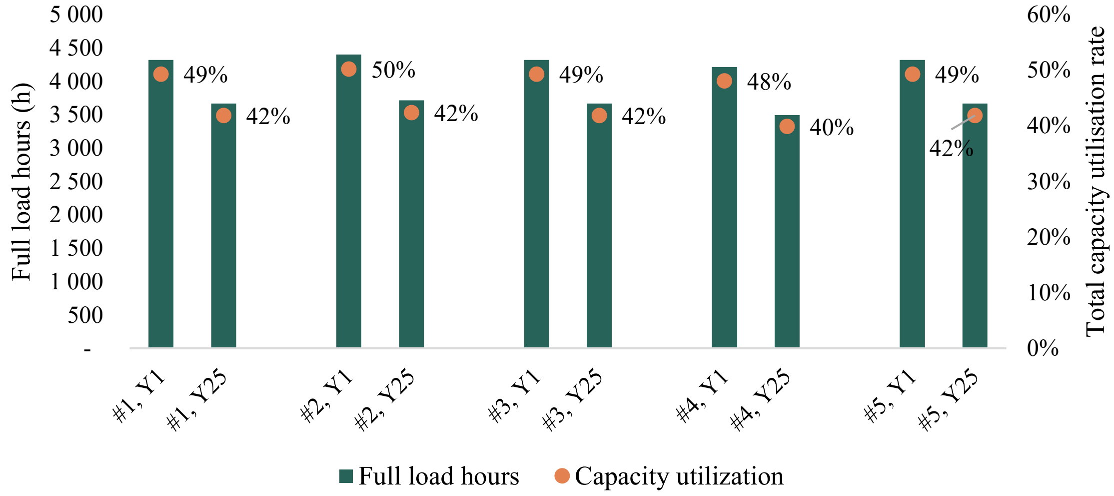

Figure 35. Portfolio level full load hours and total capacity utilisation rates for the first and last year. Values excluding oil HOBs due to their low FLHs and large back-up capacity.

Total energy efficiencies of the alternatives begin to show some more actual performance deviations among the alternatives as inefficiencies increase variable costs. EFs are compared in Figure 36, in which the portfolios with AWHP and WWHP capacities outperform the combustion-based alternatives. The efficiencies reflect well HPs' impact and the more the portfolio has electrified capacity the better the efficiency. HPs are also driving the efficiency values above 100 % given HP COP values are above one. From the figure it can also be seen that efficiencies increase over time when electrified capacities play a larger role in the PM. On a portfolio level the minimum combustion alternative reaches as high as 135 % EF in the last year. Although the combustion-based alternatives are not ranking well, their simulated total EF is still considered to be very high, 99 % for the whole period. This is explained by two factors: 1) purchased waste heat is treated as 100 % efficient and 2) large HOB and CHP units are assumed to be equipped with flue gas condensers.

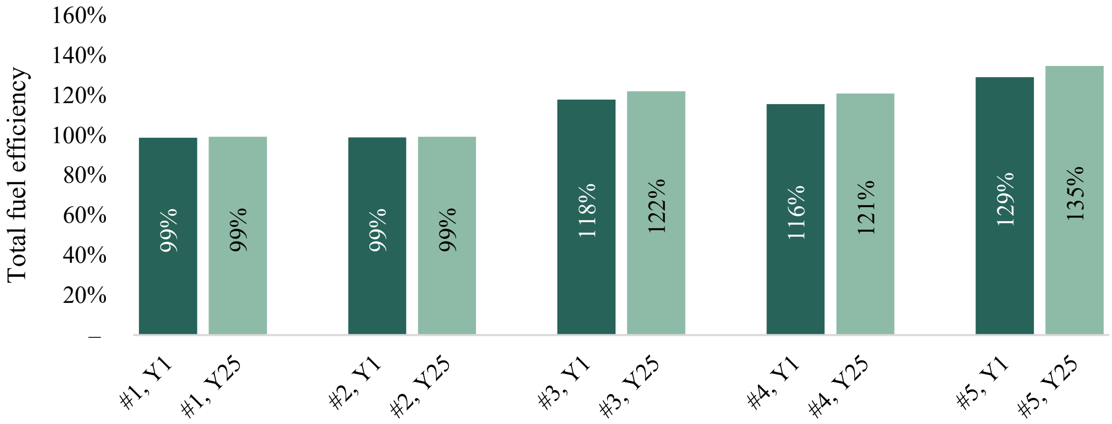

Figure 36. Total fuel efficiency for each portfolio in the first and last modeling year. The values also include produced electricity, if any.

Despite the high EFs, the relevant scenarios do not reflect the full HP potential due to the general mismatch of demand and availability of HP output. This is the case especially with AWHP that is directly exposed to the outside temperature variations. Wastewater temperature is more stable and never below zero degrees. The weather dependency and assumed minimum operating outside temperature for AWHP is well visible in Figure 37, where blank periods in the wintertime refer to hours when simulated temperature drops below -20 °C. The figure also shows relative stability of WWHP COP compared to AWHP. Annual production volume weighted COPs during the first simulated year was 2.5 for AWHP and 2.9 for WWHP in the minimum combustion alternative. Respectively, due to the timing mismatch between DH demand and HP output power availability, only 63 % of the available AWHP and 82 % of the WWHP output potential were utilised and fed into the DH grid. COP and output potential utilisation come with similar magnitudes in case of the hybrid portfolios.

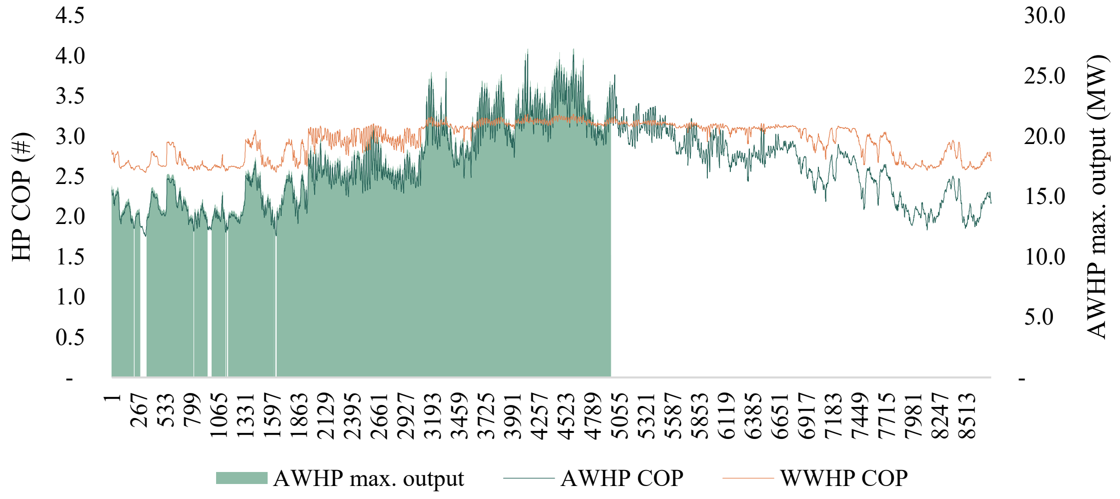

Figure 37. Simulated hourly COP values for heat pumps and respective maximum output for AWHP in portfolio alternative five (minimum combustion) during the first operating year.

Due to the varying level of production electrification the alternatives result in very different electricity net consumptions. This translates primarily into different commodity price exposure between the alternatives. Electricity balances are illustrated in Figure 38. One of the key findings is the relatively small CHP electricity production. In the bio CHP alternative electricity generation represents only 15 % of total energy production during the first operational year. In the hybrid alternative the value is even lower 5 %. The values also decrease over time along with the heat demand. Hence, based on the simulations, having CHP has only limited positive impact on revenue potential and electricity cost risk. Another key consideration is that the min. combustion alternative consumes ca. 50 % more electricity than the hybrid ones in year one, making it more sensitive to electricity markets.

The sensitivity is emphasized also by the electricity price capture factors shown in Figure 39, from which it can be seen that the most electrified scenario (#5) has limited operational flexibility to protect from market price peaks and anomalies. On average, the electric energy price paid in the minimum combustion alternative is 98% of the annual arithmetic price average, whereas the hybrid HOB pays 84 % and the hybrid CHP 84 %. On production side the hybrid CHP alternative shows again flexibility and optimisation potential with a 25-year capture factor average of 1.50 as the price variations can be exploited more effectively. Relatively small CHP production focuses on very profitable hours on average. The bio CHP alternative reaches 1.05 as the turbine is running large part of the year anyway.

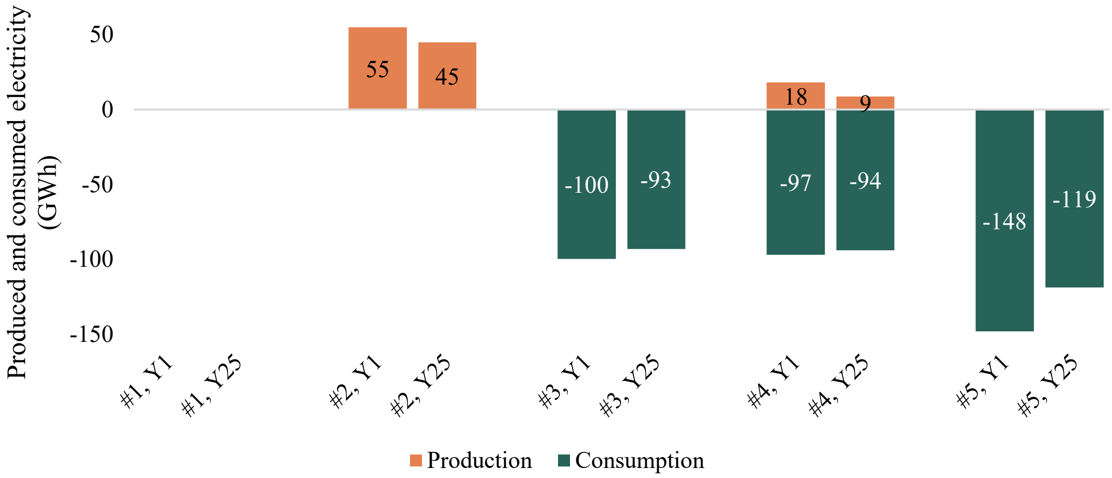

Figure 38. Produced and consumed electricity (el. to heat conversion in DH production) for each portfolio alternative during the first and last operating year.

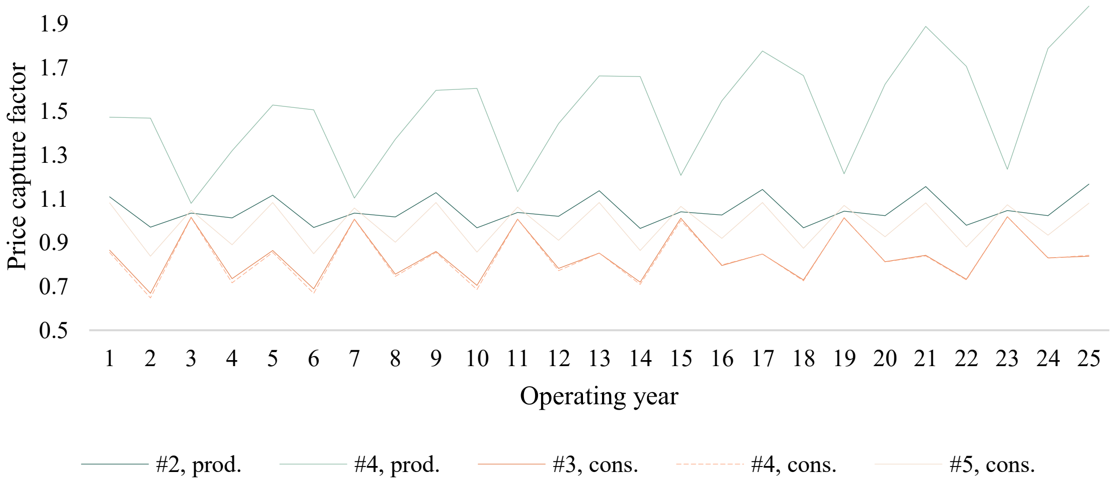

Figure 39. Simulated capture rates for produced and consumed electricity for the portfolios with electrified production and/or CHP. Relatively strong variation between the years results from different hourly wholesale electricity price profiles.

7.1.2 Environmental impact comparison

Environmental impacts were analysed from the perspective of direct (scope 1) CO2 emission intensity of produced heat. The intensity value has been calculated by dividing annual emissions with the DH volume. The related financial and operational aspects were captured in the MOM through EUA costs. Due to the uncertainty related to the biomass regulatory treatment over long term, emission intensities with full and without any biomass emission impact are shown. The emissions for each alternative have been derived from the MOM fuel consumption volumes and emission factors as in OSF's (2023a) fuel classification.

Average CO2 emission intensity of the Finnish DH was 109.9 kg/MWh in 2022. The simulated alternatives have a significantly smaller CO2 emission intensity based on current regulation as seen in Figure 40. Even the most emitting alternative (combustion HOB) has 97 % smaller emission intensity in the first year compared to the national average in 2022. The hybrid and minimum combustion alternatives utilise the oil peak boilers the least having the least emissions of 1.8-1.9 kg/MWh in the first year. Furthermore, in all alternatives the intensity is projected to decline over the modeling period. At the end of the period all alternatives have small emissions, which could likely be rather easily replaced by an electric boiler or bio-oil to fully phase out CO2 emissions based on the current regulatory treatment.

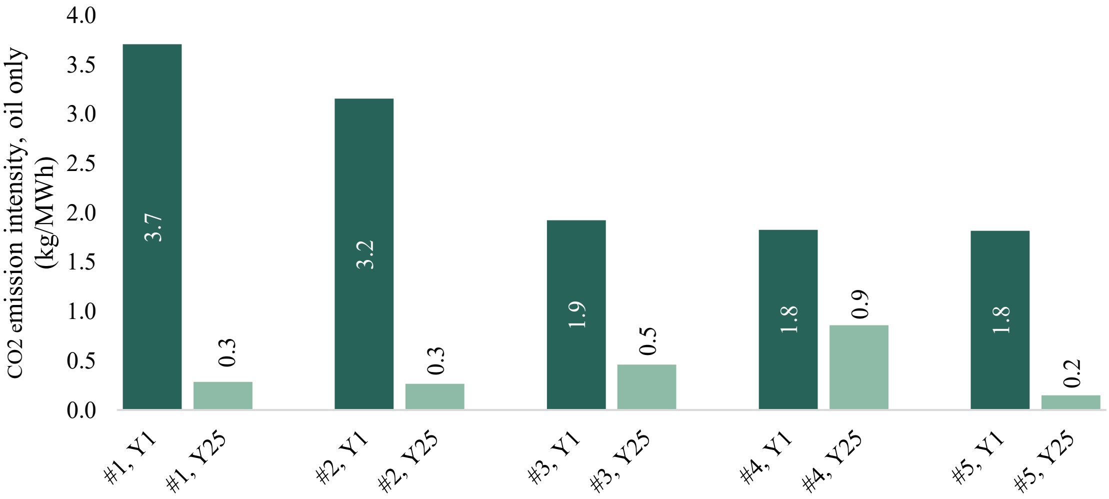

Figure 40. Simulated DH production CO2 emission intensity in the first and last operating year. The values consider only emissions from combusting light fuel oil in peak boilers.

The emission intensity would be significantly higher if all direct emissions, including those from sustainable biomass, were considered. Direct emissions summarised from all combustion for each alternative are shown in Figure 41. Waste heat and electricity are treated as CO2 neutral still. The figure illustrates well the big difference in the fuel mixes and driven by this the minimum combustion alternative has ca. 90 % smaller emission intensity compared to the combustion-based alternatives. With hybrid alternatives the intensity is 56-61 % smaller during the first year. The emission intensity and differences between the portfolios are large at the end of the modeling period also with the applied assumption that 50 % of the biomass would be treated under emission regulation by 2050. The emission intensities calculated as per the assumed regulation are also shown in Figure 41.

Although the emission intensity differences are small under the current regulation, the vast magnitude and differences in Figure 41 underline the regulatory risk for portfolios with significant share of combustion-based production. This is an important consideration as the expected lifetimes of the production assets are at least 25 years. The MOM simulations also show that high emission intensity in the combustion heavy alternatives is also having considerable impact on their financial performance under the assumed long-term emission regulation and related EUA costs.

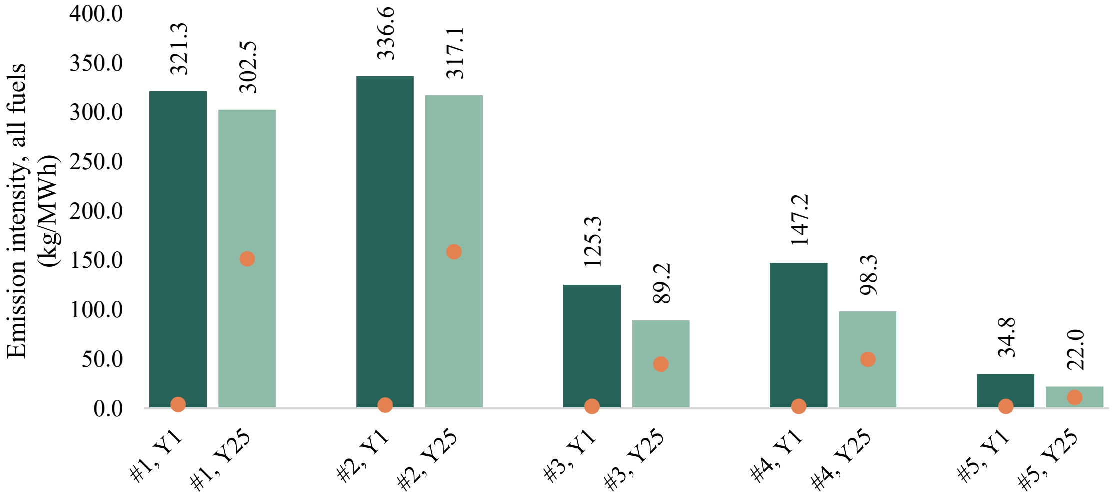

Figure 41. Simulated DH production CO2 emission intensity in the first and last operating year. The values consider all fuel combustion including wood pellets and other biomass. Green bars show total values, and the orange markers show the share applied in the marginal cost in the MOM based on the applied long-term regulatory biomass treatment assumptions.

The emission intensities discussed above are on an annual level, whereas it should be noted that there is also significant intra-year variation as the demand fluctuation is strong, which heavily impacts the production mix within the year. For instance, with the hybrid HOB alternative 58 % of the hours during the first operational year could be covered with CO2 neutral production as illustrated in Figure 42. Hence, the heat consumed during colder periods typically has higher emission intensity. This applies even with the minimum combustion alternative as pellet DFB and oil peak boilers would be occasionally utilised. Understanding and communicating the seasonal variations could unlock some DH demand side management as DH customers could consider measures to limit heat consumption during days and hours with high emission intensities.

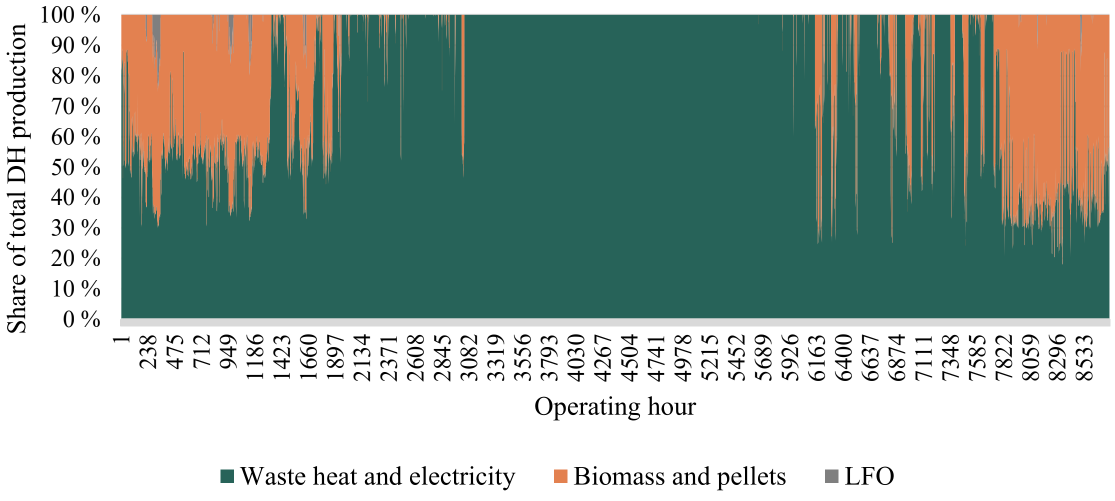

Figure 42. Share of emission categorized production methods for the combustion HOB portfolio during the first operating year.

7.2 Financial analysis

Financial performance analysis aims to analyse and compare investment profitability of each portfolio alternative over the 25-year modeling period. Three key KPIs were chosen for detailed financial review: net present value (“NPV”), levelized cost of energy (“LCOE”) and internal rate of return (“IRR”). In addition, direct production costs per energy unit are compared. Given that the investment is a production renewal investment into an existing DH business, the investment calculations and portfolio comparisons are made only from cost perspective while CHP electricity revenue is included as described in paragraph 6.1

Due to this cost focus for instance payback time was excluded from the selected KPIs. Also, NPV here represents discounted value of costs and hence the NPV values are negative, meaning that the best alternative should provide the smallest absolute NPV value in the comparison. Similarly, as DH revenue (or e.g. DH network related costs) is not included in the calculations, the costs only approach does not result in relevant IRR results. For this reason, alternative cost is considered as a relevant benchmark to study whether the new production portfolio alternatives would be financially justifiable from IRR perspective. Implied production cost of a large CHP plant was considered as an alternative cost for IRR calculations. Alternative production costs were achieved by modeling the current production capacity in Kajaani (including Kavo CHP with a 100 % biomass assumption). The related costs were based on Kavo's public financial statements. As a result, the IRR values reflect IRR of investing into the new production portfolios compared to continuing production with the existing CHP plant at cost basis. This allows comparing the alternatives, but the absolute IRRs are purely hypothetical as the method excludes the fact that the current CHP is reaching the end of its lifetime. Because of this speculative alternative cost, the approach is not applied in case of the NPV calculation. Calculation formulas for the financial KPIs are shown in formulas 12-14. Parameters in the functions have been defined in sections 6.2 and 6.3.3 .

$$NPV\ [€] = \sum_{n=0}^{25} \frac{-I_n + FCF_n + TV_n}{(1+WACC)^n} \tag{12}$$

Where n is years from the initial investment, I is the amount of initial capex that is not in FCF [€], FCF is free cash flow [€], WACC is the weighted average cost of capital [%], TV is terminal value (>0 only in year 25).

$$LCOE\ [€/MWh] = \frac{-\sum_{n=0}^{25} \frac{-I_n + FCF_n + TV_n}{(1+WACC)^n}}{\sum_{n=0}^{25} \frac{E_n}{(1+WACC)^n}} \tag{13}$$

Where E is the produced energy including DH and electricity and other variables are as defined above.

$$o = NPV = \sum_{n=0}^{25} \frac{FCF_n - FCF_{ac,n} + TV_n}{(1+IRR)^n} - I_n \tag{14}$$

Where FCF_{ac} is free cash flow for the alternative CHP production (implied alternative cost) [€] and other variables are as defined above. The function is solved numerically in the MOM.

Of the KPIs NPV represents discounted value of all cash flows over the period, also including the initial capex and potential terminal value. LCOE represents an average NPV of all energy production costs plus potential terminal value over the 25-year horizon. And finally, IRR represents the discount rate with which the NPV sets to zero. As such, the investment can be considered profitable if the IRR is larger than WACC. Given the discounting in the formulas, all the selected financial KPIs consider the time value of money.

7.2.1 Financial performance indicators

In addition to the initial investment cost, financial KPIs are driven by variable and fixed costs over the asset lifetime. Variable direct costs represent the MOM marginal cost. It is also the key factor in cash generation during the operational years. Annual average direct production costs for each alternative for the first and last year are summarized in Figure 43.

The comparison shows that the previously discussed flexibility and optimisation potential of the hybrid portfolios also converts into operational cost efficiency. The hybrid CHP alternative has the highest direct cost efficiency in the first year, but energy produced by the hybrid HOB portfolio is only 0.4 % more costly and over time slightly cheaper. Combustion based alternatives are ca. 7-9 % more costly compared to the most efficient one, but the impact of the assumed biomass emission costs is materializing over time as the unit costs for the portfolios is shown to more than double in nominal terms during the 25 years. The minimum combustion alternative is the most expensive during the first year showing 16 % higher direct unit costs compared to the hybrid CHP, but on the other hand its cost competitiveness is increasing over time and in the last year it is sharing the highest cost efficiency title with the hybrid HOB portfolio. This is namely due to the biomass emission costs and assumed increase of electricity costs compared to combustion fuels as seen in Figure 29. The electricity price development assumption is driven by increasing share of renewable electricity generation from wind and solar and inflation over long-term.

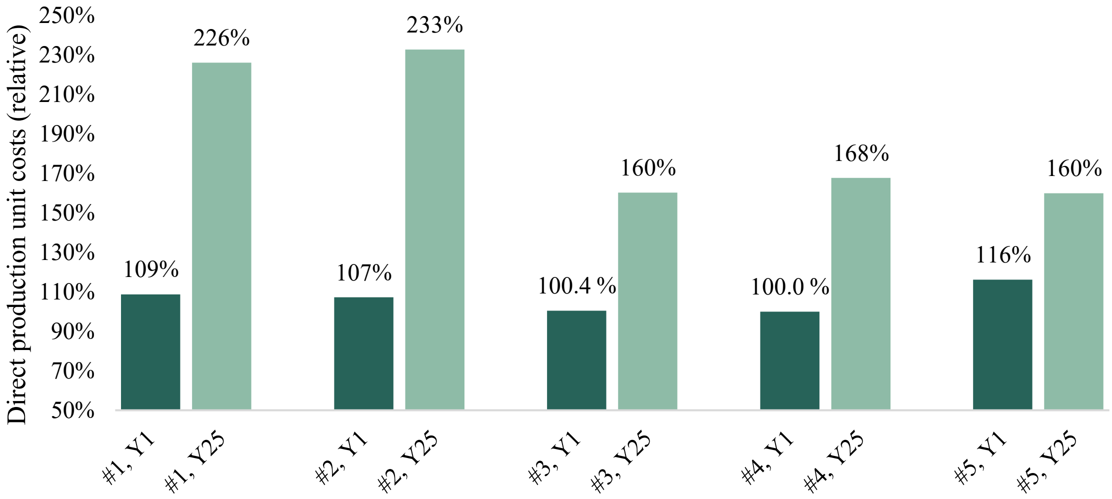

Figure 43. Direct energy production unit costs (relative €/MWh, nominal) for the alternatives in the first and last operating year. Values are relative to the most competitive alternative four in year one. Direct costs include fuels, electricity (incl. grid fees) and emission costs.

Although the direct costs represent the operational profitability, they do not reflect the actual investment profitability outlook. Initial investment costs and fixed operational costs for each portfolio were discussed in sections 6.3.1 and 6.3.3 and, for instance, the combustion CHP capex is assumed to be more than double the one for minimum combustion alternative. Similarly, fixed costs are more than three times higher, namely due to the higher staff and O&M requirements of a CHP plant compared to a fully electrified portfolio. These factors are covered in NPV, LCOE and IRR. Relative NPVs for each alternative are shown in Figure 44. In the figure the smallest value means smallest negative NPV. Hence, the higher the number the higher negative value of all discounted cash flows. Unlike in the previous cost comparison, the minimum combustion alternative now shows the highest profitability followed by hybrid HOB and combustion HOB having 4 % and 17 % higher NPV of costs, respectively. The CHP alternatives show the least profitability with 24 % (hybrid CHP) and 55 % (combustion CHP) higher NPV of costs. As such, additional investment into CHP electricity production does not appear financially attractive. The results also show that the flexibility and optimisation potential of the hybrid HOB portfolio is not enough to justify the ca. 20 % higher initial investment compared to the minimum combustion alternative. However, the 4 % NPV difference is not regarded very material and could be justified with higher fuel flexibility and security of supply.

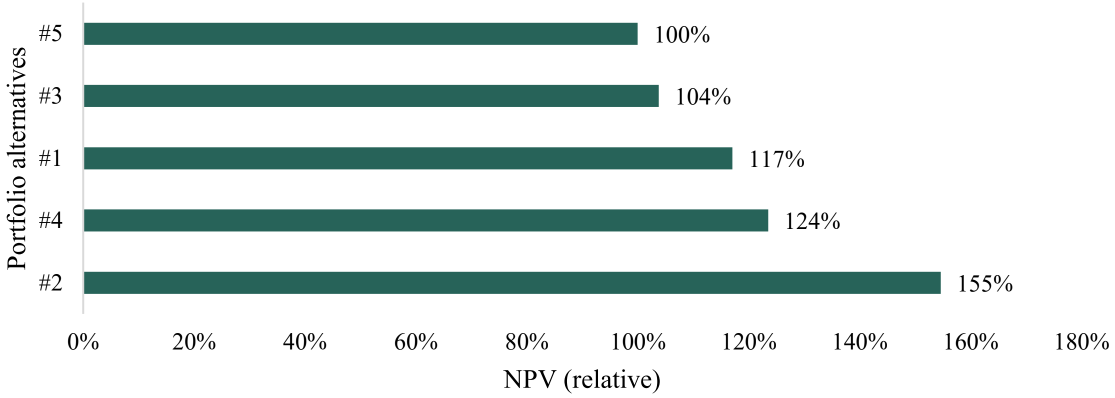

Figure 44. NPV ranking of the portfolio alternatives. NPV values shown as relative to the most competitive alternative. #4 and #2 also include the electricity generation revenue.

LCOE is a net present value of average cost per produced energy over lifetime. Hence, LCOE provides better comparability than NPV, as some of the portfolios include electricity generation and some don't. Relative LCOEs are shown in Figure 45. As seen, the LCOE analysis does not change the ranking order of the alternatives but narrows the CHP alternatives' disadvantage gap. LCOE supports the conclusion of strong investment profitability performance of the minimum combustion and hybrid HOB portfolios.

The Figure 45 also splits the LCOE into operative and investment parts. The capex part considers only the initial investment per discounted sum of produced energy over lifetime. The rest of the cash flows are in the operating part. The split shows that the CHP alternatives have relatively competitive total operating costs per energy unit, but the high cost of adding turbine and other electricity production related assets increases the LCOE into an uncompetitive region having 18-31 % higher LCOE than the minimum combustion alternative. The most attractive portfolios have a rather comparable LCOE structure where ca. one third results from capex. As such, it is worth noting that the hybrid HOB also has high operating costs despite the operative flexibility. In the case of the minimum combustion alternative, 67 % of the total LCOE results from other than initial capex emphasizing potential volatility and risks related to the electricity prices. However, the two best performing portfolios have strong LCOE advance to the rest. The combustion HOB comes third with 17% higher LCOE than the minimum combustion and has the emission cost risks.

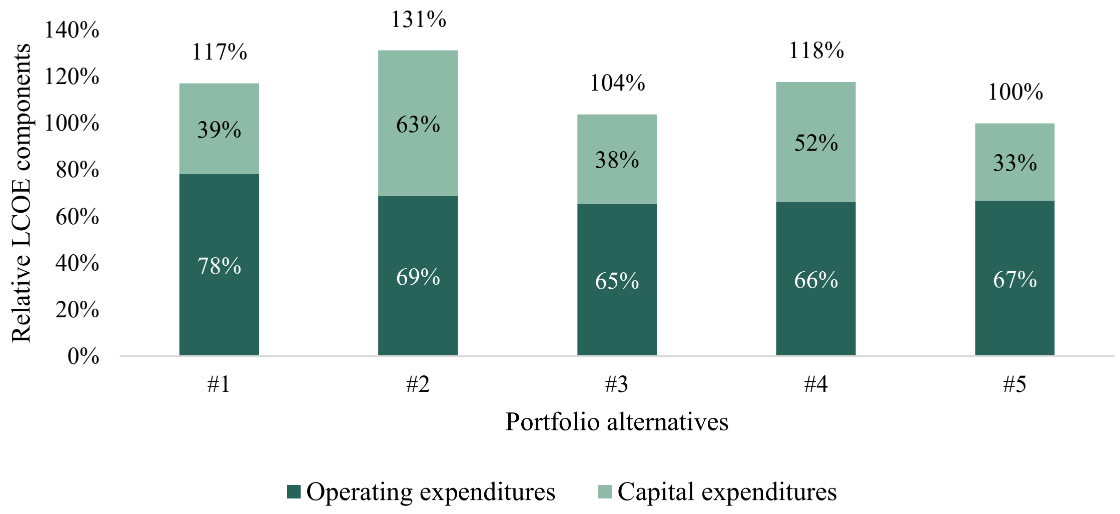

Figure 45. LCOE of the portfolio alternatives. Values are relative and compared against total LCOE of the most competitive alternative (#5).

From a purely financial perspective IRR is often the most significant KPI when considering long-term infrastructure investments. Relative IRRs are summarized in Figure 46 based on the alternative cost methodology described in paragraph 7.2 . The IRR comparison also shows the best profitability for the minimum combustion portfolio followed by hybrid HOB and combustion HOB. CHP alternatives have the lowest IRRs. The portfolios have a relatively wide IRR range emphasizing the competitiveness of the two leading alternatives.

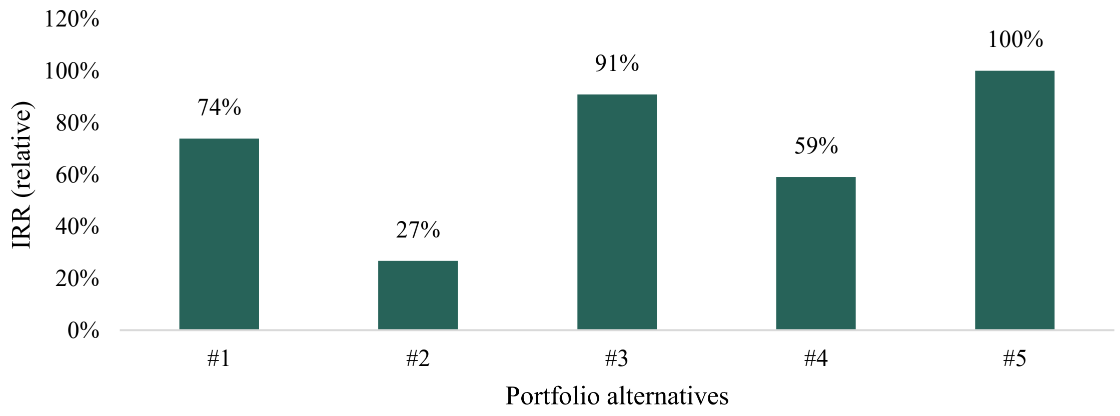

Figure 46. IRR of the portfolio alternatives compared to simulated implied costs of the existing CHP solution. Values shown as relative to the most competitive alternative (#5).

Overall, the financial KPIs showed consistent results, and the ranking order of the portfolios were the same as summarized in Table 10. The minimum combustion alternative was shown to result in the best investment profitability under the applied financial and operative assumptions. Despite having the highest average variable production costs per energy unit at the beginning, its increasing relative cost competitiveness over time and relatively low initial investment support the conclusion. Nevertheless, the hybrid HOB solution is rather close in all KPIs. Both solutions have decentralized production increasing redundancy, whereas the hybrid HOB has also fuel flexibility under normal operating conditions.

The combustion HOB portfolio comes as a third option with a wider disadvantage gap in all KPIs. It also involves elevated risks related to the biomass regulatory treatment, fuel and boiler availability as well as centralized production. The two CHP alternatives showed weak financial performance. This is driven by the high cost of electricity generation assets, low CHP full load hours and unfavourable electricity wholesale price assumption.

Table 10. Ranking summary of the alternatives based on key financial indicators. All indicators show the best long-term performance for the minimum combustion alternative.

Ranking of the portfolios (1 = the best)	NPV	LCOE	IRR
1.Combustion HOB	3	3	3
2.Combustion CHP	5	5	5
3.Hybrid HOB	2	2	2
4.Hybrid CHP	4	4	4
5.Minimum combustion	1	1	1

7.2.2 Sensitivity analysis

The financial KPIs and rankings are strongly driven by the financial and operative assumptions applied in the MOM. The operative and financial metrics have indicated varying degrees of dependencies on e.g. biomass and electricity prices, future CO2 emission regulation, fixed costs as well as the initial investment costs. To test the financial performance and related volatility of each portfolio under varying scenarios, sensitivity analysis was performed for LCOE and IRR in the MOM. The results for changing the selected key assumptions are summarized in Figure 47 and Figure 48, respectively.

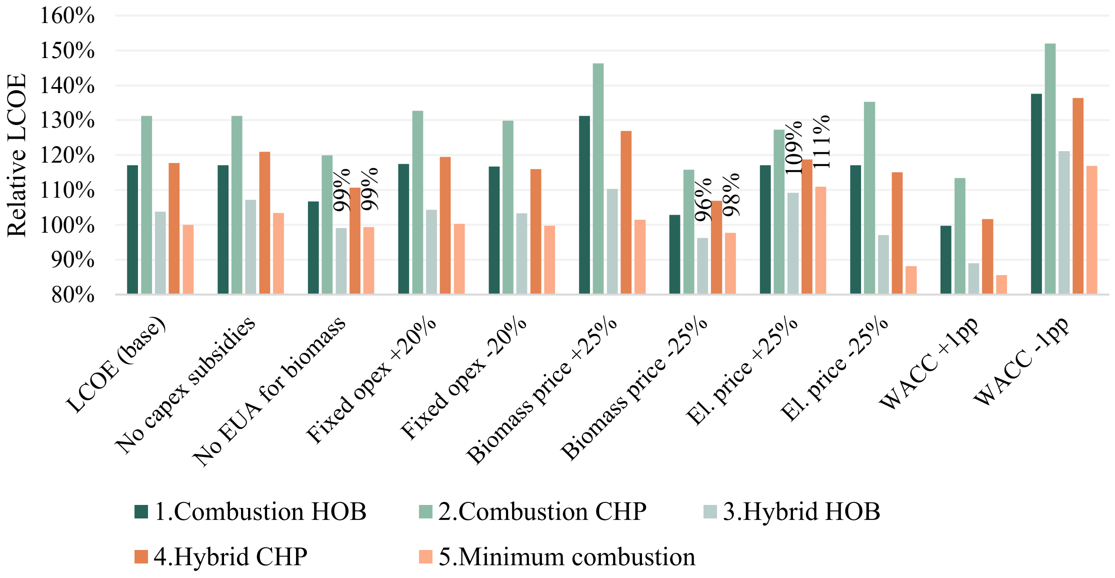

Figure 47. Relative LCOE values for each portfolio alternative under key sensitivities. In the figure 100 % value represents the most competitive alternative under the base assumptions (the left most bar group). Below 100 % value means lower absolute LCOE and vice versa. Capex subsidies refer to the already granted investment aid of 5.4 €m (see section 6.3.3).

The LCOE sensitivities underline the previously discussed small gap between the minimum combustion and hybrid HOB portfolios. Under three sensitivities the hybrid HOB shows better performance. This is the case if biomass emission costs are not applied over long-term (CO2 regulations remains as is), biomass price assumptions are decreased by 25 % or if electricity price assumption is increased by 25 % across the 25 years. Nevertheless, the differences are rather marginal, at maximum two percentage points, while 25 % movement in the commodity price assumptions are regarded significant. Otherwise, the rankings remain the same in the sensitivities. Consistent rankings of the portfolios even under significant changes in the individual modeling assumptions support the conclusions made in the previous section. However, the results show somewhat more resilience for the minimum combustion portfolio than anticipated based on the electricity price dependency.

In the IRR sensitivities the results are well aligned with the LCOE conclusions with an exception that the biomass emission allowance cost removal does not make the hybrid HOB more attractive from the minimum combustion. This is because the sensitivity also impacts the biomass heavy CHP reference solution.

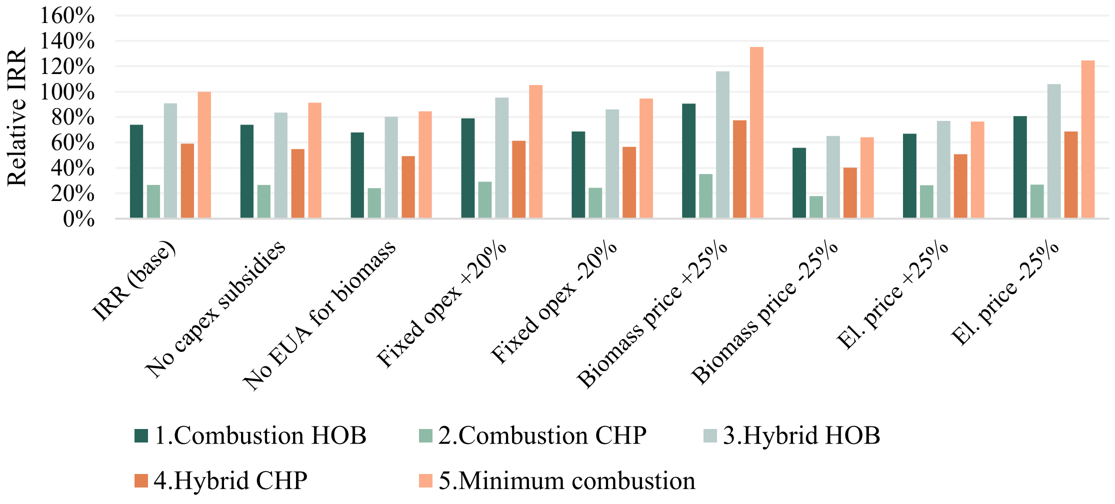

Figure 48. Relative IRR values for each portfolio alternative under key sensitivities. In the figure 100 % value represents the most competitive alternative under the base assumptions (the left most bar group). Above 100 % value means higher absolute IRR and vice versa.

Sensitizing the initial capex does not change the overall conclusions either, as with +/- 20 % capex alteration only the hybrid HOB portfolio reaches LCOE below the minimum combustion alternative as shown in Figure 49. Small 3-4 percentage point benefit in LCOE is reached only if capex is increased by 20 % only for the minimum combustion or vice versa to hybrid HOB. This shows that the minimum combustion portfolio could also sustain some capex overruns without being an unbeneficial financial decision.

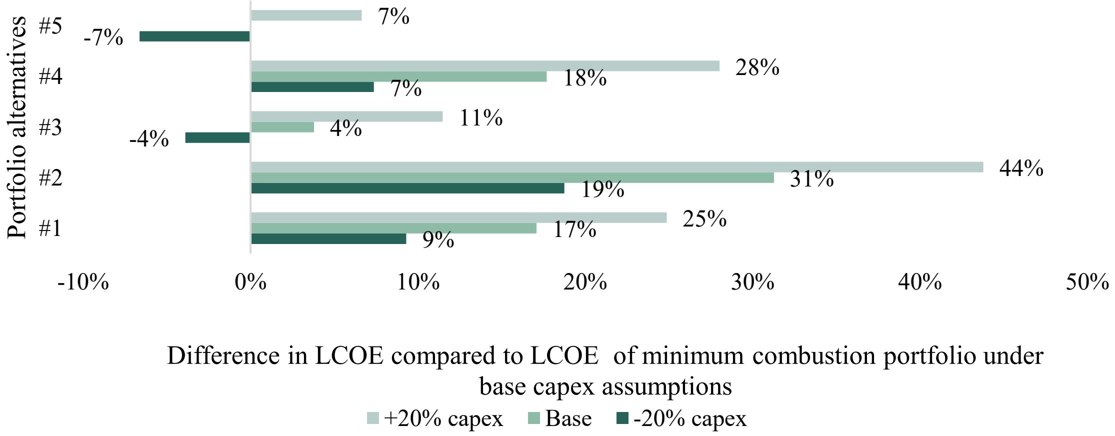

Figure 49. Initial investment amount sensitivity impact to LCOE.

8 Conclusions and discussion

District heating is the incumbent heating method in Finland that has cold climate and the second highest number of heating degree days in Europe. DH is the primary heating method for over half of the Finnish households and population (Finnish Energy 2023b). In terms of total residential space and hot water heating energy DH has the biggest share among all heating methods (OSF 2023d). Similarly, in Kajaani DH has the leading market position providing heating to nearly 70 % of the local population (Finnish Energy 2023a). As such, the future DH production assets will have a significant impact locally. The significance underlines the need for sustainable, supply secure and cost-efficient production portfolio.

Energy sector is facing and undergoing fundamental changes related to, just to name a few, share of intermittent wind and solar power production, sector integrations, demand response, energy efficiency, energy storages and PtX. Many of the trends have a direct link to DH for instance through sector coupling driven by increasing electrification of DH production. This, the need for CO2 neutral DH production and, for instance, the system level energy efficiency improvements through waste heat utilisation and lower DH supply water temperature are in the core of the investment considerations in Kajaani. These were also reflected in this study.

8.1 Heat production technologies

Overall technology considerations in paragraph 3 and 4 showed various potential production methods that fulfil the prerequisites set in paragraph 1.2 While some of the studied technologies met the environmental and social sustainability criteria, their economic feasibility or technology maturity fell short in many cases. In the studied DHS the high intra-year DH demand variation and related mismatch to available ambient heat was also considered to be a significant factor impacting the relevance of technologies like solar heat and surface water HPs. Although acknowledging the high potential, technology immaturity was considered as a profitability, timeline and security of supply risk in the case of small modular nuclear reactors and deep geothermal energy. Shallow geothermal energy (ground source heat) was considered to have a more practical system scalability related challenge.

In the context of the system prerequisites the most feasible DH production methods were considered to be biomass fired fluidised bed boiler, direct firing wood pellet boiler, electric boiler, heat pumps utilising wastewater and ambient air as their thermal energy source and waste heat from a local data center. The biomass fired boilers were considered relevant with and without back pressure steam turbine for electricity generation. While all five asset portfolios formed from these technologies met the desired prerequisites and characteristics, the study showed considerable differences especially in financial performance when studied under a long 25-year operating period. The portfolio alternatives represent different levels of diversification, electrification and reliance on combustion-based technologies.

8.2 Operational conclusions

All the alternatives performed operationally well over the whole 25-year period. They met the intra-year variations and evolving annual DH demand without deficits or material excess cooling while having overall high energy efficiency, low CO2 emission intensity under the current regulation and production capacity in efficient use on a portfolio level. The observed differences in operational and environmental KPIs relate namely to fuel and production mix and energy efficiency. While DC waste heat, pellets and oil had a considerably similar role across the modeling period and the portfolio alternatives, the key differences relate to electrified capacity and biomass fired boilers. In each of the portfolios these represented ca. 60-75% of the consumed energy inputs. Depending on the portfolio this was either fully biomass (combustion HOB and CHP) or electricity (minimum combustion) or a combination (hybrid HOB and CHP). In the combustion-based alternatives this results in a concentrated risk related to the availability and cost of combusting biomass. In the minimum combustion alternative, the key risks relate to electricity supply and costs. The hybrid alternatives showed higher operational flexibility, providing financial headroom under stress scenarios.

In the hybrid alternatives no single asset covered more than 25% of the annual DH production representing high level of diversification and security off supply. Also, the minimum combustion portfolio had decentralized production with a maximum annual share of 35 % coming from a single asset. Whilst the combustion-based alternatives covered up to 70 % of the annual production by the main biomass fired boilers.

In terms of energy efficiency, the scale of electrified capacity, especially heat pumps, was shown to have a system level impact due to HP COPs representing significantly higher energy efficiency compared to combustion technologies, even when bundled with flue gas condensers. The hybrid portfolios showed ca. 20 percentage points higher total production energy efficiency compared to the combustion alternatives. The differences with the minimum combustion portfolio was 30-35 percentage points.

As an environmental KPI all alternatives had CO2 intensity that represents at least 97 % smaller emission intensity in the first year compared to the national average in 2022. The trend over the 25-year period was also decreasing but assumes that electricity and waste heat is sourced from a CO2 neutral source. The study also demonstrated the magnitude of impact from potential future policy changes in how the biomass combustion emissions are defined. Although sustainable biomass is well available in Finland, the related risks are further mitigated in the hybrid and minimum combustion alternatives.

8.3 Financial conclusions

From the financial perspective the minimum combustion portfolio showed the best performance in all KPIs, while the hybrid HOB alternative was comparable and with a margin that is regarded somewhat immaterial from decision making perspective. The combustion HOB alternative represented moderate performance, but with a significant gap to the two leading ones. Both CHP alternatives performed weakly, while the combustion CHP was the worst in all metrics. This was driven by the low added value of the generated electricity compared to the significantly higher investment cost. Hence, the study confirmed from its part and under the chosen assumptions that the traditionally significant CHP based DH production capacity in Finland does not represent a very good replacement investment in the expected development of the market environment where wind and solar power play an increasingly significant role simultaneously when the availability and cost of sustainable biomass is potentially getting tighter. On the other hand, it should be noted that increased flexibility between electricity and DH production and e.g. coupled thermal storage capacity could change the conclusion. Compared to the best performing minimum combustion portfolio the LCOE values were 4 % higher for the hybrid HOB, 17% for the combustion HOB, 18% for the hybrid CHP and 31% for the combustion CHP.

When sensitizing the key assumptions in the modeling to reflect different future scenarios the operational or financial conclusions did not generally change. However, the hybrid HOB portfolio showed marginally more attractive financial performance under three scenarios: 1) no long-term emission costs for biomass combustion, 2) biomass price increases by 25 % across the modeling period and 3) electricity price increases by 25 % across the period. The difference is only 0-2 percentage points in relative LCOEs. This shows the robustness and financial resilience of the minimum combustion portfolio concluding it to be the most techno-economically viable production portfolio. It also shows that under uncertainties the hybrid HOB is a feasible alternative with its flexibility and other qualitative benefits.

8.4 Additional research topics

The MOM simulations were performed under hourly profiles and with hourly electricity cost. In practise, hedging the price of electricity consumption at least partly should be considered. Successful, as well as unsuccessful, hedging could have a significant impact on the realised financial performance. Although hedging is a way to mitigate risks and limit volatility, it will likely not protect from all risks related to e.g. volume uncertainties and price profiles. Hence, there is room to further examine the financial performance of the portfolios under different commodity hedging policies and hedging performances.

As in the DH research field generally, thermal energy storages were identified as one of the key areas for further study also in case of Kajaani. This applies to both seasonal and short-term storage potential. Only high-level short term heat accumulator simulations (based on the existing heat accumulator) were performed in the MOM outside this research. Although no major impact on the results was identified, a more thorough analysis is recommended. Especially larger storages could unlock significant optimisation potential for electrified production in Kajaani. It could also make more technologies relevant in the future.

While the MOM was found to be well suited method for the research, it should be noted that the capacity sizing for each asset was not optimised separately. Optimising the capacities including thermal storage with, for instance, MILP could provide additional support for the investment decision making especially due to the small financial differences between the minimum combustion and the hybrid HOB alternatives. Additional waste heat sources in Kajaani should be mapped regardless to ensure no excess new production capacity is built.

9 Summary

This study researched future alternatives for district heating production in Kajaani, Finland. The current heat production in the area relies on a large CHP plant that is reaching the end of its techno-economic lifetime over the coming years. The research aimed to identify potential district heat production technologies and the most techno-economically feasible heat production portfolio to renew the district heat production in Kajaani. The analysis was made from a system level perspective under prerequisites that the production solution shall 1) be socially, environmentally and economically sustainable, 2) be based on mature technologies with a long lifetime, 3) prefer non-combusting technologies if possible and 4) be suitable for the current operating environment while being flexible to accommodate potential changes in it.

The most feasible production methods were considered to be biomass fired fluidised bed boiler, direct firing wood pellet boiler, electric boiler, heat pumps utilising wastewater and ambient air as a heat source and waste heat from a local data centre. Five portfolio alternatives were formed from these representing different levels of decentralization, electrification and reliance on combustion-based technologies.

The portfolios were modeled on an hourly level for 25 years. The model was based on merit order of marginal costs driven by long term assumption scenarios and historical hourly profiles for electricity price, outside temperature and DH demand. The research demonstrated feasibility of the tailored modeling approach in district heat production investment analysis. Simulated data from the model was studied in terms of selected operational, environmental and financial key performance indicators.

All the DH production portfolio alternatives performed operationally and environmentally well over the whole 25-year period. They met the intra-year variations and evolving annual DH demand without material challenges and while meeting the key prerequisites. The observed differences and risks in operational and environmental KPIs relate namely to fuel and production mix and energy efficiency.

From the financial perspective the portfolio that minimised combustion resulted in the best performance in all studied KPIs. A hybrid portfolio combining biomass fired heat only boiler with all the other identified relevant technologies reached almost similar level of financial performance. It also outperformed the minimum combustion alternative under three future scenarios where 1) no long-term emission costs for biomass combustion were included, 2) biomass price was increased by 25 % across the modeling period and 3) electricity price was increased by 25 % across the modeling period. Other three portfolio alternatives resulted in a significantly less attractive financial performance. This was the case especially for two portfolios that had combined heat and electricity production. As such, the study confirmed from its part and under the chosen assumptions that the competitiveness of electrified DH production has surpassed new CHP capacity in Finland where wind and solar power and sector coupling play an increasingly significant role in the energy markets.

The study concluded that from the studied alternatives the most techno-economically viable solution to renew the district heating production in Kajaani is a portfolio that includes data centre waste heat, electric boiler, heat pumps that utilise ambient air and wastewater as a heat source and pellet direct firing boiler. Generally, the hybrid portfolio combining biomass fired heat only boiler with all the other identified relevant technologies showed high operational flexibility, production decentralization and fuel availability and price risk diversification. However, from a financial perspective these qualifications did not justify the ca. 20 % higher investment cost compared to the portfolio that minimized the use of combustion technologies.

The study complements the resent district heating research by applying sector coupling through electrified heat production in the context of local DHS characteristics, system level DH production optimisation via tailored merit order dispatching model and a new DH water supply temperature control curve with lower temperatures. Further research areas were identified namely in the field of system optimisation. These related especially to the potential value of thermal energy storages and further optimisation of the production capacity and capacity allocation between the assets.

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