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Assessing Cost-effectiveness of Heat Pumps and Biomass CHP in Future Swedish District Heating Systems

Master's thesis in Master Program Sustainable Energy Systems

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: District heating facility Idbäcksverket, Nyköping, Sweden.

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Abstract

District heating systems are predicted to become an essential part of decarbonizing heat generation now and in the future. Power-to-heat technologies, such as heat pumps and electric boilers, could help the transition to sustainable district heating production while working as a flexibility measure in the coupled electricity market. Even though several studies single out heat pumps as a cheap and effective way to produce district heating, the current production mix is mainly based on combustion technologies producing heat with biomass. Additionally, as the share of renewables in the energy mix increases, heat pumps can play an important role in addressing flexibility and utilization of energy. This thesis aims to comparatively analyze electric air-source heat pumps and biomass combined heat and power heating systems, in the context of change for the future Swedish energy sector.

Costs associated with heat production between two different energy technologies in district heating systems are investigated. A mixed linear optimization model is adapted to minimize the variable operational costs for different systems including heat pumps and biomass combined heat and power, concerning interesting techno-economic properties, electricity prices, taxes, and fuel prices. The model is based on a reference system in Nyköping, Sweden, to realistically simulate and create district heating cases over annual periods. The details in energy modeling of district heating and technologies are also investigated, focusing on heat pumps and their coefficient of performance. A present and a future scenario are investigated by using different electricity spot price curves for the years 2019 and 2050.

Results show that electricity-based heat pumps perform better in terms of cost-effectiveness in the Swedish district heating sector, both presently and in the future. A temperature-dependent approach is adapted to the coefficient of performance of heat pumps, resulting in a noticeable cost difference, underscoring the importance of accurately incorporating heat pumps in energy models. The possible savings using electricity instead of biomass are even more significant if the price of biomass continues to rise. The thesis also reveals that the power-to-heat tax, a tax on electricity to produce heat, is an important factor in further comprehending the potential of heat pumps in heat production in Sweden.

Keywords: Heat pump, Biomass combined heat and power (CHP), District heating system, Thermal energy storage, Mixed-Integer Linear Programming, Coefficient Of Performance (COP)

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Gothenburg, June 2024
Samuel Bergander and Filip Hellander

List of Acronyms

The list of acronyms that have been used throughout this thesis is listed below in chronological order:

CHP	Combined Heat and Power
VRE	Variable Renewable Electricity
COP	Coefficient Of Performance
MILP	Mixed-Integer Linear Programming
EB	Electric Boiler
HOB	Heat-Only Boiler
TES	Thermal Energy Storage
P2H	Power-to-Heat
BB	Biogas Boiler
SEK	Swedish Crowns
MW	Megawatt
MWh	Megawatt hour

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1
Introduction

In this chapter is a thesis background, aim, and limitations of the thesis described. The aim is specified, and important research questions for the investigation process are presented.

1.1 Background

To tackle future challenges, Swedish district heating systems must evolve to integrate renewable energy sources and handle increased electricity production intermittency. Companies are prioritizing a sustainable energy profile, but there's no single correct solution for achieving a profitable, sustainable district heating system [4]. Further research is needed to evaluate different district heating systems and understand what yields favorable performance and flexibility. Two noteworthy options are biomass combined heat and power (CHP) and heat pumps. A comparative study between these heat generation options could offer valuable insights into how these systems can optimally meet the evolving needs of district heating, ensuring both efficiency and cost-effectiveness.

The energy consulting company Sigholm aims to investigate the development of heating models that reflect real-life production systems. This is a crucial factor for evaluating possible future energy scenarios in the district heating industry. Since the energy market is in constant change it is important to be prepared for multiple scenarios in terms of achieving a cost-optimal pathway.

Recent studies presented by PhD students and scientists at Chalmers University of Technology have acknowledged an advantageous situation for heat pump technologies in the district heating sector [5]. With more intermittent variable renewable electricity (VRE) production and rising biomass prices, both today and in the future, heat pumps are performing the best in terms of cost-effectiveness in Chalmers models of the Swedish energy system. Still, many Swedish district heating companies invest in biomass-based solutions for their electricity and heat production [6], [1]. This background forms the basis of a hypothesis: whether the studies from Chalmers regarding heat pumps are feasible, and if so, why the industry doesn't acknowledge it and instead focuses on solutions including biomass-based production. This hypothesis is an inspiration for this study, which aims to find a cost-optimal direction for the future of the Swedish district heating sector.

1.2 Aim

This study aims to conduct a comparative analysis between electric heat pumps and biomass heating systems with CHP, in the context of change for future Swedish energy systems. The comparison will focus on how the cost-effectiveness of the energy technologies is affected by a future intermittent electricity market.

To achieve this, data and modeling tools provided by Sigholm will be utilized to create case studies and compare the usage of heat pumps and biomass CHP in a current and future Swedish district heating system. The projects will use Vattenfall's district heating facility Idbäcksverket in Nyköping, Sweden, as a reference model to represent a general Swedish district heating facility. The study will focus on several factors that can impact the cost-effectiveness. The factors concern techno-economical aspects, energy availability and mix, prices of fuel, and policies. The study aims to evaluate to what extent these factors affect the feasibility and cost-effectiveness of energy technologies for different future scenarios.

When creating various scenarios for the future energy mix, it is necessary to make predictions and assumptions that may not accurately reflect the real world. For example, when creating a heating model, a constant coefficient of performance (COP) for heat pumps or ignoring seasonal variations could be used as simplification. Therefore this study also aims to evaluate what level of detail in the energy model is required to achieve a fair and credible comparison between the technologies.

1.3 Research questions

The aim lays the ground for questions of issue based on the scope of the study. The overarching objective is to increase understanding of two different energy technologies, heat pumps and biomass CHP, and its role in the future Swedish district heating sector. The aim addresses the following research questions:

- Which heat production method, heat pump or biomass CHP, is the most cost-effective alternative to produce district heating in current and future Swedish district heating systems?

- What impact do technical aspects, energy prices, and taxation have when deciding between electricity-based heat pumps or biomass-based heat generation for a district heating system?

- How does the technical detail regarding the coefficient of performance (COP) of heat pumps affect the result in energy modeling?

1.4 Limitations

The main software that will be used in this study are Aurora by Sigholm, Python, and GAMS. These will be used to model the district heating system and the optimization of the heat production. The optimization utilizes Mixed Integer Linear Programming (MILP) and will minimize the total variable operational costs of the system on an annual scale. The model will only minimize operational costs, as the software Aurora by Sigholm does not consider investments. The investment and fixed costs are to be evaluated separately.

The technologies compared in this study are heat pumps and biomass CHP. The heat pump technology used for modeling is an air compression heat pump and the biomass CHP is a bio-fueled boiler combined with a turbine and flue-gas condenser. Other technologies used are electric boiler (EB), heat-only boiler biogas (HOB), and thermal energy storage (TES).

The model will only consider the production of district heating and will not incorporate optimization of the grid, distribution, or heat usage strategies on the demand side. The model does not consider possible economic gains from grid frequency regulations or the electricity trading market. In this thesis, the changes to the electricity market will be represented by a price curve in the energy model. The curve will be input as a parameter and not variable to electricity consumption or production. The price curves will use predictions and analyses of the future electricity prices in the Swedish energy system [7], [5], [8]. The data representing these values are based on historical data and what the Swedish energy mix might look like in the future. These predictions are based on several factors, such as an increase in renewable energy sources with intermittent generation which cause a variation in energy prices. The future electricity prices used in this study are therefore based on what the research is forecasting.

The modeling and simulation in this study are based on one facility named Idbäcksverket in Nyköping, Sweden. Idbäcksverket is used as a reference for a district heating system. The results may therefore be more adaptable for Idbäcksverket, since each district heating system in Sweden has its specific structure. It is therefore important to mention that the results might vary from facility to facility.

2
Theory

In the following sections is the theory behind the study presented. This includes an overview of the Swedish energy sector, a description of the heat- and electricity production technologies, the software and programs used in the study, and the reference model used in the energy modeling.

2.1 The Swedish energy situation

The transition towards a more sustainable and efficient energy sector in Sweden is facing various challenges. To achieve the country's goal of generating 100% fossil-free energy by 2040 and achieving a net-zero carbon economy by 2045, significant effort is required from industries, transportation, and society [7], [9]. Over the next two decades, the electricity demand is expected to double as the country becomes more electrified. This increase will mostly be supplied by variable electricity production. Today, Sweden has a large need for power balance and flexibility services, something the country not have been affected by in the past with a large capacity of balancing hydropower and base load nuclear power [10]. Problematic situations have already occurred, especially in the southern parts of Sweden with high prices and a lack of energy supply, much because of the uncertain future of the nuclear fleet and a rising electricity demand. The situation states a need for action from the energy sector, as the Swedish energy landscape is changing.

To reach the Swedish sustainability policy goals and combat the energy availability issues, there has been an increased investment in renewable energy sources producing VRE in Sweden. Primarily is wind power investments increasing as they are fast to build and are less expensive compared to e.g. nuclear or hydropower [7]. However, the intermittent generation of VRE creates a need for flexibility in the Swedish energy sector due to fluctuating electricity production levels [10]. The new situation may present new opportunities for the Swedish energy sector, particularly for the district heating sector. Two key alternatives, CHP and power-to-heat (P2H) technologies, including EB and heat pumps, provide relevant flexibility for the energy sector by alternating production in district heating systems. According to Møller Sneum *et al.* [11], flexibility is defined by the ability of a district heating system to provide frequent variations in its consumption or production of electricity, based on indicators from the electricity market. For example the use of P2H during periods when electricity prices are low, and CHP and thermal energy storage (TES) during hours when electricity prices are high. This study investigates the new energy landscape by evaluating these flexibility alternatives.

The future of bio-based fuels is also undergoing changes where supply and fuel costs become crucial factors for its future [12]. Today, biomass-based systems are the most common way of producing heat in district heating, but the Swedish energy sector is changing [1].

In 2023, biomass stood for around 65% of the input energy used for district heating production, see figure 2.1. The graph presents the development of district heating production in Sweden between 1970-2023 [1]. In this study is biomass-based heat production compared to heat pumps, which accounted for around 7% of the total production in 2023.

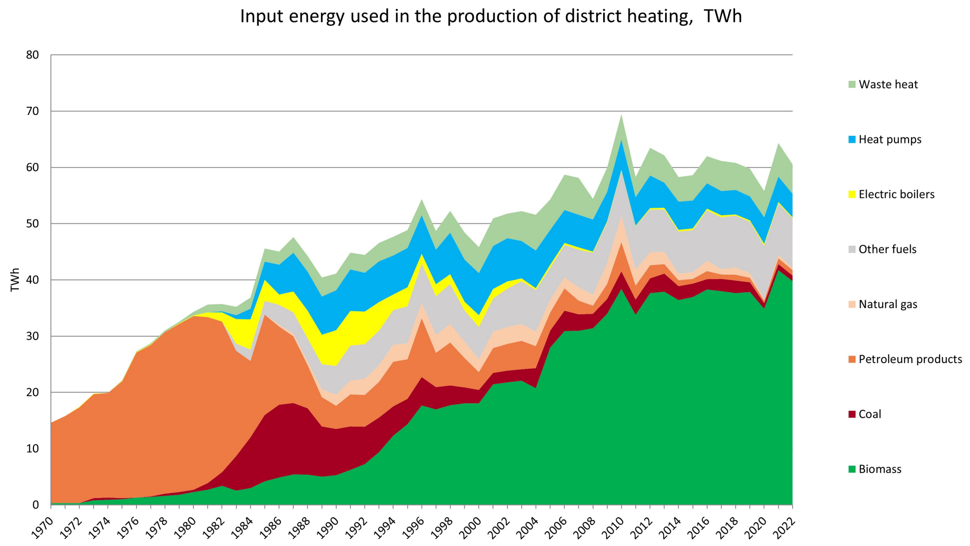

Figure 2.1: Input energy used in the production of district heating, from 1970-2023, in TWh [1].

2.2 District heating

District heating systems are predicted to become an essential part of decarbonizing heat generation now and in the future [13]. District heating has been a widely known technology for over four decades, and today has heat generation from district heating evolved into a crucial factor both in terms of sustainability and economic aspects. In the following section are the general characteristics of district heating systems described.

District heating systems can be divided into a generation-, transmission-, and storage side where the generation of heat comes from one or more producing facilities, such as power plants, industries, and waste incineration plants [14]. These use water as the medium to transfer heat. The water is then distributed through a transmission network of heat exchange pipelines connected to a distribution grid serving the end consumers, see figure 2.2. A district heating distribution grid can differ in size, from a small uptake area to a large city. Heat can also be stored in thermal storage for later usage, or be used for district cooling (DC) during summer periods. Many different heat production systems can be connected to ensure stable and versatile district heating generation. Some conventional district heating technologies are; CHP plants producing both heat and electricity, excess heat from industry, agricultural processes and combustion of waste, renewable geothermal heat, solar thermal heat, heat pumps, and heat water boilers.

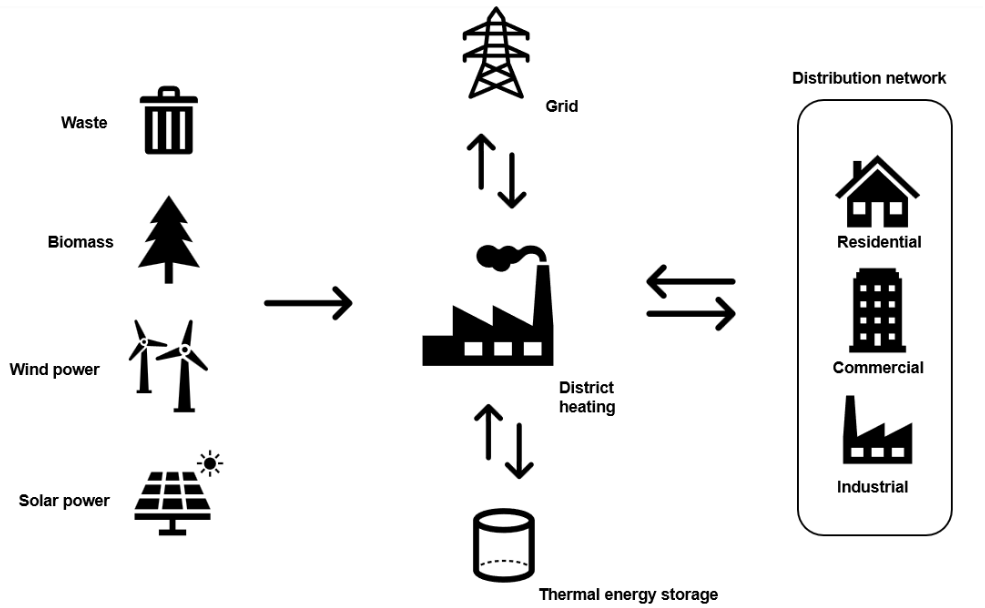

Figure 2.2: Schematic of a district heating network.

The rising electricity prices in Sweden have led to a decrease in electricity-based production in district heating systems [10]. This is during the same period when the need of flexibility and power balance in the energy sector is increasing because of more VRE. Fernqvist *et al.* [10] estimates the potential of P2H to be around 0.2-8.6 TWh in Swedish district heating systems. Even though P2H is an important part of the sector today, more P2H would increase the potential of utilizing district heating as a flexibility actor. His study promotes the opportunity for district heating systems to play an important role in the Swedish energy system, with an increased focus on adjustments of heat production, usage of more P2H technologies, and the utilization of electricity production in CHP plants.

2.3 Heat pumps

Large industrial compression heat pumps use electricity to convert energy from external heat sources, such as water or air, to useful heat [3]. The heat can then be used for space heating and hot water supply for homes and buildings. Their generation efficiency, output of around 3 times the input energy, makes heat pumps an effective technology for producing district heating. By consuming electricity from renewable energy sources can heat pumps produce sustainable district heating. It is important to note that heat pumps only can be sustainable if the electricity consumed is from renewable sources, with no harmful emissions. Heat pumps have a lower start-up time and cost in contrast to other conventional district heating technologies [2], such as CHP. By pairing heat pumps with TES can production be planned to produce heating when electricity prices are low, potentially reducing operational costs and greenhouse gas (GHG) emissions while providing a flexibility measure for the sector-coupled electricity market [3].

In Nordic countries, heat pumps make up a significant part of P2H production in district heating systems [3]. The deployment of heat pumps is region-specific in terms of connections, operations, and heat source availability. There is therefore no universal solution for the integration of heat pump systems. The integration of heat pumps does not always imply optimal heat production and if heat pump hours are limited, e.g. because of high electricity prices or restricted heat source availability, other alternatives such as conventional boilers can be more profitable.

2.4 Biomass boilers and CHP

Biomass boilers are used to produce heat by using bio-material as fuel [15], [16]. Their efficiency is around 90% produced heat per input energy. Biomass material can for example be wood pellets, wood chips, agricultural residues, crops, and some industrial and municipal waste. Biofuel can be used in solid, liquid, and gaseous states to produce energy, depending on availability. The boiler design is dependent on their fuel composition and state. Biomass heating typically includes a large boiler, backup boilers, fuel storage, and connected with pipelines to the local district heating distribution. District heating with biomass can be combined with CHP plants to generate heat and electricity, providing higher efficient systems and lower carbon emissions than individual boilers. This is because more of the produced heat can be utilized in turbines depending on the heat or electricity demand. Biomass CHP plants connected to district heating systems also enable a good opportunity to increase the percentage of renewable sources in energy systems as their production can act as a flexibility measure, producing heat or electricity depending on the demand.

The most economical alternative to run biomass CHP is to use the CHP as base load and keep back-up boilers for peak load [16]. There are also alternatives to include heat storage systems to maximize biomass CHP efficiency during fluctuations in heat demand, which could be caused by consumer behavior, VRE, and temperature variations. TES makes use of energy when demand is low, and stores it for usage during peak load periods. This study will include biomass CHP and biogas boiler to produce district heating, also analyzing how bio-fuel prices affect the cost-optimum outcome.

2.5 Aurora by Sigholm

Aurora by Sigholm is an operational software developed by the consultant company Sigholm to optimize production and planning for energy companies [17]. The tool gives a cost-optimal plan for different energy systems, based on their structure and needs, so energy plants can operate more cost-efficiently. The plans and models Aurora by Sigholm provides are based on the system structure, predicted weather forecast, historical data, and market electricity prices to deliver an optimized production plan for facilities. In this study, Aurora is used to evaluate the production of Vattenfall district heating system in Nyköping. By using the back-end model of their facility can new cases of operation be evaluated based on the data and structure of the system.

2.6 Idbäcksverket, Nyköping

The district heating system Idbäcksverket is a large facility producing both heat and electricity to the city's inhabitants in Nyköping, Sweden [18]. The facility is mostly fueled by renewable biomass, more precisely wood chips. Idbäcksverket is owned by the Swedish energy company Vattenfall. This study has had the opportunity to use Vattenfall's facilities for analysis and modeling.

The total capacity of Idbäcksverket is 82 MW, mostly producing heat from three boilers named: P1, P2, and P3. The facility also includes a TES, referred to as an accumulator in their facility, and a bio-oil boiler. The main producing unit is P3, which consists of a large boiler producing heat for distribution and by-products in the form of flue gas. The heat from the boiler can also be used in a turbine producing electricity, as flue gas is used in a flue gas condenser to produce extra heat, or by-pass directly to distribution. The P3 boiler system therefore works as a CHP system. The main parts of the boiler are illustrated in figure 2.3.

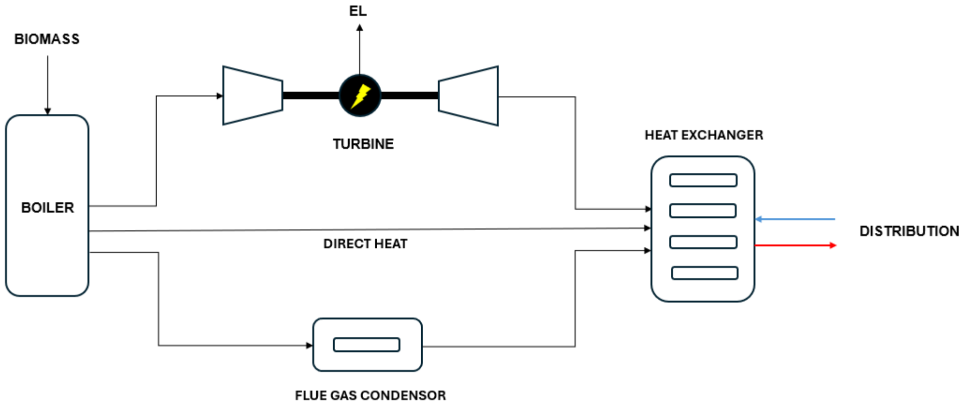

Figure 2.3: Schematic of the boiler P3 from Idbäcksverket used as a reference for the biomass CHP in this study.

The boilers P1 and P2, together with the bio-oil boiler, are wood chips boilers used for peak production in the facility. In this study was the P3 boiler and the TES used as inspiration for the biomass CHP modeling, together with the heat demand of Nyköping's facility. The following information regarding the plant was distributed by Vattenfall:

- Annual heat load data.
- Min & max-power on energy producing facility P3, its flue gas condenser and turbine. Fueled by mostly reclaimed wood and pressure-treated wood.
- Min & max-power on energy producing facility P1 & P2. Fueled by wood chips.
- Effect of oil-fuel boilers. Fueled by bio-oil. In operation until the latest 2025.
- Accumulator, its capacity and effect.
- Capacity of using Nyköpingsån, a stream, for cooling.

3
Methods

This section describes how the work is structured to achieve the aim and answer the research questions. The method's purpose is to give an understanding of the workflow of the thesis and how reliable results can be conducted. The method includes a description of the literature review and the data collection, followed by the system and model setup for the simulations. Last, the simulation cases were described together with the investment cost method.

3.1 Literature review

To design all components in the optimization model, the energy technology methods were studied to understand how to portray them accurately and construct respective constraints. The main focus of this research was on developing accurate models for heat pumps and biomass CHP in the context of linear optimization. This is crucial to identify the technical level at which results differ significantly.

The literature review also included a thorough examination of the various sensitivity factors presented in section 3.6. This enabled a better understanding of how to effectively incorporate them into the optimization model. Additionally, it helped identify the most significant factors influencing the operation and cost-effectiveness. Previously documented work in academia regarding energy modeling was reviewed, as well as already existing models in Aurora by Sigholm. From the literature review, mathematical formulations were created and used in the district heating model.

Since the model was built based on the reference Vattenfalls district heating system Idbäcksverket in Nyköping, communication with representatives was maintained to understand the heat demand, plant figuration, and systemic structure.

3.2 Data collection

To set up a district heating model, overall techno-economic parameters concerning the energy equipment in the model were required to make accurate estimations of performance, costs, and energy output. This data was taken from the Danish Energy Agency [2] and from existing models in Aurora by Sigholm.

Historical heat load curves were necessary to set up the heat demand for the simulation model. As mentioned in section 2.6, heat load data from Vattenfall was utilized to achieve this. The statistics were heat load demand during the years 2019-2023, where the load curve of 2019 was used in this study. Data from the years 2020-2023 was used to compare and mitigate faults in the load curve of 2019.

The annual spot price of electricity used in the simulations, illustrated in figure 3.1, was distributed by Chalmers University of Technology for the years 2019 and 2050. The two curves represent a present and future scenario on the electricity market. These were used to evaluate the performance of the heat-producing technologies in the context of great change to the future electricity market. The prices are electricity spot prices in SEK/MWh. The year 2019 was selected because Chalmers had estimated their future price curves for 2050 on this year. The prices are based on work by Göransson *et al.* [7], Bertilsson *et al.* [5], and Öberg *et al.* [8] from Chalmers, in their linear investment optimization model of northern Europe.
Their work applied a greenfield approach to the year 2050 by using weather data and demand from 2019, and thereafter identifying cost-optimal investments and operations. This resulted in an optimal marginal cost of electricity, which was used as a proxy for a future electricity spot price. The future energy mix in their model was dominated by wind power, nuclear power, and solar PV. All investment decisions are therefore predicated solely on the energy demands of the modeled year, without any pre-existing production technologies or storage systems for heat and electricity, except for existing hydropower and recently built nuclear power. This resulted in a prediction of the electricity price curve in 2050 with more intermittent electricity production. In this study are the prices for the area of southern Sweden (SE3) used for both 2019 and 2050.

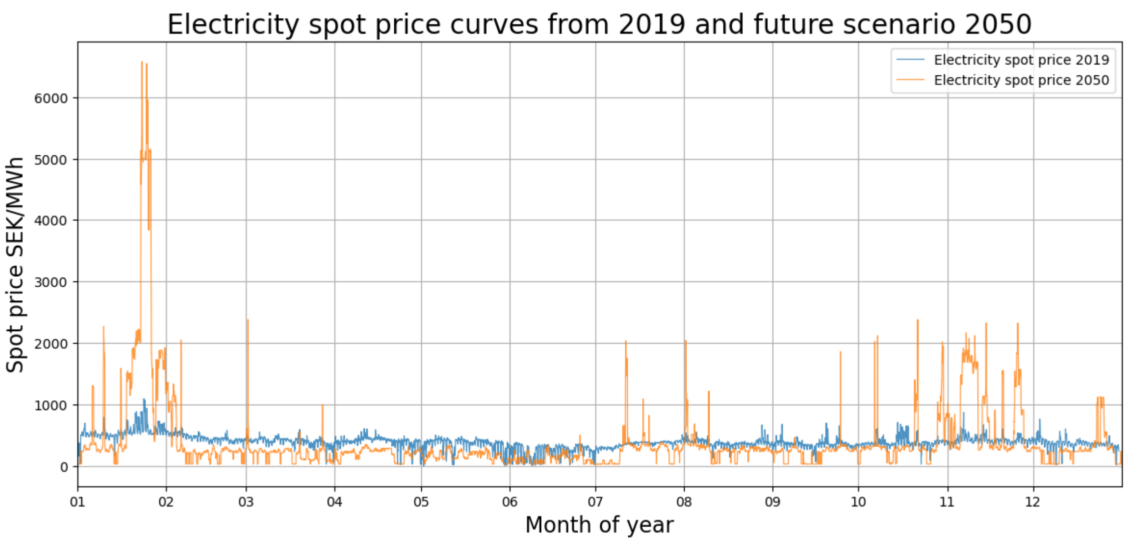

Figure 3.1: Prices for electricity over time. The orange line represents the projected future electricity price of 2050. The blue line represents the actual electricity spot market price in year 2019.

Other related curves for the model were temperature distributions, which coincide with the price curve in terms of date. The temperature distribution included supply- and return temperatures, distributed by Vattenfall in Nyköping. The outside ambient air temperature during the year 2019 in Nyköping was found on Open-Meteo [19].

The availability of heat sources for the heat pumps affects the COP. The common source medium for large-scale heat pumps used in district heating is ambient air and water. Vattenfall system has access to both.

Heat pumps using air have lower efficiency and performance compared to heat pump systems using water. To bring depth to the study and the hypothesis, as described in section 1.1, that heat pumps are a more cost-effective alternative for heat production compared to biomass CHP, was ambient air compression heat pumps used in this study. This reasoning suggests that if air compression heat pumps are more profitable than biomass CHP, the same outcome is predicted for water source heat pumps.

3.3 District heating system

Information regarding the district heating system Idbäcksverket was distributed by Sigholm and collected through their software Aurora by Sigholm, together with data exchange and communication with Vattenfall. The district heating model incorporates already existing constraints and limits in the Idbäcksverkets model with additional parameters to fit the purpose of this research.

Idbäcksverket system was illustrated in data files, including the main units and their parameters. Units representing heat pump and boiler technologies were included, as well as parameters for loads and efficiency. The files also include heat- and electricity balances, electricity price curves, load duration curves, taxes, biomass prices, and tariffs. The data files were edited to fit the preferred set-up for the study, mainly by controlling parameters and unit availability from a script.

By using these scripts, new energy technology methods, such as heat pumps and boilers, were included in the system, and additional parameters were introduced. These were based on the information gathered from the literature review on how to create detailed and accurate models of energy technologies. Some of the important parameters used were new load curves and electricity-price curves, as well as heat-producing components. The end goal was to create a configurable model where the different factors, shown in section 3.6, are customized to create different scenarios and cases.

The power-to-heat tax, tax for electricity, was set to 428 SEK/MWh which is the current tax value in Sweden [20]. The import and export tariffs for Idbäcksverket were 66 SEK/MWh - 189 SEK/MWh [21]. The selected price of biomass was 335.7 SEK/MWh (30 €/MWh) for both scenarios 2019 and 2050 [5]. This was set as a constant price during the simulations and is further analyzed in the sensitivity analysis.

It is important to note that the model only considers calculations of the variable cost of the annual production, as mentioned in section 1.4. Investment analysis is not included in the simulation. Instead, investment costs and fixed costs are included as external factors in the comparison between the technologies by a levelized cost of heat (LCOH) analysis.

3.3.1 Heat pump system

To model the heat pump, technical data from the Danish Energy Agency was used to collect parameters for capacity, start-up costs, and variable costs [2]. The parameters were based on a 10 MW air source compression pump. The COP was selected to be 3.0, a conservative estimation as the COP usually is estimated to be higher. Since the COP is dependent on source temperature, a lower value is often selected to mitigate underestimations of the performance during cold seasons. For example, a value of 3.8 is selected for COP according to the Danish Energy Agency. A similar conservative estimation of heat pump performance, 3.0 COP, was used by Bertilsson *et al.* [5] and Gaur *et al.* [22].

To realistically model the heat pump system, it was necessary to investigate what max capacity would be reasonable for an 82 MW district heating plant, considering a sensible amount of full load hours. This is crucial for investment opportunities and to ensure a system that generates more than it remains idle. Based on the conducted research, it was recommended that each heat pump of the system should be operational for at least 4000-5000 hours per year, as suggested by Bertilsson *et al.* [5]. In his research, the heat pump's max capacity ranged around 50-52% of the total maximum capacity of the observed systems.

To explore this further, a model was set up with heat pumps divided into units of 10 MW district heating each, totaling 8 heat pump units with a total capacity of 80 MW heat. This implies a framework for analyzing the operating hours for each unit. The operating hours and heat production for each heat pump were observed qualitatively in a stacked load duration curve. Using Bertilsson's *et al.* [5] work as a guideline and the simulation results of a heat pump-only model, a suitable heat pump capacity was selected to represent the heat pump generation in forthcoming simulations.

Moving forward, the heat pump system was represented as a single unit, despite consisting of multiple 10 MW air source heat pumps in the capacity analysis mentioned above. This is not entirely accurate as each heat pump incurs a start-up cost. However, the start-up cost is very low for heat pumps and has a negligible effect on the variable cost of the system [2]. Therefore, for simplicity and convenience, the heat pump system was still modeled as a single unit in the simulation.

3.3.2 Biomass CHP system

The units used in the Biomass CHP system are based on the setup in Idbäcksverket, with a capacity of 82 MW. The system model includes a main biomass-fueled boiler, a turbine running on steam, and a flue gas condensing system. This was inspired by the P3 unit used in Idbäcksverket, see section 2.6. The system can therefore produce both heat and electricity at the same time depending on the situation. This as the turbine provides an extra alternative for the system to produce electricity when the heat demand is lower, and at the same time delivers heat by-passing the turbine system.

To create a feasible and profitable system where the biomass boiler, turbine, and flue gas condenser cover a large part of the heat demand during the year was the full load hours for the biomass CHP unit evaluated for different capacity levels. The full load hours were calculated by dividing the total production of the biomass CHP unit by the maximum heat capacity. The capacity of the biomass CHP units was then selected to match at least 5000 full load hours. The selected capacity after this analysis was then used for all the simulations.

The efficiency of heat production was set to 90% and for electricity 28% [2]. Additional technical data for the biomass CHP system is presented in Appendix A.2.

3.3.3 Peak production units

The comparison in this study revolves around two main technologies, namely, heat pumps and biomass CHP. These technologies will be used as base load technologies in their respective simulations. Additionally, to manage seasonal variations and meet peak heat demand, backup production is required. When producing heat for peak production, also known as spiking or shaving, additional technologies were implemented in the model to support the system. Two different technologies are used for this purpose: an EB with electricity as input fuel, and a biogas boiler (BB) producing heat from biomass converted into biogas. The simulation will determine which technology to use in each specific situation, based on whether electricity or biomass as fuel is the most profitable solution.

EB uses electricity to produce heat, with an efficiency of around 99% [23]. The EB is feasible to run during hours when heat production costs for heat pumps or biomass CHP are high, and it's the current optimal P2H choice of support.

The other alternative for peak production to support the system is BB, a type of heat-only boiler (HOB). This technology uses biogas as fuel for heat production. The choice of running the BB is much dependent on the main production unit and the gas price. The price for biogas in €/MWh in the model is estimated from the biomass price according to equation 3.1, similarly was done by Bertilsson *et al.* [5].

$$Price_{biogas} = \frac{Price_{biomass}}{0.7} + 20 \tag{3.1}$$

3.3.4 Thermal energy storage

All models include thermal energy storage (TES), referred to as an accumulator. The storage stores heat produced from the district heating system for later usage. In this way can the system take advantage of excess heat during production and make use of the stored heat when electricity prices are high. Under optimal conditions, the TES has a storage capability of up to 500 MWh according to Vattenfall. However, in the existing model used to optimize the production of Idbäcksverket, the maximum storage level of 370 MWh was used, which is an estimate of volume in poor conditions. The minimum storage level in the model is set to 100 MWh, which reflects the storage usage as a safety measure. With these parameters, the effective energy storage in the model is estimated to be 270 MWh. The impact of the size of the TES is investigated further in the sensitivity analysis.

3.4 Model definition

The applied mixed integer linear programming (MILP) optimization model is developed by Sigholm and their software Aurora by Sigholm. The model minimizes the variable cost of the system by using an objective function taking running operational costs, capacity, produced electricity, and heat production into reference.

The total variable cost of the system was minimized by considering the energy sources used (biomass, biofuel, or electricity) and multiplying appropriate costs based on the system and unit. These costs include fuel and electricity costs, variable costs, and emissions costs. A start-up cost was added each time a unit was started. Any economic gains from selling produced electricity using the CHP decreased the total variable cost. The total variable costs were calculated for each timestep, summarized, and minimized as part of the objective function. The model incorporates binary values to set minimum and maximum criteria for units, constraining units to work within set limits or be turned off.

For each hour, it is necessary to produce enough heat or discharge it from the accumulator to meet the district heating demand and accumulator charging requirements. State of charge concerning the accumulator was determined by the charge level of the previous timestep. Limits on unit and accumulator capacities were determined using parameters for min and max load provided by Vattenfall or found through literature study.

3.5 Optimization strategy

Annual optimization strategies, referred to as simulations, of the production of the district heating systems were made in this study. The systems were divided into two different operational cases, one with compression heat pumps and another with biomass CHP producing heat and electricity. The total annual variable cost was minimized for both technologies during several scenarios. Simulations including the factors in the sensitivity analysis, see section 3.6, were set up as part of the comparison between the technologies. Initially, the first focus was to establish the base setup of the model, assess the factors, and enable feasible and correct yearly simulations for all scenarios.

The software Aurora by Sigholm currently simulates and forecasts weekly predictions of the systems operation, and delivers the optimized production plan to their customers. In this study was this method used to simulate a whole year of operation for the district heating system in Python, using GAMS as a solver.

A possibility to simulate a whole year, showing results hour-by-hour, was created by dividing the simulation into 52 sub-simulations, representing the number of weeks in a year. This shortened the simulation time. For the simulation to generate a realistic representation of the yearly production was the weekly sub-simulations programmed to overlap. This was made by making each simulation 9 days long, while only 7 days were used in the results. The overlap enabled to save data from the previous week and use it as reference points for the upcoming sub-simulation, which ensured that the simulations could predict and prepare a more optimal pathway for the system. Otherwise, each sub-simulation would have been more independent. Instead, each simulation got better foresight of the production. The reference points saved in the semi-perfect foresight were data on the TES levels and the operating status of the units.

3.6 Sensitivity analysis

The study includes a sensitivity analysis and case-oriented evaluations. This investigates under which circumstances technical aspects, energy prices, and taxation affect the result in the model and the consequences they bring in terms of operational and investment decisions. The following factors under analysis and how they are explored are presented in a list below to answer the research questions of the thesis.

- **Temperature-dependent COP**
  One of the greatest factors that affect the performance of a heat pump is the temperature difference between the heating supply and the source. The performance and cost-effectiveness of heat pumps in an energy system are therefore heavily reliant on the temperature conditions and might not operate if this difference is too large. The temperature dependence of heat pumps is therefore investigated by exploring different approaches to COP estimations.

- **Prices of biomass fuel**
  The variable cost of producing heat when using a biomass is heavily dependent on the cost of fuel. This factor influences the cost-effectiveness of boilers. Biomass prices were gathered from the literature review and future price changes were predicted to simulate this impact on the system cost.

- **Power-to-heat tax**
  The power-to-heat tax is the added tax when using electricity to create heat. This affects the variable cost of P2H technologies such as heat pumps and EB. This factor was analyzed by implementing different scenarios of taxation on electricity-based heat production.

- **Thermal Energy Storage**
  TES involves the capture of heat energy for later use. This technology allows for additional heat capacity paired with other heat production technologies in a district heating system. By mitigating fluctuation in heat production, TES can enhance overall energy efficiency in a system, yet this often results in a higher investment cost. The influence on the system due to storage capacity was analyzed by varying the size of the thermal storage.

3.7 Cases

The following section describes how the district heating cases are set up for each simulation. The investigated cases were based on the model set-up as described in section 3.3. Then, each case was described with its specific parameters and equations. The cases were simulated for a contemporary and a future scenario: 2019 and 2050. Last, sensitive factors from the sensitivity analysis are explored for each technology individually or together. See figure 3.2 for a schematic of the case structure.

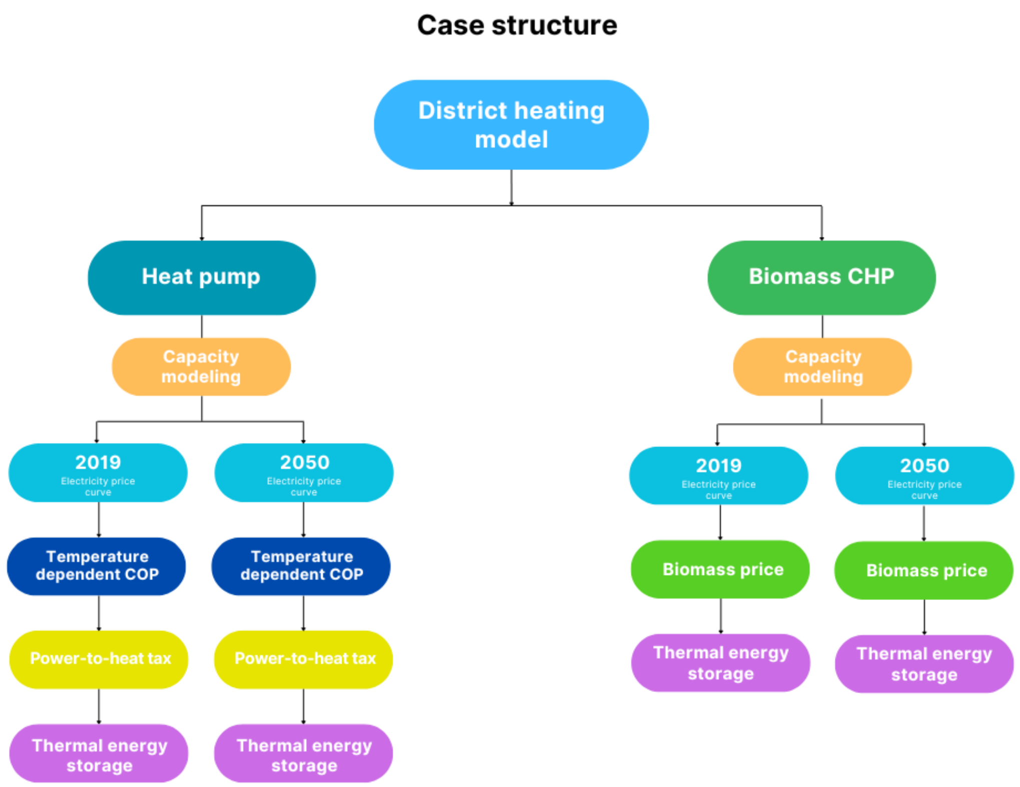

Figure 3.2: Schematic of the case structure showing the analysis of each technology. Both heat pumps and biomass CHP have capacity modeling, simulations for 2019 and 2050, and investigation of TES size influence. For heat pump, the COP approximations are simulated together with a sensitivity analysis of the electricity tax. The biomass price for the biomass CHP system is also analyzed as separate cases.

3.7.1 Heat pump and biomass CHP simulation

To investigate which heat production technology is the most effective and profitable alternative in the Swedish energy sector, today and in the future, was two cases created based on the method presented in section 3.3. One case includes heat pumps as the main heat production unit, and the other a biomass-based CHP system. Peak production technologies, EB and BB, were included in both systems to cover the remaining heat demand, together with TES. The two different systems were simulated with parameters and electricity curves from both 2019 and 2050, resulting in the total annual variable cost for each system and scenario.

3.7.2 Biomass price

The price of biomass is expected to change in the future, something that already has an impact on district heating production using biomass as fuel. To investigate how the price affects the total annual variable cost of biomass CHP production were different prices evaluated. The highest prices was set to 50 €/MWh and the lowest price to 20 €/MWh. The results are compared to the current price of 30 €/MWh. The lower price was set as the tipping point from where biomass CHP becomes more profitable compared to heat pumps according to the work of Bertilsson *et al.* [5], and Göransson *et al.* [7]. The price levels above 20€/MWh should be favorable for heat pump production. The biogas price in the model was also varied according to equation 3.1. This sensitivity analysis was conducted for both electricity price scenarios 2019 and 2050.

3.7.3 Power-to-heat tax

The electricity tax in Sweden is currently around 428 SEK/MWh (39 €/MWh). The taxation is under discussion to be decreased to a lower level to further increase incentives for the expansion and use of electric-driven heat production. To test the impact of a lower electricity tax the electricity tax regulations from Finland used, which is part of the European Union minimum level, and was lowered by 97 % in 2022 [24], [25]. This states an electricity tax of 0.63 €/MWh to represent this potential catalyst to promote electricity-based heat production. A tax of 20 €/MWh was also investigated to bring depth to the analysis.

3.7.4 Sizing of TES

In this case, the capacity of the TES was varied to investigate its impact in the comparison between the heat pump and biomass CHP cases. The storage was expanded to a capacity of 1000 MWh effective storage. This was done to evaluate the storage impact and flexibility on the system and the total variable cost in 2019 and 2050.

Data was taken from the Danish Energy Agency [2], for TES properties (lower capacity), and the higher capacity is a reasonable increase of the storage to analyze based on current establishments on TES in the Swedish system today.

3.7.5 Beneficial scenario for electricity-based heat production

Additionally, a heat pump scenario beneficial for electricity-based heat production was created. This brought further depth to the analysis of the future situation for the Swedish district heating sector. The case included a large TES combined with a low electricity tax, indicating a potential direction toward a system where heat production is produced from electricity. The scenario was simulated for both the electricity prices of 2019 and 2050.

3.7.6 Performance modeling of Heat pumps

The following cases investigate the impact of the COP on heat pumps. The cases were simulated with electricity prices from 2019 and future scenario 2050.

3.7.6.1 Constant COP

Firstly, a simulation heat pump case with a constant COP was created to serve as a reference for temperature-dependent COP estimation. The constant COP was set equal to 3.0 [22]. This estimation was also used in all other heat pump cases, e.g. the sensitivity analysis of the electricity tax and TES.

3.7.6.2 Lorenz COP approach

A more detailed model of a heat pump and its effect on heat production can be made by having the COP dependent on supply-, return-, and source temperatures in the system. The source temperature is the outside air temperature for each hour in Nyköping. The supply and return temperatures are the required temperatures to produce heat in the heat pump. The Danish Energy Agency proposes the usage of the Lorenz formula for estimating the COP for industrial-scale heat pumps [2]. The Lorenz COP is shown in equation 3.2 below, taking the logarithmic mean of the in- and outflows of the heat source and heat sink respectively:

$$\mathrm{COP_{Lorenz}} = \frac{T_{\mathrm{lm,\ sink}}}{T_{\mathrm{lm,\ sink}} - T_{\mathrm{lm,\ source}}} \quad \text{where,} \quad T_{\mathrm{lm}} = \frac{T_{\mathrm{in}} - T_{\mathrm{out}}}{\ln\left(\frac{T_{\mathrm{in}}}{T_{\mathrm{out}}}\right)} \tag{3.2}$$

The real COP value, practically attainable, is lower because of component efficiency. In other words, mechanical and thermal losses, and can be calculated by using the Lorentz efficiency for heat pumps:

$$\text{COP}_{\text{real}} = \text{COP}_{\text{Lorenz}} \cdot \eta_{\text{Lorenz}} \tag{3.3}$$

Where η_{Lorenz} is between 0.4 - 0.6. The efficiency used is 0.5 in this study for heat pumps with capacity of 10 MW according to the Danish Energy Agency [2].

3.7.6.3 Empirical approach of COP

Another way of modeling heat pump performance is investigated by using an Empirical approach to calculate COP, a method adopted by Schlosser *et al.* [26], Jesper *et al.* [27], and Trabert *et al.* [28]. The studies investigate the influence of system design and operation conditions on the COP for large-scale heat pumps, both air and water source heat pumps. They recommend one advantageous estimation, bringing justice to the COP calculations as the Lorenz approach can estimate COP very differently from reality.

The approach was made for heat pumps with thermal power >0.8MW and a natural refrigerant called R717 (ammonia), operating at high inlet temperatures. An approximation of a theoretical estimation for COP, as made in the previous heat pump case and section 3.7.6.2, was made through regression analysis. The analysis uses mathematical correlations between COP and operation conditions for the heat pump to find the most realistic COP with the lowest residuals (deviations). The approximation reduces the standard deviation and increases the coefficient of determination. This resulted in an Empirical equation, see equation 3.4, using fit parameter a, b, and c together with the temperature lift ΔT_{lift} and heat carrier temperature at condenser outlet $T_{\text{H,out}}$ (inserted unitless) in [K].

$$COP_{\text{Empirical}} = a \cdot (\Delta T_{\text{lift}} + 2b)^{c} \cdot (T_{\text{H,out}} + b)^{d} \tag{3.4}$$

Fit parameter [-]

$a \;\; = 1.4480 \cdot 10^{12}$
$b \;\; = 88.730$
$c \;\; = -4.9460$
$d \;\; = 0.00$

Range of validity:

$-10^\circ\,\text{C} \leq \Delta t_{\text{l,in}} < 60^\circ\,\text{C}$
$25^\circ\,\text{C} \leq \Delta t_{\text{h,out}} < 100^\circ\,\text{C}$
$10\text{K} \leq \Delta T_{\text{lift}} < 78\text{K}$

To further approximate the influence of more detailed modeling of heat pumps was $COP_{\text{Empirical}}$ implemented and simulated as a new case. This brings depth to the analysis of the COP.

3.8 Summary of the cases

To bring further understanding of the cases were the mentioned factors under analysis for the simulations summarised and listed in table 3.1. Peak production units and TES were included in both heat pump and biomass CHP cases. This was also the simulations of current- and future scenarios (modeled with different electricity price curves). The investigation of a more detailed approach for modeling heat pumps is included in the heat pump cases. The biomass price was analyzed for biomass CHP and electricity tax for heat pumps.

Factors under analysis	Heat pump	Biomass CHP
Peak production units	Yes	Yes
Capacity analysis	Yes	Yes
Current scenario (2019)	Yes	Yes
Future scenario (2050)	Yes	Yes
Lorenz formula COP	Yes	No
Empirical approach COP	Yes	No
Biomass price analysis	No	Yes
Power-to-heat tax analysis	Yes	No
Thermal energy storage	Yes	Yes

Table 3.1: Included factors in cases for heat pump and biomass CHP.

Technical data and costs for all the production units are listed in table A.1 in Appendix A.2 based on data from the Danish Energy Agency [2]. The parameters were used in the models and simulations of the different cases.

All values used for fuel prices and tax are presented in table 3.2.

Fuel/Tax	Scenario 2019	Scenario 2050	Sensitivity Analysis
Biomass (€/MWh)	30	30	20 / 30 / 40 / 50
Biogas (€/MWh)	62.8	62.8	48.6 / 62.8 / 77.1 / 91.4
Electricity tax (€/MWh)	39	39	0.63 / 20 / 39

Table 3.2: Prices and tax-values used in the different cases.

3.9 Levelized cost of heat

The investment cost calculations were made by taking technical data from the Danish Energy Agency [2] and calculating the investment and operational costs of the different systems using the levelized cost of heat (LCOH) concept [29], see equations 3.11 - 3.14.. This was made by taking the levelized investment cost (INV), variable O&M cost (VAR) (from results in simulations), and the fixed O&M cost (FIX). LCOH also includes the capital recovery factor (CRF), the net annual production (AEP_{net}), installed capacity (s), a discount rate of 5% (r), and the economic lifetime (n) of the technology.

$$LCOH = INV + FIX + VAR \tag{3.5}$$

Where the levelized investment cost and CRF is:

$$INV = \frac{I \cdot s \cdot CRF}{AEP_{net}} \tag{3.6}$$

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{3.7}$$

The fixed O&M cost can be calculated in a similar way:

$$FIX = \frac{F \cdot s}{AEP_{net}} \tag{3.8}$$

The values used to calculate the LCOH (€/MWh), including nominal investment cost (I) and fixed costs (F), for each technology are listed in table 3.3 below. The variable O&M cost, including fuel costs, for each system was generated through the simulations.

Technology	**I (M€/MW)**	**F (€/MW)**	$\mathbf{AEP_{net}}$ **(MWh)**	**s (MW)**	n **(years)**
Biomass CHP	3.5	149 000	Simulation	40	25
Heat pump	0.86	2000	Simulation	40	25
Electric boiler	0.07	0	Simulation	50*	20
Biogas boiler	0.06	1700	Simulation	50*	25

Table 3.3: Data for the technologies biomass CHP, heat pump, EB, and BB. The values are for 2019 [2]. The AEP_{net} was conducted in the simulations. Note that the nominal investment cost for Biomass CHP was for MWe (electricity).
* Used as peak production limit, org. around 25 MW.

4
Results

In this chapter are the results presented and explained by figures, tables, and descriptions. The results answer the research questions and include variable total cost, LCOH, COP estimations, and sensitivity analysis for the simulated cases.

4.1 Heat pumps compared to Biomass CHP

The following section presents the results that lay the ground for the comparison between heat pumps and biomass CHP.

4.1.1 Heat pump capacity

The capacity of heat pumps was explored by analyzing the operating hours per MW installed capacity per unit, see figure 4.1 and Appendix A.1.

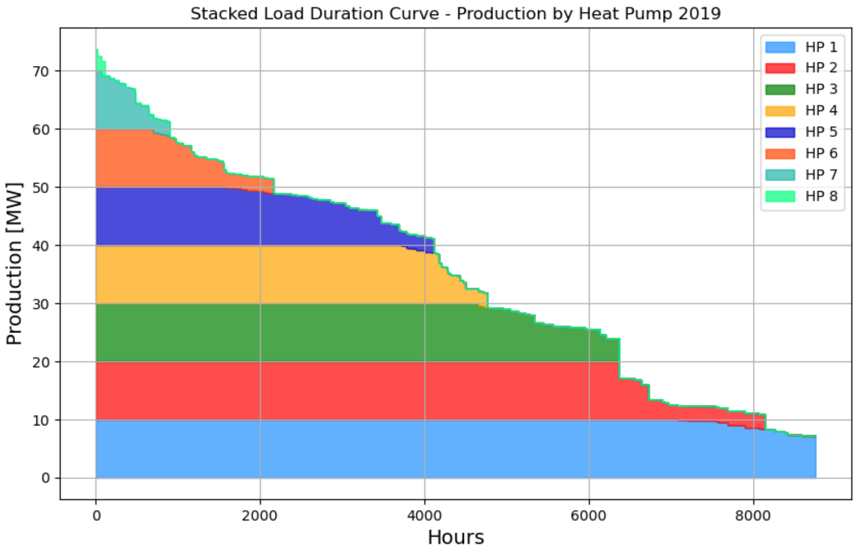

Figure 4.1: Stacked load duration curve of heat pump production. A minimum of 4000-5000 operating hours indicates around 40 MW production capacity, see the yellow heat pump number 4 as the limiting unit.

The district heating system with heat pumps was divided into 10 MW units, ranging up to a total of 80 MW capacity. This analysis indicated that around 40 MW capacity for the heat pumps is reasonable to achieve a minimum 4000-5000 operating hours for each heat pump. Therefore, a maximum capacity of 40 MW was selected for the heat pumps. This also aligns with Bertilsson *et al.* [5]; the heat pump system has a max capacity of approximately 50% of the whole system's max capacity.

The heat pump model used throughout this thesis is based on this evaluation, heat pumps are represented as a 40 MW unit with available peak production and TES. The full load hours for the heat pump unit in this system were calculated to be 6300 hours.

4.1.2 Biomass fired CHP capacity

Load level simulation using the Idbäcksverket model as reference showed that 40 MW of max heat capacity for the biomass CHP proved to yield a fair comparison with heat pumps, see table 4.1. This resulted in 6743 full load hours for the system. This was determined by dividing the annual biomass CHP production by its maximum capacity. The aim was to have over 5000 full load hours but also to generate a fair system comparison with the heat pump system. Two simulations, 40 and 50 MW, both accomplish enough full load hours. The latter of 40 MW was selected to yield the study and comparison. The selection was based on creating a more efficient production for the system and minimizing costs by using a system where all units are active most of the operational time. This yields 14.8 MW nominal maximum- and 3 MW minimum power generation generation by the turbine.

Max Capacity CHP [MW]	**Full Load Hours [h]**	**Total Heat Production [GWh]**
40	6743	270
50	5719	285
60	4820	289
70	4079	285
82	3463	283

Table 4.1: Full load hours and total heat production for different max capacity levels of biomass CHP.

4.1.3 Total variable cost

The total annual variable cost of the cases was calculated in the simulations. The results are used in the comparison between the heat pump and biomass CHP systems. The total cost depends on the structure of the system, the main heat-producing technology, the overall efficiency of the system, and the prices of electricity, biomass, and fuels. The two heat- and electricity-producing technologies, heat pump and biomass CHP, are simulated for the year 2019 and 2050. The four different cases are presented in figure 4.2. The annual operational strategies, including heat demand and production over the year, for the cases can be viewed in Appendix A.3, in figures A.2 to A.5.

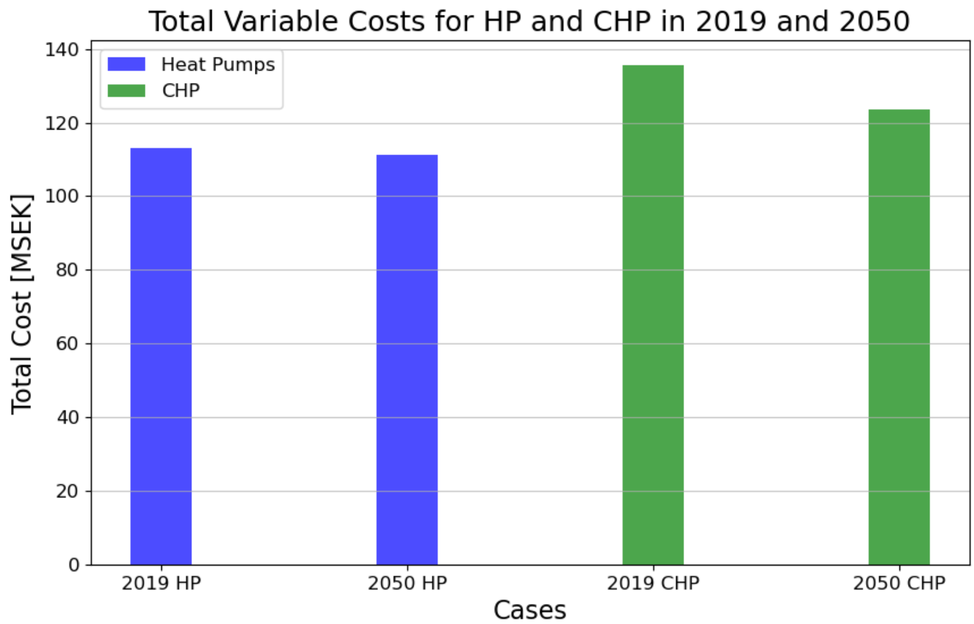

Figure 4.2: The total annual variable cost for the heat pump case and the biomass CHP case, simulated for both 2019 and 2050.

The bar chart illustrates the heat pump system to be around 20 MSEK more profitable than CHP during 2019, and approximately 12 MSEK in 2050. Important to note is that the biomass price is the same for all cases (30 €/MWh). Both cases show a reduction of cost in the future scenario.

4.1.4 LCOH

The calculated levelized cost of heat (LCOH), from equations 3.11 - 3.14, for each system is presented below, see figure 4.3. The simulated AEP_{net} was 310 332 MWh.

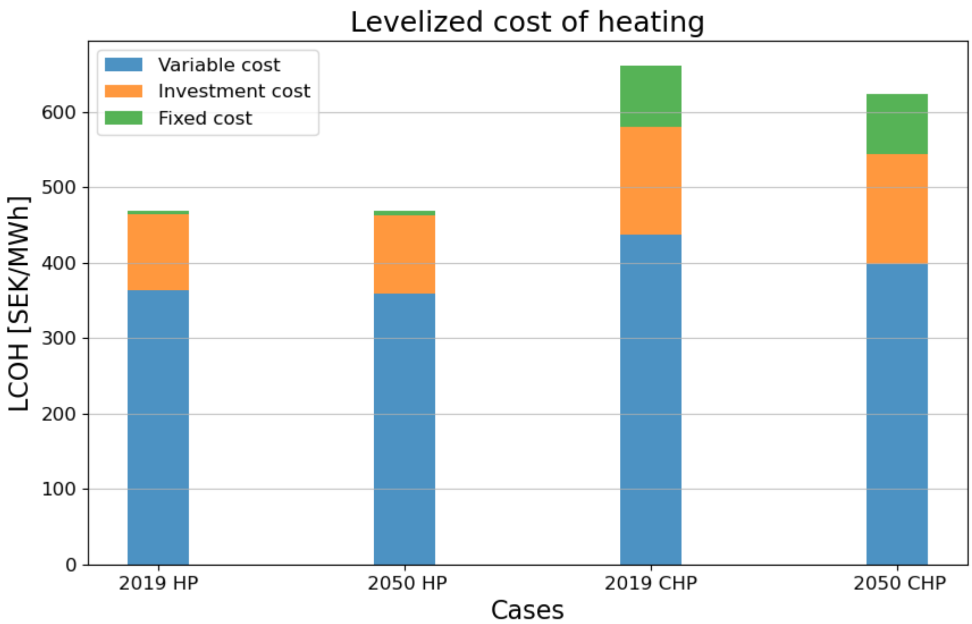

Figure 4.3: The LCOH for each system case showing the investment-, variable- , and fixed costs in SEK/MWh.

The results show a lower LCOH for heat pump systems, around 470 SEK/MWh. The LCOH is higher for the biomass CHP, reaching a total levelized cost of heat of 650 SEK/MWh in 2019 and 620 SEK/MWh in 2050.

4.2 Price of Biomass

The following results show the sensitivity analysis of the biomass price and how it affects the variable cost of the biomass CHP district heating system, for simulation years 2019 and 2050. Prices in the range between 20 €/MWh to 50 €/MWh were simulated to see how the market price of biomass influenced the results and the comparison. The analysis is presented in figure 4.4. The annual operational strategies can be viewed in Appendix A.3, in figures A.6 to A.9.

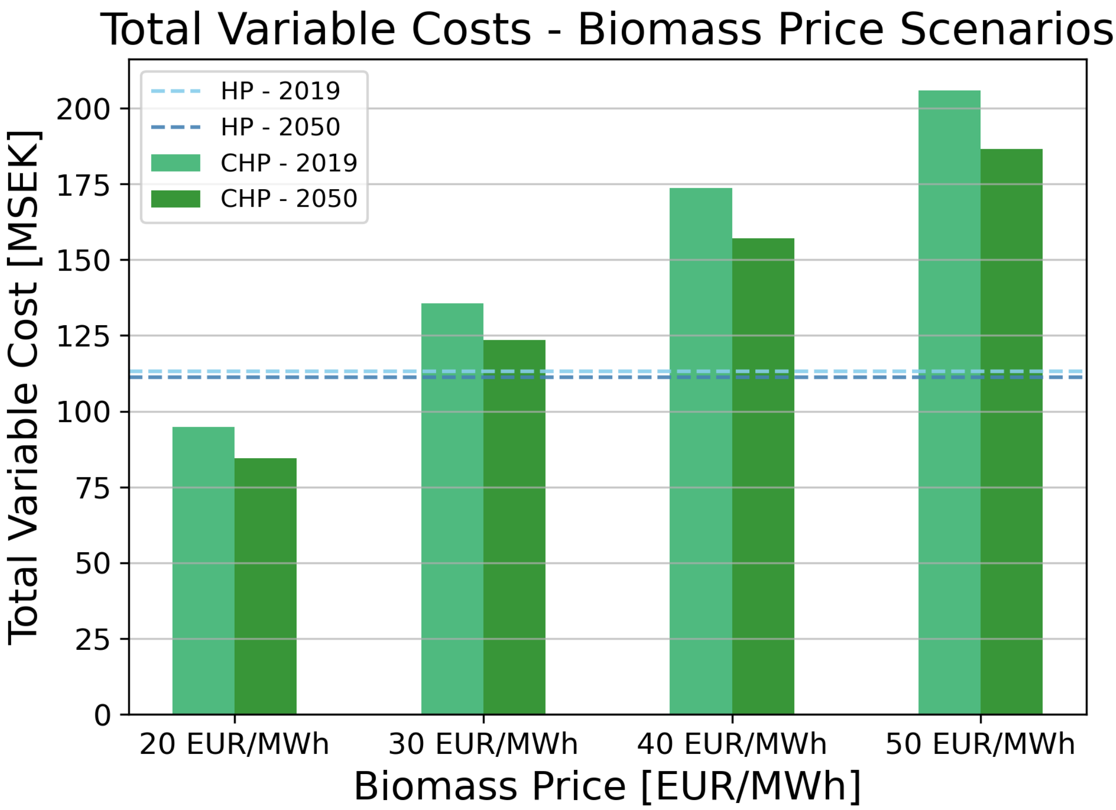

Figure 4.4: The biomass CHP system simulated with different prices of biomass. The dotted blue line shows the variable cost for the heat pump system using bio-price 30€/MWh, in 2019 and 2050. Biomass price scenarios are shown for both simulation years 2019 and 2050.

The results indicate an increasing variable cost for the system when the price of biomass increases. The tipping point between heat pumps being more profitable than biomass CHP occurs when the price is lower than 30 €/MWh, more precisely around 20€/MWh. The cost decrease in scenario 2050 compared to 2019.

4.3 Electricity tax on heat generation

The impact of the electricity tax, power-to-heat tax, is investigated by simulation of the district heating system powered by heat pumps. Three levels of tax are evaluated: 6, 200, and 428 SEK/MWh for simulation years 2019 and 2050. This resulted in the following total variable cost for the system, see figure 4.5. Annual operational strategies using different electricity tax rates can be viewed in Appendix A.3, in figures A.10 and A.11 respectively.

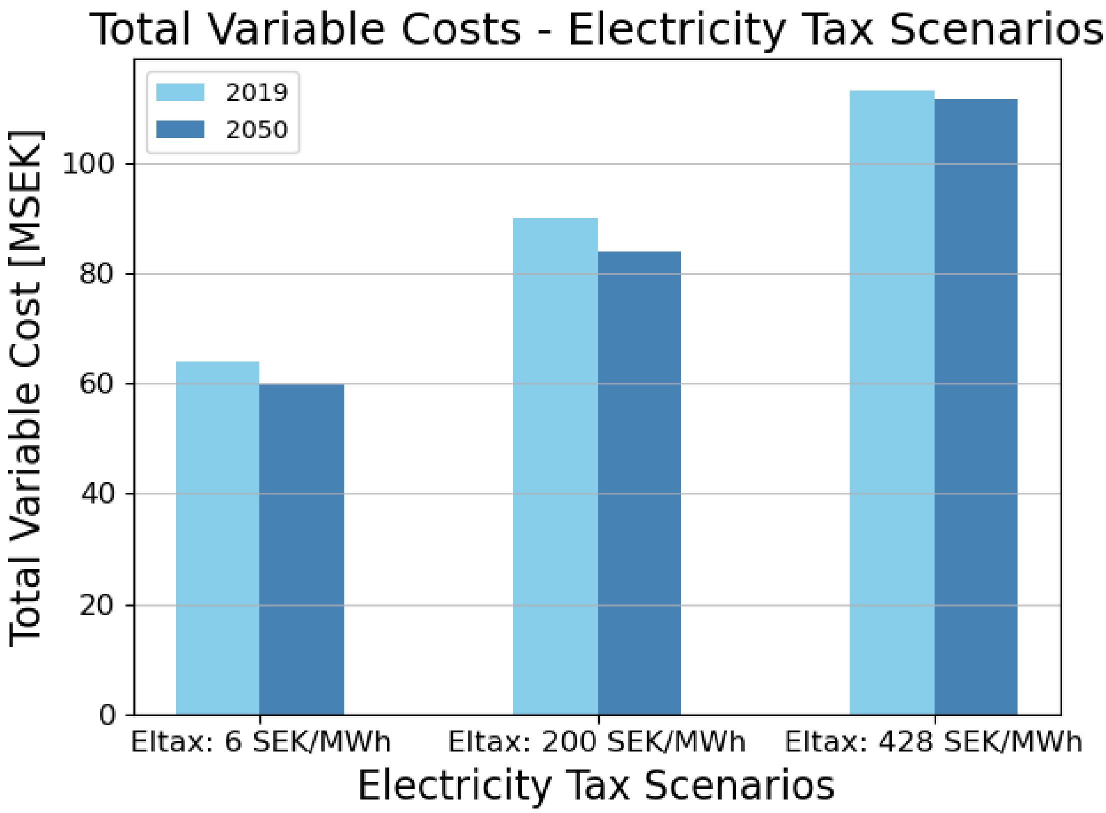

Figure 4.5: Total variable cost for the HP system, simulated with three electricity tax scenarios for simulation years 2019 and 2050.

The sensitivity analysis of the electricity tax shows a great difference between the tax levels. The values for a lower tax could reduce the system's annual variable cost by around 60 MSEK, if the tax is reduced from 428 to 6 SEK/MWh. A 200 SEK/MWh tax decreases the variable cost by around 25 MSEK. The cost reduction is apparent for both simulation year 2019 and 2050. The variable costs are lower for the simulation year 2050 compared to the simulation year 2019.

4.4 Sizing of Thermal Heat Storage

The thermal heat storage is analyzed by adjusting the storage maximum and minimum capacity and the output and input of the thermal tank. Two levels of 270 and 1000 MWh with increased in- and output capacity scaled in proportion to the energy volume increase/decrease, see table 4.2. The results are for scenarios 2019 and 2050. The annual operational strategies can be observed in Appendix A.3, in figures A.14 to A.15.

Thermal Storage Scenarios	**Total variable cost [MSEK]**	**Total Peak Production [GWh]**
HP 2019 - Storage 270 MWh	113.1	52.5
HP 2019 - Storage 1000 MWh	112.6	51.6
CHP 2019 - Storage 270 MWh	135.6	36.9
CHP 2019 - Storage 1000 MWh	134.3	36.4
HP 2050 - Storage 270 MWh	111.3	55.8
HP 2050 - Storage 1000 MWh	109.2	55.9
CHP 2050 - Storage 270 MWh	123.5	55.9
CHP 2050 - Storage 1000 MWh	122.6	62.1

Table 4.2: Thermal storage scenarios, raging from 270 MWh to 1000 MWh.

The impact of the TES shows small changes in the total variable cost. Still, with a higher capacity for TES, the cost is decreased, and so also the peak production of the district heating system.

4.5 Potential future scenario beneficial for electricity-based heat production

To further investigate how the storage can be important in the future and as a flexibility factor is a large storage of 1000 MWh included for a simulation with electricity curves for 2019 and 2050 and an electricity tax of 6 SEK/MWh. This represents a scenario strongly influenced by a system preferable for electricity-based heat production. The result is illustrated by annual operational simulations and strategies in figures 4.6 and 4.7.

The total variable costs for the 2019 and 2050 cases were 62.7 MSEK and 56.0 MSEK respectively.

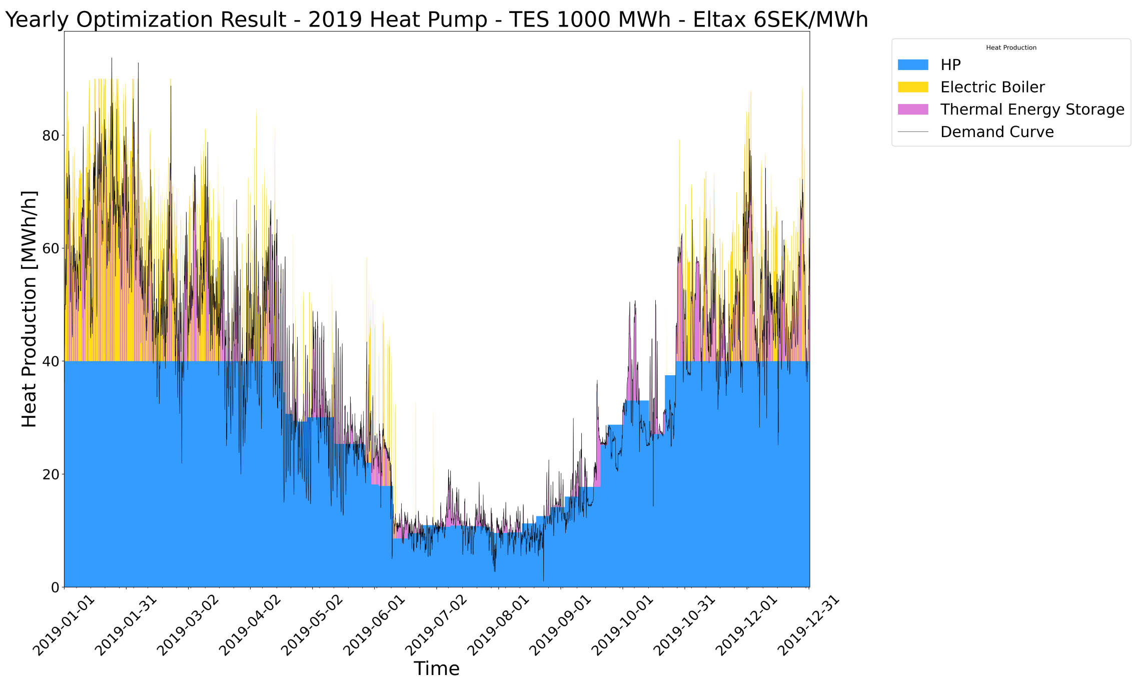

Figure 4.6: Optimization results for annual heat production using heat pumps as base load, 2019 price curve, 1000 MWh storage, and an electricity tax of 6 SEK/MWh.

The optimization results for the heat pump system in 2019 show the annual heat production in MWh/h and the time in hours over the year. The heat demand is higher during winter, spring, and autumn, resulting in a higher peak production demand. The base load is covered by the heat pump. Peak demand is mainly the EB together with a large fraction of TES. The BB is not utilized.

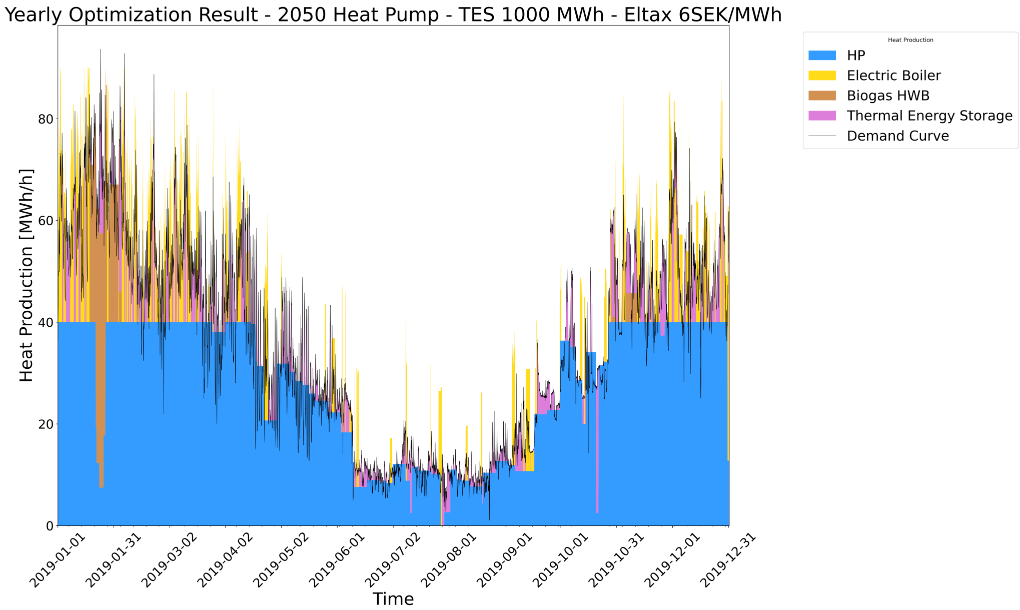

Figure 4.7: Optimization results for annual heat production using heat pumps as base load, 2050 price curve, 1000 MWh storage, and an electricity tax of 6 SEK/MWh.

The optimization results are changing with the electricity price curve for 2050. The model adapts to higher electricity price peaks by using more BB, especially during January. Bio-gas becomes important in terms of cost-effectiveness in the future scenario, even though the electricity tax is very low. The peak production seems to mix and match between BB and EB.

4.6 Detailed modeling of Heat Pumps

Two cases of a more detailed modeling of heat pumps are simulated and compared to the standardized and simple modeling of COP for heat pumps. The two approaches use a temperature-dependent COP to investigate how it affects the total variable cost of the systems. All three cases of COP are listed below:

- Constant COP
- Lorenz COP
- Empirical COP

To visualize the variations in the COP for the heat pump cases are the three different COP approaches over the year presented in figure 4.8. The calculations are based on return-, supply- and source temperatures in 2019.

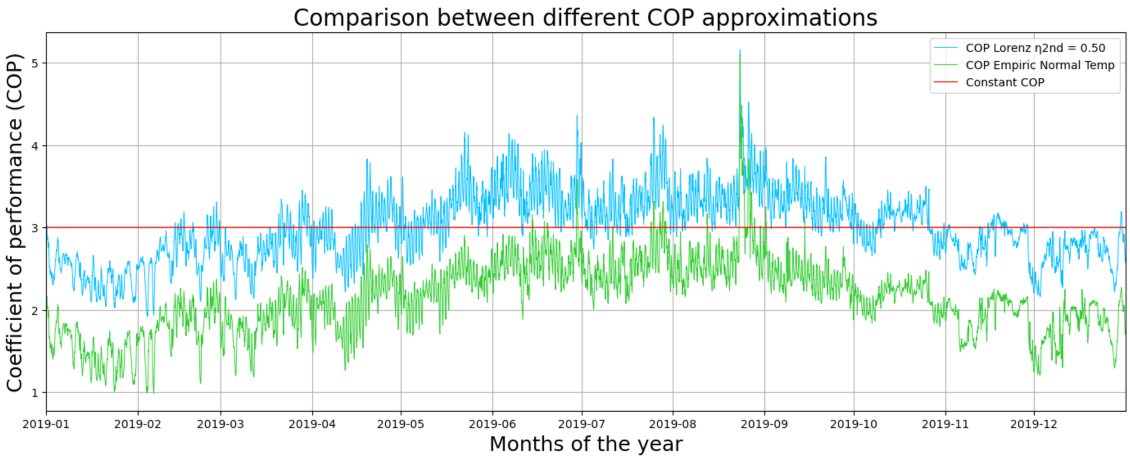

Figure 4.8: COP approximations in the year 2019 based on air temperature and constant COP, Lorenz, and Empirical approaches.

The red line shows a constant COP of 3.0. The blue-lined curve is the Lorenz formula for COP. This curve varies from around 2.0 to 5.0 in ratio. The results show a higher COP in the summer when the temperature lifts are lower, and a lower COP during winter and colder seasons when the temperature lift is higher. The green curve represents the Empirical approach of COP and has the lowest results of COP during the year. The values vary from 1.0 to 5.0, but mostly appear to be between 2.0 and 3.0 over the year.

The total variable cost for the three different heat pump cases, with different approaches to COP, were simulated for the years 2019 and 2050. These are illustrated in figure 4.9 and 4.10 respectively. The total variable cost increases with temperature-dependent modeling of COP, especially with an empirical approach. The Lorenz approach yields a similar value to the constant COP, but it accounts for a more realistic model of the performance of heat pumps and therefore results in around 5 million SEK higher annual cost. The results show a tangible difference in modeling detail which accounts for a higher cost. Both simulation years show a similar trend in terms of variable cost for modelling of COP.

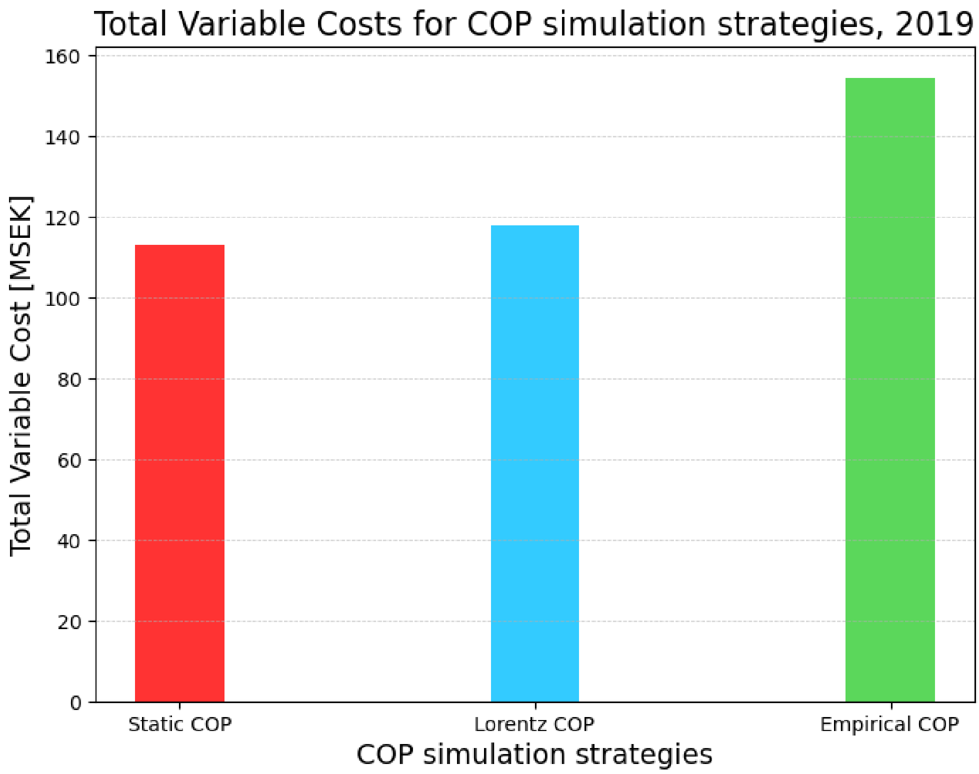

Figure 4.9: The results for simulation year 2019 indicate a cost of 113.1 MSEK for the constant COP, a higher cost for the Lorenz COP of around 118.0 MSEK, and a very high annual value for Empirical COP rising to 154.6 MSEK.

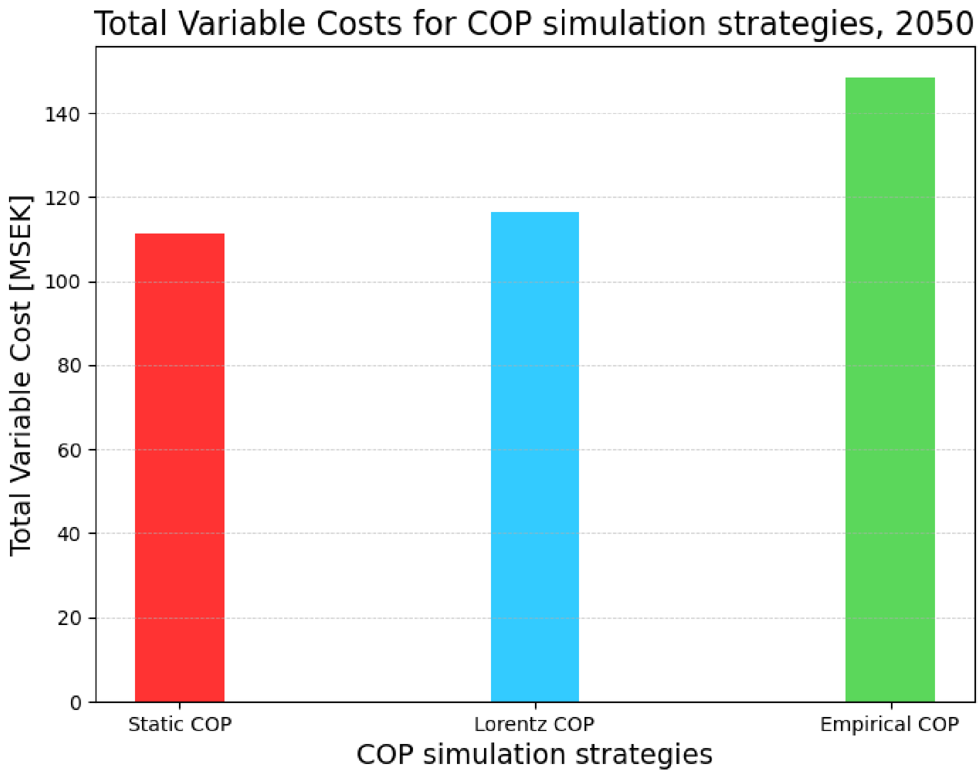

Figure 4.10: The results for the simulation year 2050 indicate a cost of 111.3 MSEK for the constant COP, a higher cost for the Lorenz COP of around 116.5 MSEK, and a very high annual value for Empirical COP rising to 148.5 MSEK.

5
Discussion

The results of this thesis reveal that heat pumps are more cost-effective than biomass CHP in the modeled Swedish district heating system, both currently and potentially in the future. The variable cost of heat pumps is lower in every simulation except for two debatable scenarios: when the biomass price is around 20 €/MWh and when the COP for heat pumps is calculated by the Empirical approach.

The capacity for heat pumps and biomass CHP units were determined based on the operational hours and full load hours of the respective technology and system. The production of each technology was scaled down according to the maximum capacity of 80 MW to a reasonable size in terms of full load hours, operational hours, and system size. For the heat pump system, this resulted in a capacity of 40 MW. Similarly, our simulation for the biomass CHP system also showed that a capacity of 40 MW is preferable. Both systems reached over 6000 full load hours during simulations after the capacity modeling. We aimed to create a realistic system with a capacity that reflects the setup in other district heating systems. The theory suggests it is unprofitable for an industrial company to construct and design a district heating system with only base load production to cover the maximum heat demand. Instead, our method and results suggest that the remaining peak demand should be covered by cheaper and smaller production units such as EB and BB. It is noteworthy to mention that optimal full load and operational hours for a district heating system are also dependent on the fixed costs and investment costs of the system, besides variable costs. Since these are not taken into reference in the energy models for the capacity modeling, the capacity results may not provide the most optimal recommendation. The investment and fixed costs are lower for heat pumps compared to biomass CHP, the maximum capacity set by a model with incorporated investment decision-making would therefore be higher for heat pumps than biomass CHP systems.

The cost-minimization of heat pump and biomass CHP systems yielded results in terms of operational strategy and total variable cost. These results indicate that the heat pump system has a lower variable cost compared to the biomass CHP system. Furthermore, the cost decreased for both systems in scenario 2050. On average, the price of electricity was lower compared to 2019 which favors electricity-based heat production. There were also greater variations in the electricity price, resulting in high price peaks. During such peaks, biomass and biogas district heating production are preferred. Biomass CHP experienced a larger decrease in total variable cost, electric peak production could be utilized to a larger extent during low electricity prices and larger economic gains from electricity production during peaks. The heat pump system had a lowered average variable cost in 2050 but increased biogas heat production when electricity prices rose. The system's flexibility and fluctuations in electricity prices create a better opportunity for a more profitable solution in the simulations for 2050. The electricity price curve for 2050 is based on an estimation of the future energy and electricity system. Therefore, the results in this thesis may not fully and accurately estimate the future situation of the electricity market. However, it does include potential indications of more fluctuations that are predicted in the future.

The electricity prices have shown significant variation in the past few years due to the current energy transition in Sweden and Europe, particularly the increased use of VRE [30], [7], [5]. These fluctuations in the energy and electricity market have caused prices to drop and vary more frequently and even resulted in negative electricity prices. To achieve beneficial production, it is crucial to make use of flexibility and adapt to variations in the present. The ongoing development strongly supports this idea and justifies the electricity price curve for 2050. By comparing the effects of using the electricity price curve of 2019 to that of 2050, this study provides a more significant comparison between the past and future, as opposed to using recent years' electricity prices, e.g. 2024.

The LCOH analysis supports the hypothesis that heat pump systems are more cost-effective than biomass CHP. All costs, including variable costs, investment costs, and fixed costs, are higher for the biomass CHP system. Yet, the method used for the LCOH calculations can be questioned, as the variable costs were taken from simulations and the remaining costs were estimated using recommended values from the literature. Despite the simplicity of the calculations, the results reflect the expectations and show a clear difference between the systems. Similar calculations of LCOH estimate the same conclusion. For example, a study by the Danish Energy Agency showed that air source heat pumps had a LCOH of around 250 SEK/MWh, while a biomass boiler on wood pellets had a value of 500 SEK/MWh [31]. Their results only consider the technology alone, while the results in this study include the costs of a system with both base load and peak production. Nonetheless, the results from both studies indicate the same outcome in terms of comparison between the technologies.

The Empirical estimation of COP can be stated to be more accurate than a constant COP, which is explained by Schlosser *et al.* [26], Jesper *et al.* [27], and Trabert *et al.* [28] in their studies. It's important to note that their results are mainly based on water source heat pumps, which have a higher temperature for the source medium and a lower temperature lift, resulting in a higher value for COP. Water source heat pumps are also the most common industrial heat pumps used in district heating systems. For this study, air compression heat pumps were selected because they are the least effective type of heat pump. The choice was made since the stated hypothesis and the research believed more in heat pumps compared to biomass CHP. Even with this selection, the simulations still showed that air-source heat pumps performed better than biomass CHP in the given circumstances, except when the COP was estimated with an empirical approach. To determine the effect of the selection can we compare the COP estimation for water source heat pumps by other studies, showing a COP between 3.7 - 4.5 [2], [3]. The analysis clearly shows, as stated, that heat pumps perform better in terms of cost-effectiveness in almost every simulation and are a more optimistic investment for future district heating establishments, even with air instead of water as the source for the heat pumps, and with heat pumps as the base load production.

The results of the COP approximations and modeling designate that the selection of the COP approach affects the total variable costs. A more detailed modeling of COP leads to higher costs. The temperature-dependent methods, Lorenz and Empirical, highlight the importance of energy model detail. This study emphasizes the need to evaluate the significance of the details in COP modeling to ensure an estimation that corresponds to reality. This is especially important during seasonal variations affecting the source temperature. The recommendation is therefore to at least take seasonal variations in the COP estimations into reference, and preferably change the COP to a more accurate value depending on a temperature-dependent estimation during the season. To further comprehend the potential savings or losses based on the COP calculations, a comparison between the actual outcome of a system's production costs with a simulation using different COP approaches should be investigated.

The sensitivity analysis of the biomass price indicates that the total variable cost of a biomass CHP system is very dependent on the price value. To be a profitable alternative, the biomass price must decrease from today's levels of around 30 €/MWh. Something that seems unlikely to happen. The biomass price is predicted to increase in the following years due to competition and limited availability. The risks of a price increase have already been seen, just in the last five years the price in Sweden has increased by more than 100 SEK/MWh [32], [33]. Similar conclusions were made in the study Heat Roadmap Europe brought by the University of Zagreb, where the future price of biomass was estimated to increase to 42 €/MWh in Sweden by 2050 [12]. The results are also similar to the analysis made by the Energy Transition Commission on biomass use in the European Union, now and in the future [34]. The article predicts an increase in biomass usage, limiting the availability, and increasing the price. Stating that biomass would only be competitive if it were available at prices lower than the 21 - 28 €/MWh.

The power-to-heat tax scenarios showed very high savings in variable costs for the heat pump system. From around 110 MSEK to 60 MSEK when reducing the tax from 428 SEK/MWh to 6 SEK/MWh for both 2019 and 2050 scenarios. In comparison, the total variable cost for biomass CHP with a biomass price of 30 €/MWh is 122 MSEK in 2050. With a reduction in the electricity tax to 200 SEK/MWh could a heat pump system cost 82 MSEK, saving 40 MSEK compared to the biomass CHP system, and a tax of 6 SEK/MWh could save as much as 62 MSEK as the systems total variable cost is 60 MSEK. This is a significant amount, saving more than 50% of the total variable costs between the cases. It is important to note that the biomass CHP case has not been simulated with the low tax values. This means that the total variable cost is probably a few million SEK beneath 122 MSEK with a lower tax value due to the peak production of EB.

An additional sensitivity analysis was carried out to determine the impact of TES on total variable costs. The results indicated that there were no significant effects on the variable costs of the observed district heating systems when TES capacity was increased. There was a small decrease in variable costs, around 0.5 - 2%, observed with additional TES capacity in all simulation cases. With an investment cost of 3000 €/$MWh_{capacity}$ for a large-scale hot water tank [35], a TES capacity of 1000 MWh would take several years to pay off.

Since both biomass CHP and heat pumps operate as base load in the simulation models and at max capacity during periods of high demand, there is no flexibility to be added to the system since the peak production was mainly reliant on BB which has a constant fuel price throughout the year. When comparing simulation results with high electricity peak production penetration, the event of increased storage capacity still yields an insignificant decrease in total variable costs.

The analysis conducted on TES was limited to the investigation of tank thermal storage due to the simulation model's restricted foresight. The investigation of seasonal storage could have been possible with a model that has perfect foresight, such an extension could reduce peak production significantly and increase the full load hours of the base load technologies. Grid frequency regulation and the electricity trading market were also not investigated through simulation, these flexibility services could affect the cost-effectiveness of TES.

In the last section of the results, a specific scenario was assessed. The scenario involved a heat pump system with favorable circumstances for electricity-based heat production. The sensitivity analysis of the electricity tax, using Finland's level, showed that a low power-to-heat tax together with a large TES had remarkable effects on the total variable cost of the system. The resulting cost was the most cost-effective alternative for all cases, with 62.7 MSEK for 2019 and an even better 56 MSEK in 2050. In comparison, the best result for biomass CHP was around 95 MSEK, but this was with a very generous biomass price level of 20 €/MWh. Other studies have also acknowledged the effect that an adjusted tax brings to the district heating sector. For example, Bertilsson *et al.* in his study exploring an optimal composition of Swedish energy systems, and Fernqvist *et al.* explains that the Swedish electricity tax is static today, and how a dynamic and lower electricity tax would provide more flexibility services beneficial for TES and large heat pumps in district heating systems.

Another important point to consider is that heat pump systems are still more profitable than biomass CHP, even without a decrease in the taxation rate. It is therefore difficult to understand why the industry almost unidirectionally is choosing to invest in biomass-based district heating projects despite this fact. For instance, the Rya facility in Gothenburg owned by Göteborg Energi is currently building a biomass district heating system, including CHP, with a capacity of 140 MW heat and 35 MW electricity [36]. The facility will run on wood fuels and is predicted to be finished by 2025. Another example is a new large facility in Lugnvik that started construction in 2023. The district heating system will also run on biomass materials such as waste wood products and chips [37]. The mentioned projects are part of the around 40 new bio-based facilities that were under planning during 2023 [6]. The total amount of biomass district heating systems increased by 23 new facilities between 2022 and 2023. It is important to note that the implementation of electricity-based heat production introduces an additional load and congestion to the electricity grid. This aspect might hinder the industry from focusing on P2H technologies. Required infrastructure for biomass-based production is already established and expanding. Therefore, an investment decision can be determined by other factors, such as the capability of the grid to distribute the required electricity demand.

However, this thesis does not recommend that all biomass-fueled district heating production systems should be shut down and rebuilt to electricity-based systems. Most of the facilities in Sweden are already biomass-based systems, and it would be inaccurate to suggest that all district heat production should be electricity-based. The choice of system depends on local conditions, available resources, and preserving and utilizing already existing investments in the Swedish district heating sector. Rather, the recommendation that the results of this thesis want to present is that the industry should consider increasing their use of electricity-based production in the future. The advantages that P2H technologies bring in terms of cost-effectiveness and flexibility are crucial for the future of the Swedish energy sector. By using and combining these technologies, both heat pumps and biomass CHP, we can create a more robust system that is capable of utilizing more of the energy provided by our renewable and varying, energy and electricity systems.

6
Conclusions

This study investigates the cost-effectiveness of two different technologies, heat pumps and biomass CHP, producing district heating in Sweden. The comparison takes the current and future energy situation into a reference in terms of more varying electricity prices, different levels of biomass prices, and techno-economic properties. The analysis provides recommendations for the optimal development of the future district heating sector. The results highlight the following conclusions:

- In both 2019 and 2050 electricity price scenarios it can be concluded that the observed air-source heat pump system yielded a lower total variable cost and LCOH compared to the observed biomass CHP system. The potential difference in total variable cost between heat pumps and biomass CHP systems is 22 million SEK in 2019 and 12 million SEK in 2050. This variance is also evident in the LCOH analysis, leading to a difference of up to 180 SEK/MWh between the two cases. The observed air-source heat pump system can therefore be concluded to be more cost-effective in contrast to the observed biomass CHP system.

- The power-to-heat tax analysis in this study showed that the total variable cost for the observed heat pump system is heavily dependent on the power-to-heat tax. The findings were distinguished for both year 2019 and 2050 electricity price scenarios. With a tax reduction, the observed heat pump system could cost around 50% less to operate than the biomass CHP system.

- In the analysis of different biomass price scenarios, it can be concluded that the total variable cost of the observed biomass CHP system was strongly influenced by the biomass price. The price needs to decrease from today's value of 30 €/MWh down to approximately 25 €/MWh in order to match the total variable cost of the heat pump-based system. Most forecasts indicate an increase in biomass prices, which does not benefit biomass heat production.

- The sensitivity analysis revealed that increasing TES capacity from 270 to 1000 MWh effective storage has minimal effects on variable costs for the observed district heating systems. However, the analysis was limited, and a broader investigation covering seasonal storage and flexibility services could provide valuable insights.

- In the investigation of the technical detail regarding the COP of heat pumps it can be concluded that a temperature-dependent approach yields higher total variable costs. The COP depends strongly on the temperature difference between source and supply, making the analysis important to consider in terms of cost-effectiveness. A higher temperature lift yields more electricity usage and increases the overall costs, especially during the winter when electricity prices are elevated.

- To model heat pumps should at least the seasonal variations be taken into reference, especially during colder periods when the temperature lift is higher, based on the finding in this thesis. The recommendation in this thesis is to further investigate the usage of a temperature-dependent COP and compare it to real-life district heating facility data to evaluate the accuracy of COP modeling.

- The cost-optimal pathway for Swedish district heating systems should include more electricity-based heat production, allowing for a mix-and-match approach between electricity and biomass. Our study, supported by theory and recently published research from Chalmers University of Technology, reinforces the conclusion that electricity in district heating production should increase and become a crucial component in the future.

In summary, this study provides valuable insights into the optimal development of the Swedish district heating sector, with heat pump technology emerging as the frontrunner for cost-effective heat production. Recommendations for dynamic COP estimation and a keen awareness of electricity tax dynamics serve to guide future endeavors in advancing district heating infrastructure in Sweden.

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A

Appendix 1

A.1 Multi-unit segmentation

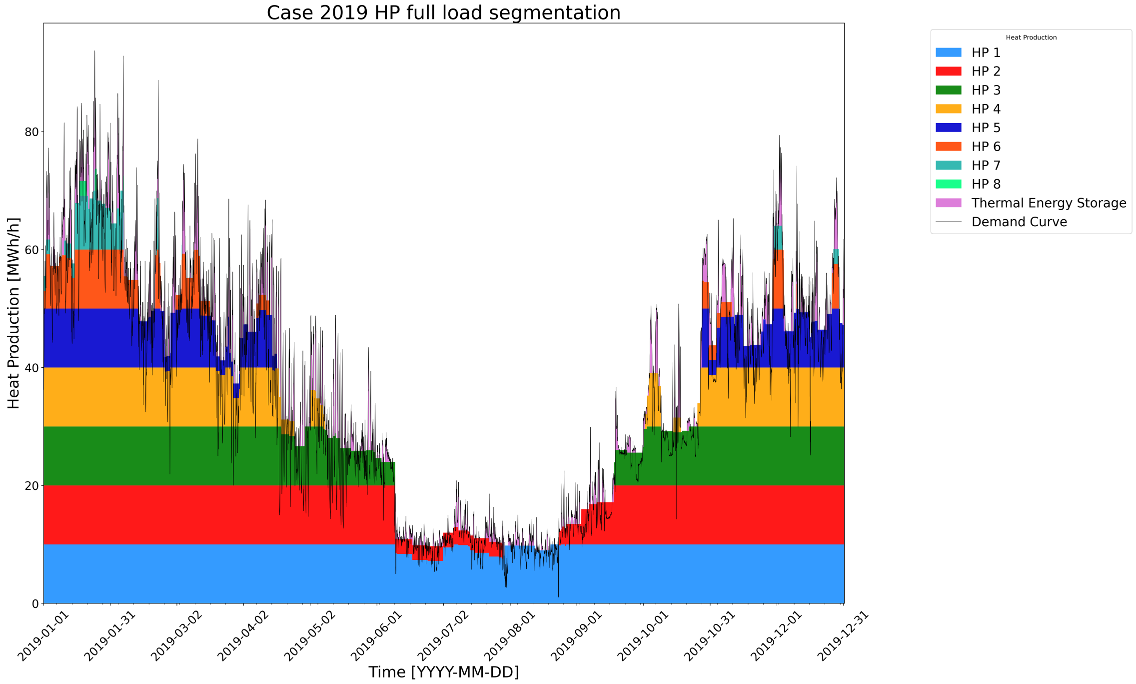

Figure A.1: Annual simulation of heat pump system with units HP1-HP8 each of 10MW showing the heat production per unit. The year is 2019.

A.2 Techno-economic data for all technologies

Technology	Investment cost [M EUR/MW]	Fixed OM-cost [EUR/MW]	Start-up cost [EUR/MWh]	Min.output [MW]	Max.output [MW]	Lifetime [n]	Efficiency / COP	Fuel
Biomass CHP (Bio_CHP)	3.5	149 000	30 000	12.2	40	25	-	Biomass
Boiler (P3_dv)	-	-	-	12.2	40	-	0.9	Biomass
Turbine (P3_turb)	-	-	-	3	14.8	-	0.28	Steam
Flue-gas condenser (P3_fgc)	-	-	-	1.46	4.8	-	0.12	Flue gas
Heat pump (HP)	0.86	2000	10	2.5	40	25	3.0	Electricity
Electric boiler (EB)	0.07	0	0	1	50*	20	1.0	Electricity
Biogas boiler (BB)	0.06	1700	0	1	50*	25	1.0	Biogas

Table A.1: Techno-economical data for all heat- and electricity-producing technologies used in the models and simulations [2], [3]. The turbine and flue-gas condenser capacity was scaled by boiler capacity and the facility's original size of 82 MW.
* The capacity of EB and BB was set to a large value to ensure that the system make a cost-effective decision, not based on capacity, otherwise around 25 MW in size.

A.3 Annual Optimisation Results

A.3.1 Current and Future Electricity Price Scenarios, 2019 & 2050

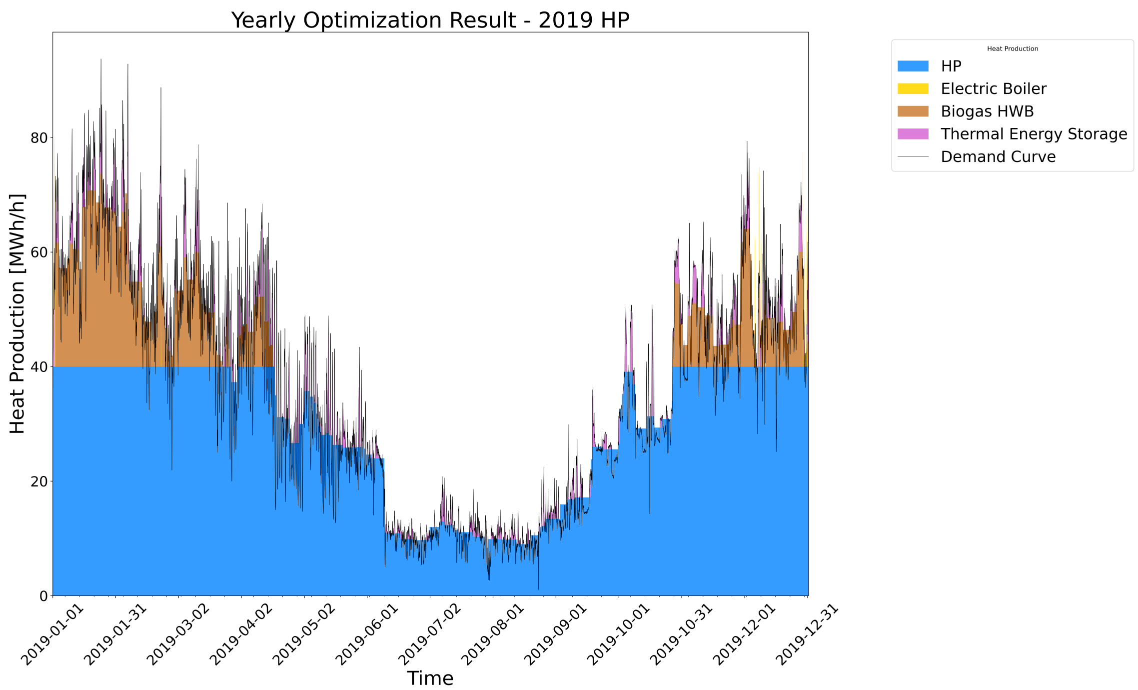

Figure A.2: Annual simulation of heat production strategy for heat pump system. The simulation year is 2019.

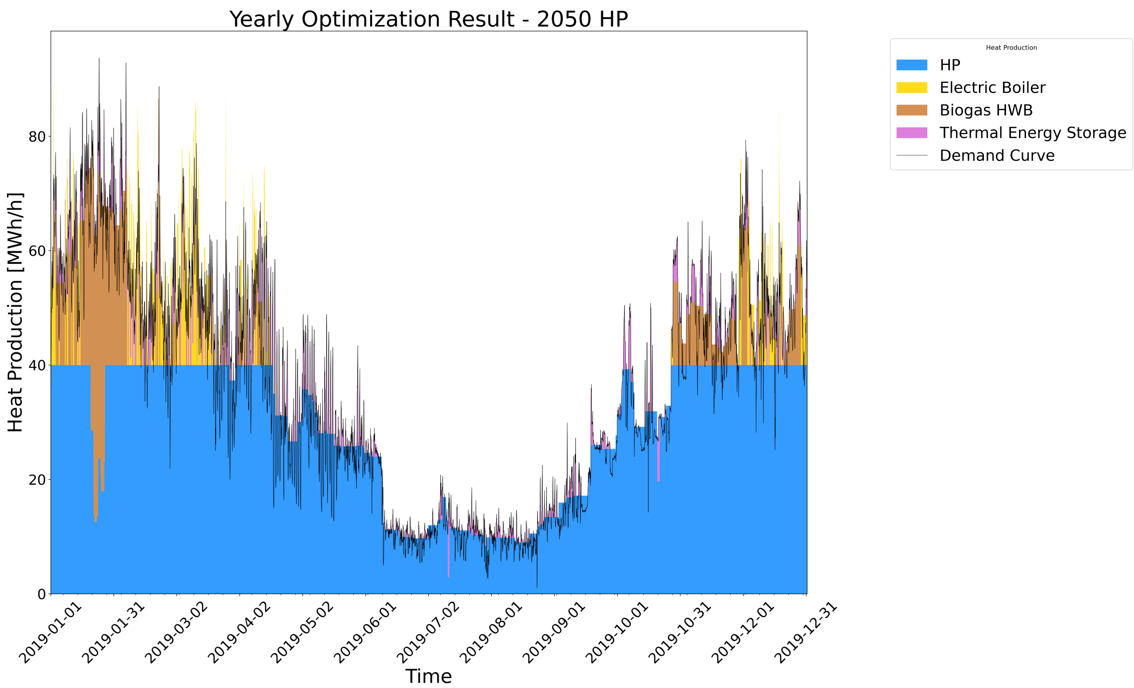

Figure A.3: Annual simulation of heat production strategy for heat pump system. The simulation year is 2050.

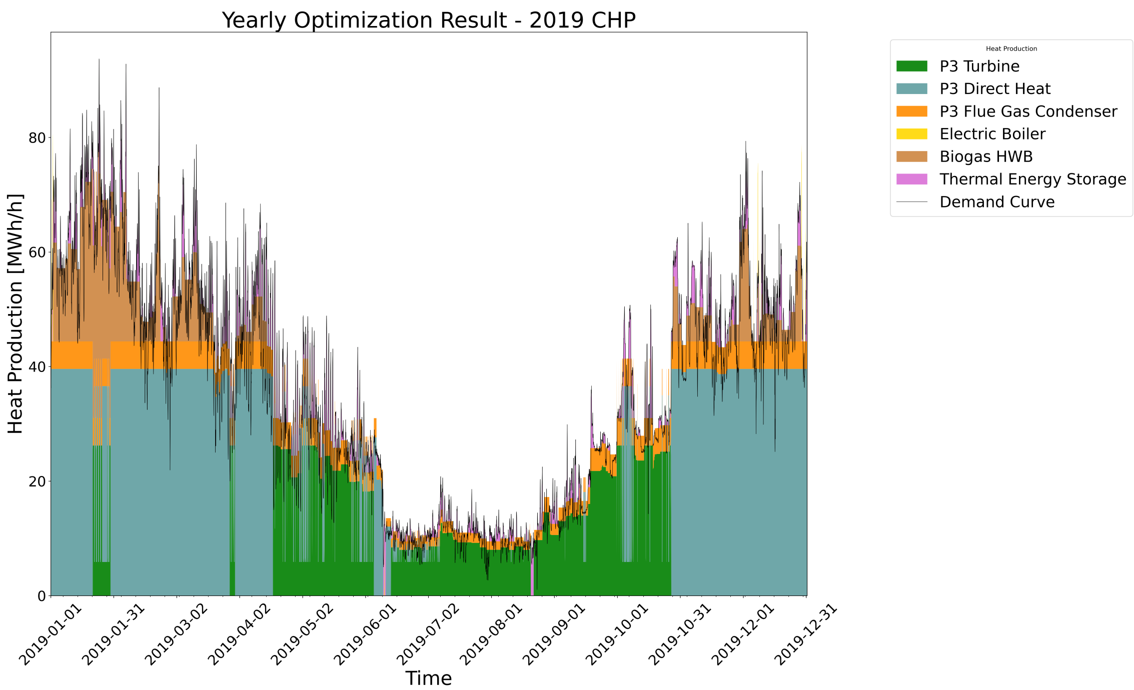

Figure A.4: Annual simulation of heat production strategy for CHP system. The simulation year is 2019.

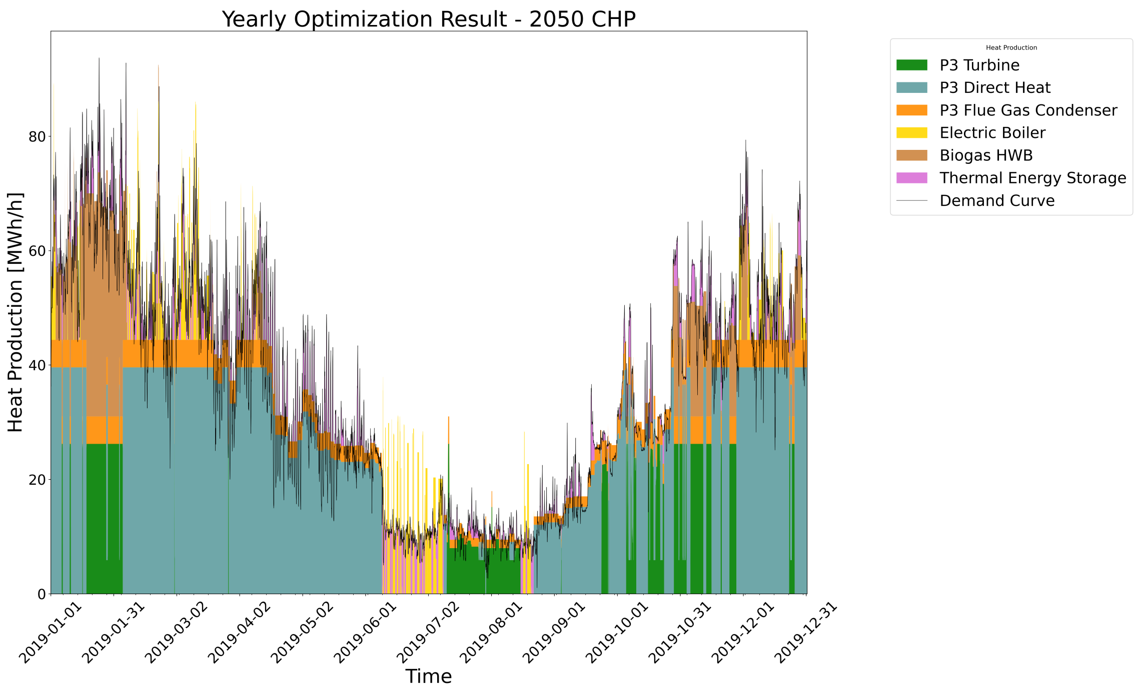

Figure A.5: Annual simulation of heat production strategy for CHP system. The simulation year is 2050.

A.3.2 Biomass Price Scenarios

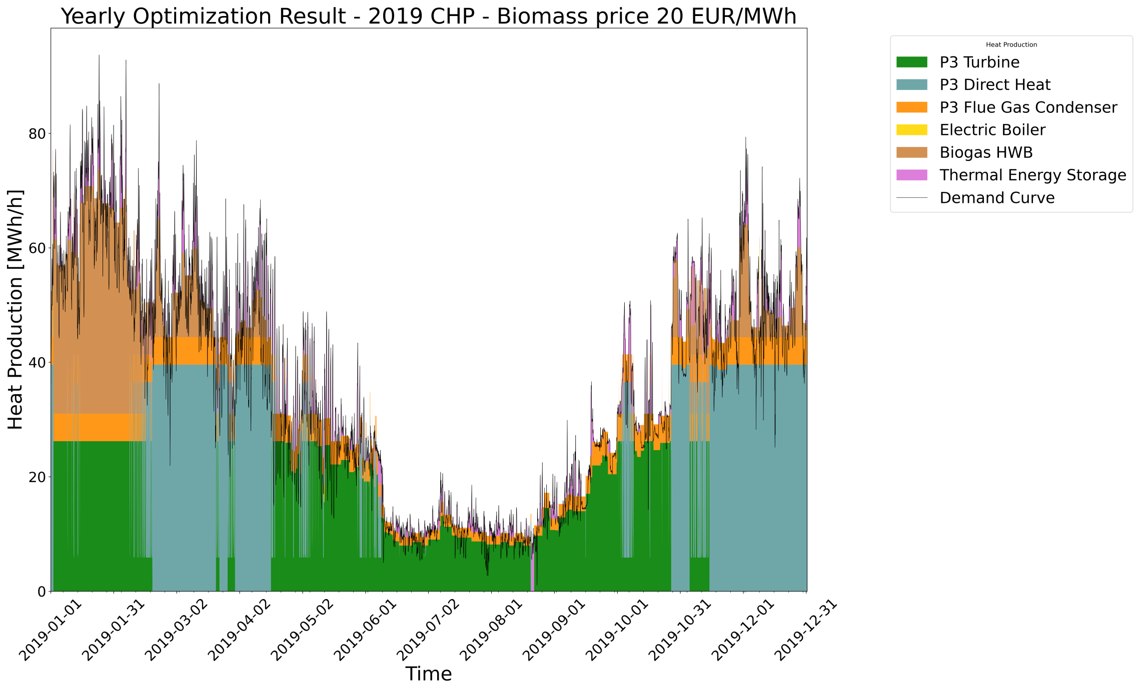

Figure A.6: Annual simulation of CHP system, biomass price set to 20 EUR/MWh. The simulation year is 2019.

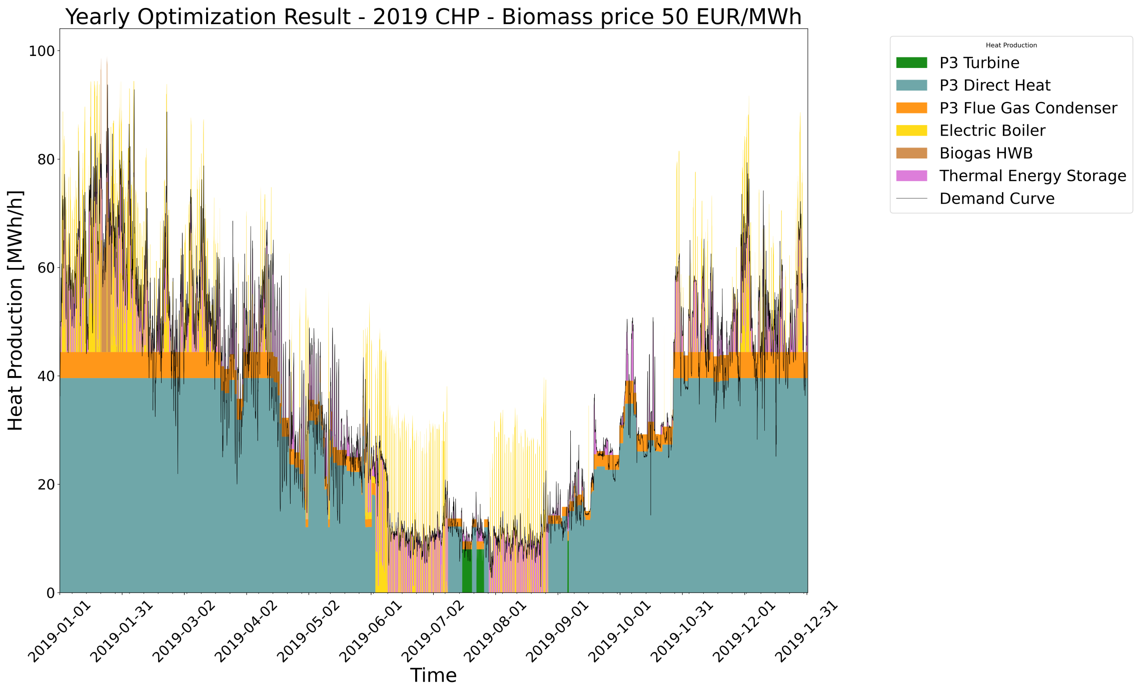

Figure A.7: Annual simulation of CHP system, biomass price set to 50 EUR/MWh. The simulation year is 2019.

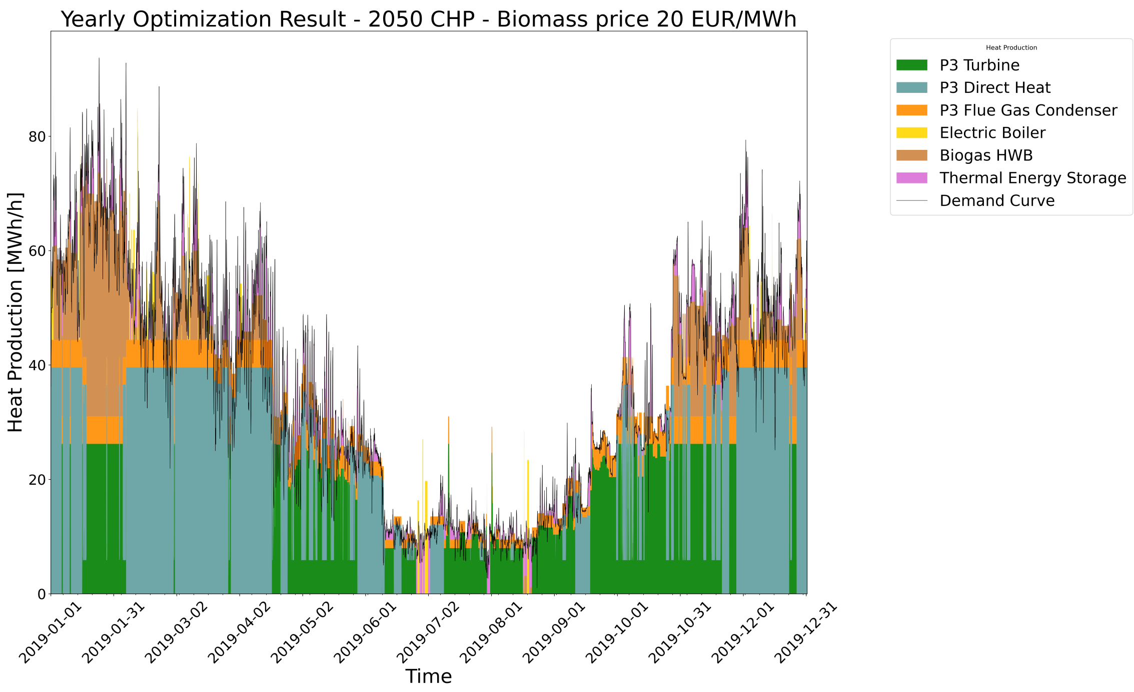

Figure A.8: Annual simulation of CHP system, biomass price set to 20 EUR/MWh. The simulation year is 2050.

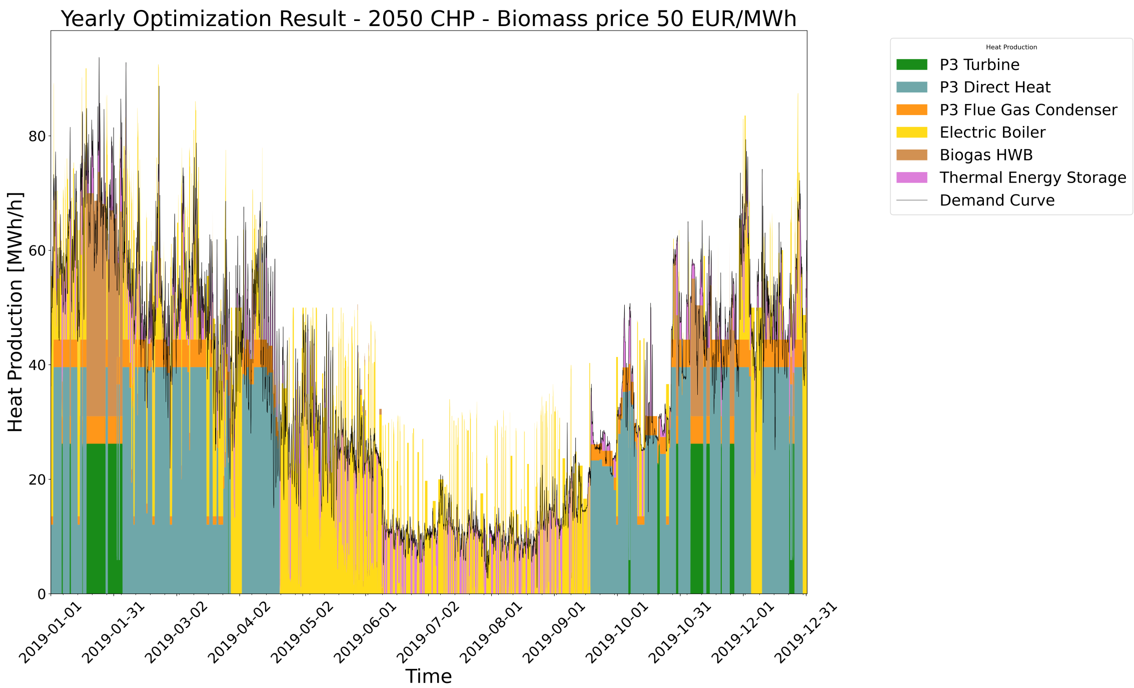

Figure A.9: Annual simulation of CHP system, biomass price set to 50 EUR/MWh. The simulation year is 2050.

A.3.3 Electricity Tax Scenarios

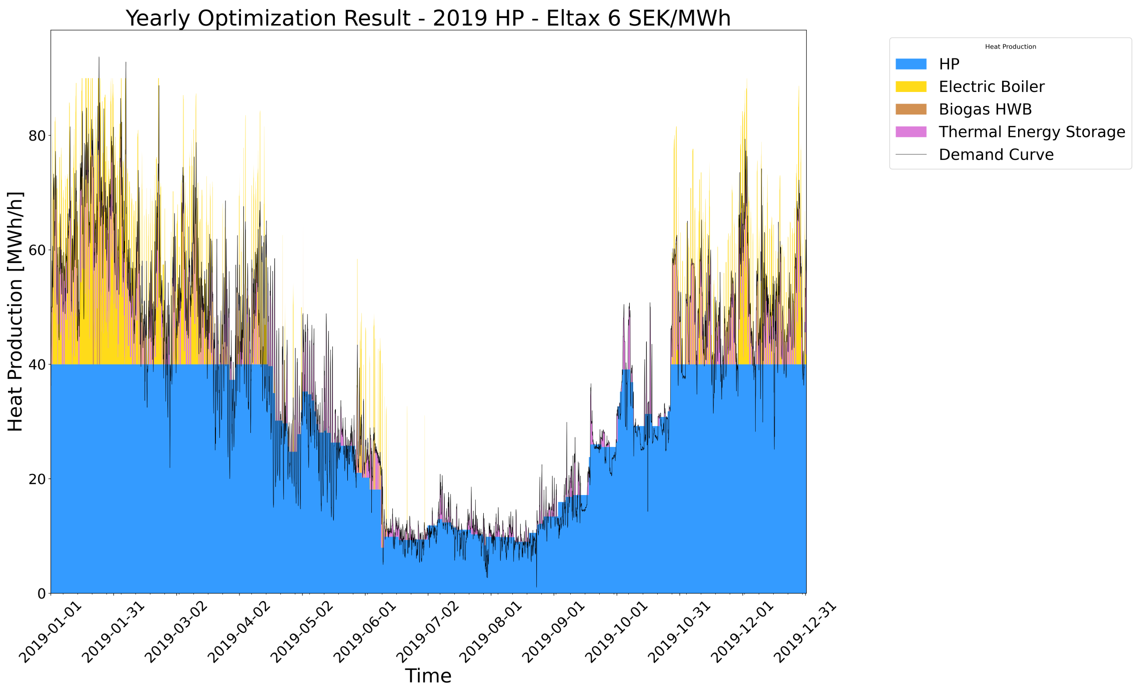

Figure A.10: Annual simulation of heat pump system, electricity tax set to 6 SEK/MWh. The simulation year is 2019.

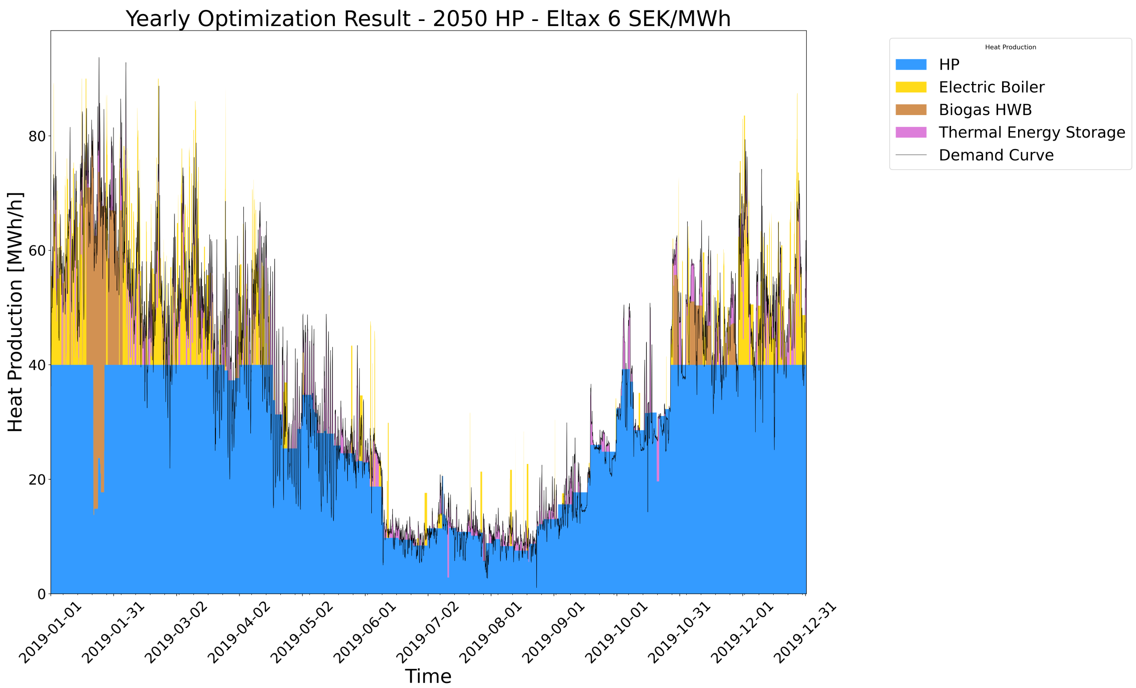

Figure A.11: Annual simulation of heat pump system, electricity tax set to 6 SEK/MWh. The simulation year is 2050.

A.3.4 Sizing of Thermal Heat Storage

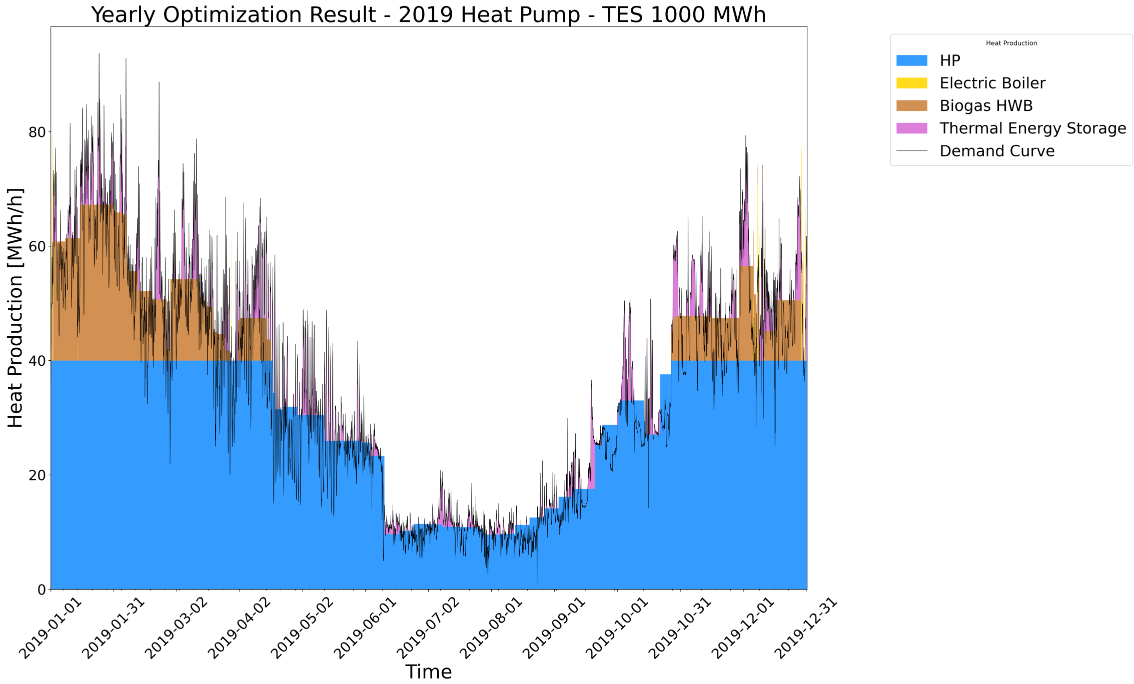

Figure A.12: Annual simulation of heat pump system paired with 1000 MWh TES. The simulation year is 2019.

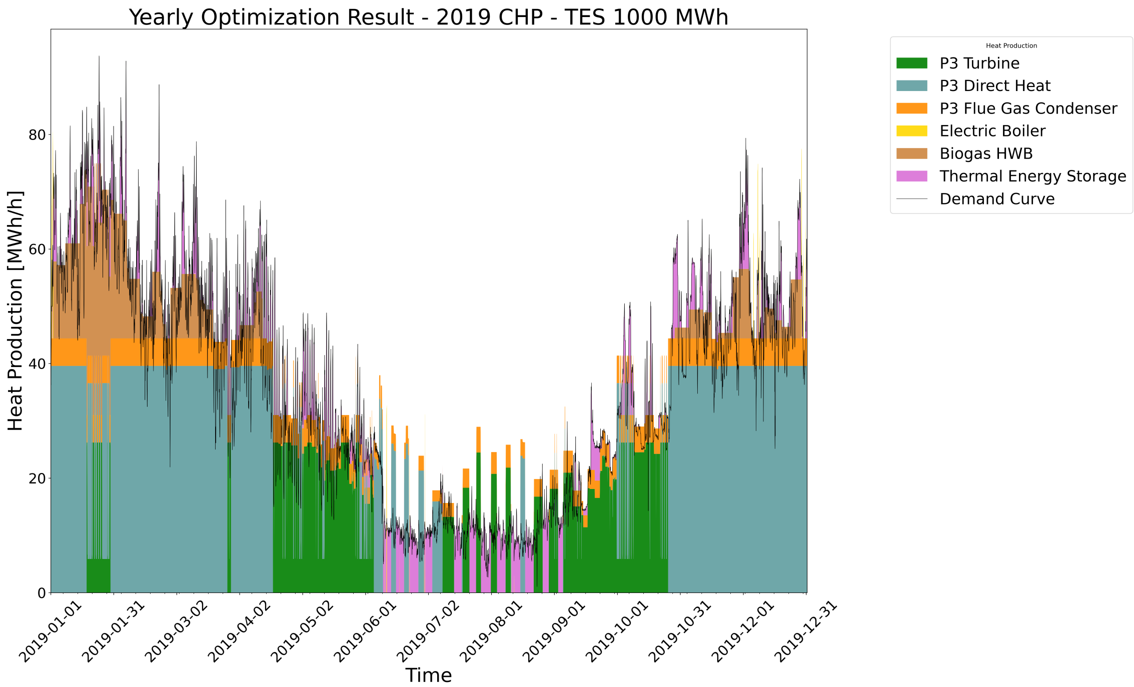

Figure A.13: Annual simulation of bio CHP system paired with 1000 MWh TES. The simulation year is 2019.

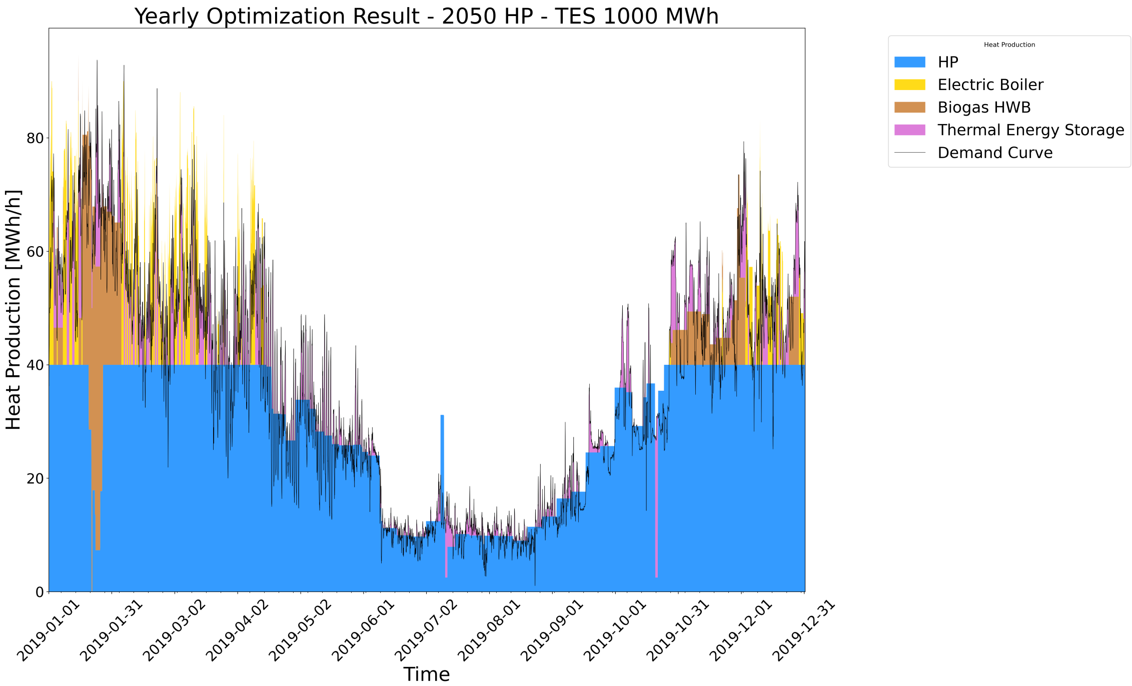

Figure A.14: Annual simulation of heat pump system paired with 1000 MWh TES. The simulation year is 2050.

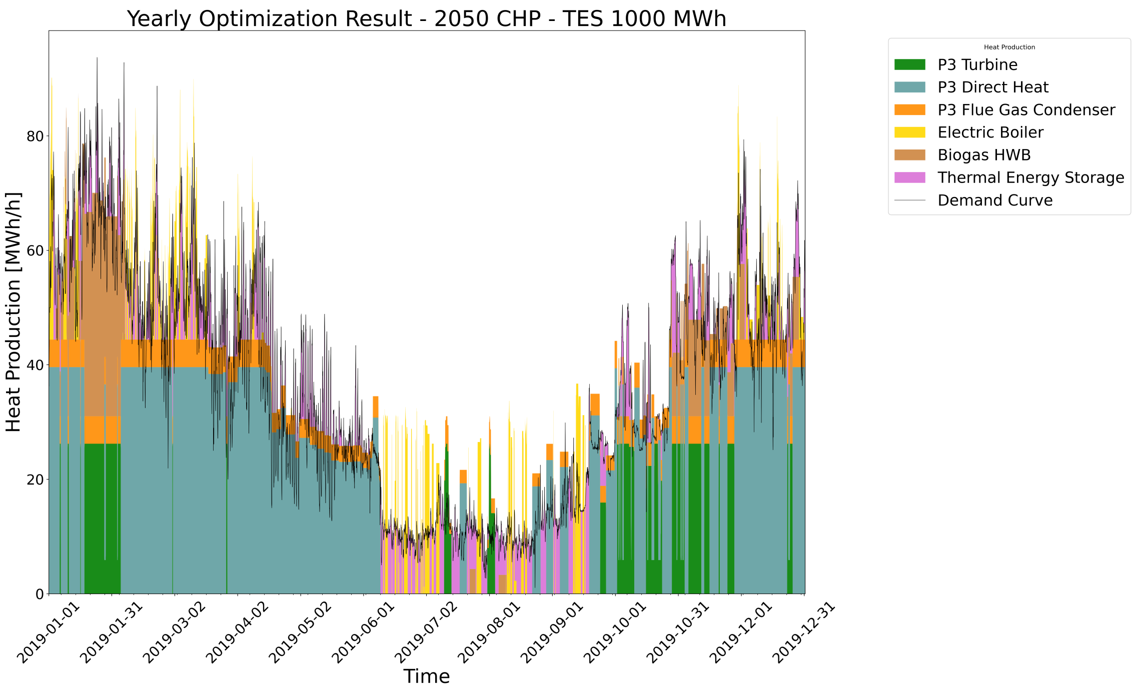

Figure A.15: Annual simulation of bio CHP system paired with 1000 MWh TES. The simulation year is 2050.

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