Shifting Heat Sources Between Ground-Source Heatpumps and District Heating

A simulation study on the economic impact of hourly energy prices on residential hybrid heating systems

Master’s thesis in Structural Engineering and Building Technology

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Abstract

In recent years, Sweden's residential energy market has become increasingly complex. Energy prices for electricity and district heating have been steadily increasing. During 2022, fluctuations in electricity prices reached new heights, and interest in energy-smart, price-governed hybrid heating solutions has since grown. This master thesis aims to analyze the potential economic gains in yearly energy costs using a heating system that shifts the energy source between district heating (DH) and a ground-source heat pump (GSHP) based on hourly energy prices. The economic evaluation is conducted in greater detail by developing and validating a simulation model incorporating the specific system with the building energy simulation software IDA ICE.

The evaluation showed that varying spot-price levels for electricity and fees for power subscriptions for DH significantly influence yearly energy costs. Using electrical spot prices from 2021-2023 demonstrated that the hybrid solutions had approximately the same yearly energy costs, even though the amount of shifted energy varied. Comparisons with solutions involving only DH or GSHP as heating providers, based on the electrical prices in 2022, revealed the sensitivity to electric spot price levels, making it difficult to distinguish between the yearly costs for hybrid or GSHP systems. The study could not show that the evaluated hybrid configuration had lower yearly energy costs than only GSHP. Since combining DH and GSHP will come with higher investment costs than choosing only one, customers may need other motivational factors to invest in a hybrid heating system.

The conclusion is that although this system type could provide benefits such as redundancy and flexibility for property owners and energy suppliers, it is not currently promoted under the existing DH price models. To increase the adoption of such systems, refinements of price models are encouraged. This kind of system can play an important role in the future energy landscape; by combining the effective heat pump technology with the robustness of the district heating network, the hybrid system could help balance both the district heating and electrical networks if utilized correctly.

Keywords: Ground-Source Heat Pump (GSHP), Heat Pump, Hourly pricing, Smart Grids, District Heating, Decentralized Heat Pumps, Hybrid Energy solutions, Building energy modelling, Control, Cost Efficient

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Mats Persson, Gothenburg, June 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

COP	Coefficient of performance
DH	District heating
DHW	Domestic hot-water
DCW	Domestic cold-water
EUR	Euro
GSHP	Ground-source heatpump
HWC	Hot-Water circulation
SEK	Swedish krona

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1

Introduction

In recent years, Sweden's residential energy market has become increasingly complex. Hourly electricity spot prices have experienced significant fluctuations, reaching new record highs. At the same time, district heating prices have also been steadily increasing due to higher interest rates, inflation, and rising costs (Nils Holgersson Gruppen, 2024). The rising energy costs and the search for energy efficiency measures have created a quest for flexible and energy-smart solutions. Consequently, the interest in using hybrid systems that combine several energy sources is increasing. Currently, the two most common energy providers for residential buildings in Sweden are district heating and electricity (Energimyndigheten, 2020b). The question arises: How can these energy providers be combined, and how would this affect property owners' economy?

To contribute to this topic, this thesis will examine a specific hybrid heating system that combines district heating (DH) with a ground-source heat pump (GSHP). The system is studied in more detail by developing a plant model and simulating it in a reference building using the building energy simulation software IDA ICE. The simulation model is used to perform simulations that shift energy sources based on custom price control and to determine the hourly energy demand of each energy carrier, which is later used in the economic evaluation and energy cost calculations.

1.1 Background

Since the oil crisis in the 1970s heat pump technology has played an important role in transforming the heating energy supply for buildings in Sweden(Johansson, 2021). The usage of heat pumps has gradually increased, and as of 2017, heat pumps covered 30%, around 30TWh of the energy needed in residential and commercial buildings throughout the country Energimyndigheten (2020a).

One of the most efficient heat pump types is ground-source heat pumps (Björk et al., 2013). Approximately 300,000 geothermal systems with boreholes and ground-source heat pumps are operational across the country (SGU, 2023). Despite district heating being the predominant heating method for 90% of multi-residential buildings(Energimyndigheten, 2020b), the increasing adoption of heat pumps suggests a possible shift towards hybrid heating solutions.

Due to energy market developments and the potential enhancements in energy efficiency and cost-effectiveness, such systems are of increasing interest. Kensby et al. (2017) studied the impact of shifting heat sources between district heating and exhaust air heat pumps in multi-residential buildings based on the hourly marginal cost of district heating and electricity in Gothenburg. Showing that around 3% savings could be achieved on marginal costs by changing the controls to prioritize the exhaust air heat pumps when the marginal cost for electricity is lower than that for district heating. Lygnerud (2018) highlights the challenges faced by the district heating industry in Sweden if it does not adapt to the changing market with more flexible heating systems. Lygnerud et al. (2021) further explored the economic and environmental benefits of using combined systems of district heating and ground-source heat pumps. Findings were that economic and environmental gains could be achieved by combining the two energy providers in a hybrid system.

This master thesis focuses on whether economic benefits in yearly energy costs exist when ground-source heat pumps and district heating are integrated within a multi-residential building in Gothenburg. Key factors influencing this solution are the energy price models. Simulating this hybrid system in greater detail will allow for simultaneous assessment of the impact of power tariffs and control based on hourly electrical spot prices from recent years. Energy prices for electricity and district heating have a geographical differentiation across Sweden. By placing the building in Gothenburg, knowledge of how the local energy price models impact a hybrid heating system will be added.

1.2 Aim

This master's thesis aims to evaluate the economic viability of a hybrid heating system combining ground-source heat pumps and district heating in a multi-residential building in the context of fluctuating electrical spot and district heating prices. Using the IDA ICE software for simulation, this study will analyze whether variable energy costs significantly influence the cost-effectiveness and system choice in an operational building in Gothenburg, assessing the potential profitability and decision-making thresholds impacted by these price variations.

1.3 Limitations

The study is geographically focused on the region of Gothenburg, though the simulation reference building is located in Ulricehamn. To align the study with the energy market of Gothenburg, assumptions are made that the building, while physically in Ulricehamn, experiences similar environmental and usage conditions as it would in Gothenburg. This is justified by using Gothenburg-specific weather and energy price data in the simulations to assess the impact of the local price market specifically. The assumption that energy consumption patterns and tenant behavior are consistent across these locations introduces potential limitations in accurately representing localized variances, which may affect the applicability of the results to actual buildings in Gothenburg.

Additionally, the analysis is confined to simulations based on historical data regarding weather patterns and energy prices. While this approach provides a controlled environment for study, it may not fully capture future market dynamics or unexpected shifts in weather patterns, potentially affecting the generalizability of the findings.

The economic evaluation focus on yearly energy costs. Investment costs for technical systems and connections to the district heating network are not be studied.

The reference building has solar hybrid panels that produce electricity and charge the boreholes with thermal energy through a liquid circuit. The impact of these is disregarded in the simulation model and further analysis. The boreholes' charging could positively influence the heat pump's COP, especially during summer. However, since most of the yearly energy produced by the GSHP is utilized during the colder months, the impact on the analysis done in this project is expected to be limited. Due to the same reason, no validations are made between measured and simulated borehole brine temperatures.

1.4 Defining the research problem

To achieve the objectives outlined in this thesis, the following specific questions will be investigated:

- **Building simulation model and validation**
  Can an existing IDA ICE model of the reference building be calibrated and validated against measured data to ensure its accuracy and reliability?
- **Plant simulation model development and validation**
  How could a plant model, including DH and GSHP, be developed and implemented in the existing simulation model? To what extent can it be calibrated and validated with data from the reference building?
- **Economic evaluation:**
  How could the heating plant that utilizes DH and GSHP be operated and controlled based on hourly energy prices? What would be the expected yearly energy cost of the hybrid heating system utilizing this control compared to systems with only DH or GSHP?

2

Theory

The following chapter presents the theory used in this thesis project. It begins with a background of the general energy supply for buildings, beginning with an overview of the two energy providers, district heating (DH) and electricity. Followed by the basic technological background of heat pumps and ground-source heat pumps. Lastly, a literature review concerning the studied topic will be presented.

2.1 District heating

District heating is the most common heating provider in residential buildings in Sweden, among 50 % of all residential buildings are connected to the a DH network and if turning to multi-residential buildings as many as 90% are connected (Energimyndigheten, 2020b). From a historical point of view, district heating networks were first built to create a better local environment, initially since there was a need for better air quality (Energimarknadsbyrån, 2024). Until the 1980s the DH plants main heat source was oil burning (Warfinge & Dahlbom, 2010). Since then, oil has been phased out and replaced by other fuels such as biofuel, waste incineration, and industrial waste heat, among others. Centralized plants improve energy efficiency and utilization rates by allowing for optimization and technical advancements that benefit many users, unlike local boilers.

DH companies in Sweden own the DH network and the plant producing heat. The DH network consists of pipes transporting hot water with a supply temperature between 70-120°C, depending on the season (Energimarknadsbyrån, 2024). A building's local heating system connects to the district heating network through a heat exchanger in the local heating central. The primary side to the district heating networks and the secondary to the local heating system. Separating the DH network and the building's internal heating system creates a safer system. If, for example, a leak arises in the building or the DH network, they won't impact each other (Warfinge & Dahlbom, 2010).

The DH market is free from monopoly, but due to the large investments associated with installing the DH network and plants, there is usually only one local provider in a city or community. In practice, this means that although the market is free, there is a local, natural monopoly and no possibility of changing operators for the connected customers in a city or community.

2.2 Electricity

Sweden and Europe have deregulated electricity markets, where electric energy is traded competitively on a free market (Svenska kraftnät, 2023). However, there is a distinction between electric power supply and electric energy. Due to the ownership structure of the electrical grid, the electric power distribution operates as a monopoly. Energy market directives regulate the electrical market in the European Union to ensure fair pricing and reliable provision of electric energy (European Commission, 2024).

Four price areas, SE1-SE4, diversify the price levels throughout Sweden. The main purpose of the price area is to handle distribution bottlenecks and geographical differences in electricity production (Svenska kraftnät, 2024). Allowing different energy prices throughout the country enables higher prices in areas with lower electricity production and lower prices in areas with higher production. This approach also helps compensate for bottlenecks in the electrical grid.

Day-ahead trading balances the amount of electric energy needed and produced in the European market. This system involves forecasting the next day's energy needs and adjusting production to maintain equilibrium. Electric energy pricing models are then based either on hourly spot prices or monthly rates derived from the average of spot prices. Since spot prices are determined a day ahead, consumers can adjust their electricity usage based on these prices. Due to the two-part electricity market, the electricity bill for customers in Sweden consists of two parts. One part covers the connection to the electrical network, representing the customer's power connection to the grid. The other part accounts for the energy cost, based on the energy consumed.

Details on electrical prices used in the project are presented in more detail in chapter 3.6.3.

2.3 Heat pump

Heat pump (HP) technology allows for more efficient energy usage, particularly in buildings traditionally heated by electric radiators or boilers. Heat pumps can draw heat from various sources, including air, ground, water, and geothermal boreholes.

The main principle of an HP is consistent regardless of the heat source. The technology involves a gaseous refrigerant circulating in a closed loop. The process starts with the refrigerant absorbing heat from a colder environment in the evaporator, causing it to turn into a low-temperature vapor (Warfinge & Dahlbom, 2010). The compressor then increases the pressure and temperature of the vapor, which moves to the condenser. In the condenser, the hot vapor releases heat to the heating system, cools down, and condenses into a liquid. The liquid refrigerant then passes through an expansion valve, reducing its pressure and temperature, and is ready to absorb heat again in the evaporator, continuing the cycle. Figure 2.1 shows the simplified layout of components and the principle of a heat pump.

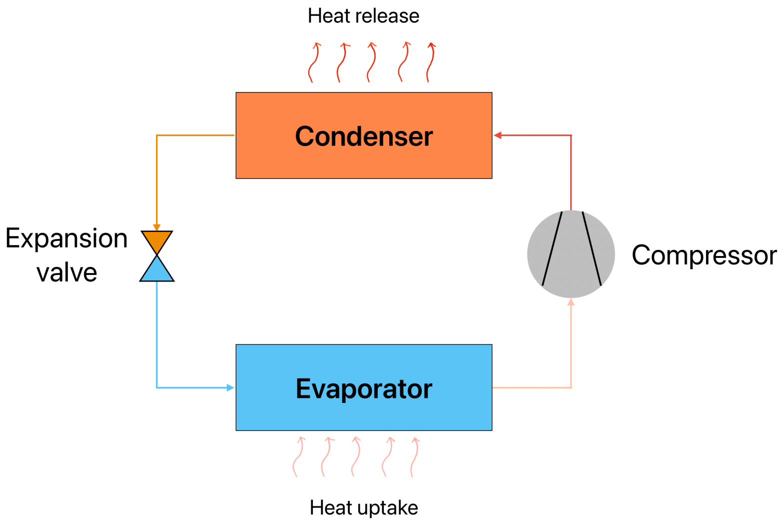

Figure 2.1: The principle of a heat pump.

The efficiency or coefficient of performance (COP) of the HP, presented in equation 2.1 is calculated by dividing the gained heat from the condenser by the electricity input to the compressor.

$$COP = \frac{\dot{Q}_{out}}{\dot{W}_{in}} \tag{2.1}$$

Where Q_{out} is the heating power provided to the warm side and W_{in} is the power input needed for the compressor (Chiasson, 2016).

The COP depends on the temperature difference between the evaporator and the condenser; the smaller the difference, the higher the COP. Thus, HPs using ground or borehole sources typically have a higher COP than air-to-air HP due to lower seasonal variations in ground temperature than air temperature (Chiasson, 2016).

2.4 Ground-source heat-pumps

A ground-source heat pump utilizes geothermal energy collected through a ground heat exchange (GHX) through U-tubes in horizontal and vertical variants. Figure 2.2) shows the vertical variant, which are most common in Sweden and, therefore, the focus of this chapter. The vertical GHX consists of boreholes reaching a depth between 150-300 meters (Erlström et al., 2016). A brine is circulated in the U-tube and connects to the heat pump's evaporator side in a closed loop.

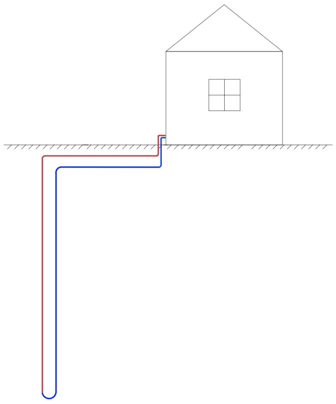

Figure 2.2: Verical borehole with GHX.

Since the ground temperature is rather stable below a depth of 10-15 meters, it is possible to utilize the heat exchange during colder periods in the year. The undisturbed ground temperature in Sweden can be between 5°C in the north and 10-11°C in the south (Rosén et al., 2002). Due to the high groundwater level in Sweden, the boreholes are groundwater-filled, which positively influences GHX.

One important design factor of a GSHP system is that the GHX must be balanced over the year, or the potential future energy extraction can be significantly reduced (Erlström et al., 2016). This means that if heat is extracted from the ground in winter, it needs to be replenished in the summer in approximately equal amounts. While the ground is warmed by the sun during summer, there may still be a need for active heating. One way to achieve this is by utilizing GSHP for cooling during the summer.

SGU (2023) estimates that around 300,000 borehole systems are installed in Sweden. GSHP technology has become increasingly popular in detached houses and remote areas where district heating (DH) is unavailable. The technical advancements in creating more efficient heat pumps and improving drilling techniques, which have reduced drilling costs, contribute to this growth (Björk et al., 2013). Due to the high efficiency of GSHPs, heating energy can be delivered for around one-fourth of the cost, assuming a COP of 4. This translates to lower energy costs for property owners and potential economic benefits, despite the relatively high initial investment cost.

2.5 Literature review

A brief literature review was conducted to find similar research and relevant works. The focus lies on studies concerning hybrid heating systems involving DH and heat pumps.

As mentioned briefly in the introduction Kensby et al. (2017) studied the impact of shifting energy sources based on marginal cost for electricity and DH. Since it was common for multi-residential buildings in Gothenburg to have exhaust air heat pumps and DH, this was the analyzed setup. The study found that a saving of approximately 3% on marginal cost could be achieved by controlling the shifting of the heat sources based on hourly price.

In the master thesis by Langerak (2022), the focus was on creating a calculation model for designing hybrid heating systems with GSHP and DH. It was based on the local market of Umeå and involves the development of an optimization model that determines the most suitable power coverage from GSHP if combined with DH. The method involved a few simplifications regarding, for example, electrical energy prices, which were assumed to be constant. The results indicated economic benefits from the combined system and that the size of a heat pump in the design shouldn't be too small. The author also emphasized the impact of the local price markets since DH and electricity vary throughout the country. The model, therefore, needs to be adjusted if used elsewhere.

Lygnerud et al. (2021) elaborate on the fact that new business models combining heat pumps and DH in buildings could be needed if they should be promoted. The results show that a maximum cost saving of 30% and CO_2-emissions savings of 70% could be achieved if HPs were used in the DH network. Important details are that the results are based on proposed business models where economic savings from shifting the energy sources are divided between the energy supplier and the property owner.

This brief literature review highlights the interest in studying heating systems that combine DH and GSHP. All reviewed studies involved simplified calculations of the building's energy consumption and cost, suggesting that more detailed studies might be needed to validate these results.

3

Methods

The overall method of the project follows a few steps with different characters. The main steps are presented in figure 3.1. The two first steps of the method concern the handling of measured data and the calibration of the existing IDA ICE model from the reference building. Step three concerns the development of the simulation model with a hybrid heating system with a strong focus on calibrating and validating the GSHP to behave as the system of the reference building. The last step is the economic evaluation of the impact of shifting energy sources based on hourly energy prices, which is conducted with the help of the developed simulation model. The following sub-chapters will describe the method in more depth.

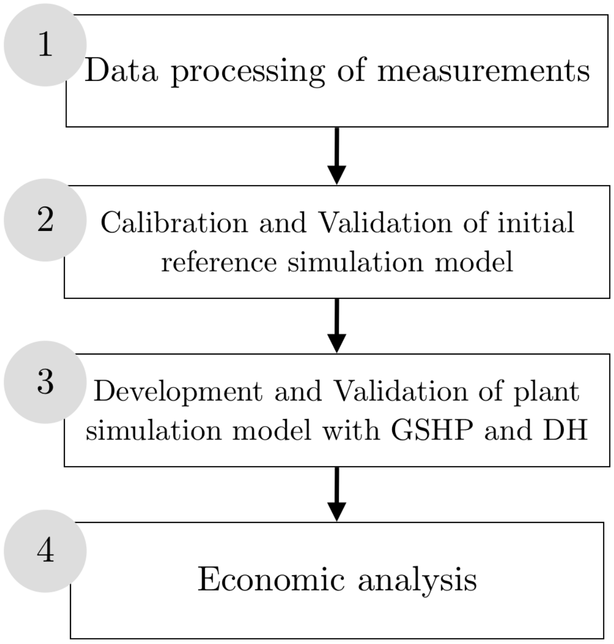

Figure 3.1: Describing the outline of the main methodology used in the project.

3.1 Reference building

A reference building from a prior project of the consultant firm Bengt Dahlgren AB has been used to get calibration data to improve the developed simulation models. The building is located in Ulricehamn and is multi-residential, with 8 floors and 17 apartments. The heated space (A_{temp}) is 2700 m^2, and as a relatively new, finished in 2022, the building standard follows BBR and normal building standards Sweden(Boverket, 2011). The construction is made of prefabricated concrete elements. It comprises an in-situ casted concrete slab, exterior walls of concrete sandwich elements, and timber-trussed roofing. The assumption has been made that the existing initial simulation model provided is correct enough, considering building details such as slabs, walls, roofs, and windows. The available data about the building has been limited to architectural drawings, technical documentation, and measured data.

A geothermal heating system with boreholes and a ground-source heat pump (GSHP) supply the building with heating and domestic hot water (DHW). The heat pump model is Thermia Mega L, with a capacity between 14-59 kW and COP of 4.5 (Thermia, 2024). The seasonal coefficient of performance (SCOP) is 5.29 for floor heating (35°C) and 4.2 with radiator systems (55°C). The system has top-up heating from electricity for heating and DHW, which ensures the correct supply temperatures when the heat pump capacity is insufficient. The heating system is hydronic with radiators and heating for the air handling unit (AHU). The AHU has supply- and exhaust air and a heat exchanger with efficiency of 84%. The building also has solar hybrid panels that produce electricity and charge the boreholes with thermal energy through a liquid circuit. These are disregarded in the simulation model and further analysis as mentioned in the limitations (1.3).

The technical system has numerous meters for heating-, AHU-, and electricity centrals. The data from the meters are logged to provide detailed information for follow-ups and analysis of energy consumption. By utilizing the logged data, this thesis project has used the building as a reference when validating the developed model. However, the primary aim of using this building as a reference has not been to analyze the building itself but to use its similarities with the technical system studied throughout the project.

3.2 Data processing

The measured data from the reference building was accessed through the building energy management system with permission from the property owner. Data was available from when it was finished at the start of 2022 and onwards. However, it was not consistent and reliable enough during 2022, so 2023 was selected as the reference year. Although more consistent during 2023, there had also been issues with data logging during the year, with missing data periods as a result. Despite this, it was noted that April, September, and December had complete data, and the decision was made to use them as the main detailed calibration data representing days and months. Thanks to the accumulation of measured data when saved(meaning that each saved value includes all previous measurements), it was also possible to recover the yearly totals for 2023 by using the difference between values from 31 December 2022 and 31 December 2023.

The datasets provided were based on five-minute intervals. Therefore, the goal of the data processing was to create datasets where hourly, daily, monthly, and yearly data for energy consumption and other parameters of interest could be compared. The measured data of interest was partly coupled to the heating system concerning heating energy and domestic hot water (DHW) energy usage. The second part revolved around the electrical meters and especially the electrical energy usage from GSHP's , top-up for heating, top-up for DHW, property electricity, and tenant electricity.

Due to their speed and flexibility, Python and Excel were used for data analysis and processing. The Python package Pandas was essential in data processing since it allowed for quick imports and transformation of large datasets from provided CSV files. Each data entry was timestamped at 5-minute intervals with a "Year-Month-Day Hour:Minute: Second" format; the data could, therefore, be indexed using the DateTime function in Pandas. The time-based indexing made it possible to easily resample the data based on hour, day, month, and year at later stages.

The logged data had generic labeling based on their meter names, and the data processing was therefore divided into the following steps:

1. Import the datasets in both Excel and Python
2. Classification of columns by analyzing meter names from schematic drawings and logging system data. Mapping of the parameters to the right columns.
3. Collect relevant data in a new dataset in Python.
4. Calculate or extract hourly heating and electric energy values dependent on meter type.
5. Identify gaps in the data, errors in saving or logging. Create plots and other controls to verify the consistency of the data.
6. Remove outliers or extremely high values created by faulty logging from the extracted/calculated hourly data.

Python and Excel were also used for calibration and validation processes to compare results between measured data and predicted values from the simulations. For the final validation and calculation of statistical metrics, CV and NMBE, mainly Python was used.

3.3 Building energy simulation

To forecast building energy demand, the impact of retrofits, and investigate code compliance or applicability of green certificates, building energy simulations can be made(U.S Department of Energy, 2024). The modeling takes input such as geometry, location, climate, technical equipment (for example, HVAC and heating systems), lighting, and occupancy rates. It simulates the overall energy demand or indoor climate of a building. By setting up a detailed simulation model it is possible to achieve advanced models with high accuracy. There are numerous validated software available for conducting building energy simulations; examples are, EnergyPlus, ESP-r and IDA ICE.

The accuracy of a building energy model(BEM) is highly dependent on the quality of the input data. For modeling buildings before construction, there is a need for many assumptions concerning user patterns and other unknowns. These discrepancies, often called "gaps in performance" are significant factors in building energy simulations (De Wilde, 2014). Understanding and mitigating these gaps is essential for improving the reliability of energy modeling predictions. A few metrics have been proposed by ASHRAE (2002) to create common ground for validating models and to cope with these uncertainties. Two of these metrics are used in this master's thesis and are described further in 3.3.2

3.3.1 IDA ICE

IDA ICE (Indoor Climate and Energy) is a software for building performance simulations with its roots from KTH in Sweden (Equa, 2024). The software can model multiple zones dynamically with whole-year details. The software is validated according to standards the Ashrae 140 (2004) and CEN Standard EN 15255 and 15265, (2007) (Equa, 2024).

The simulations in IDA ICE are done in adaptive time steps, meaning that different time steps are used depending on which parameters it calculates. However, it is possible to retrieve hourly results from whole-year simulations, a feature utilized to get the results. There are presets for presenting/logging results, but it is also possible to log custom parameters of interest. For example, the parameters in the plant developed in the project needed custom logging to collect data for calibration and validation of the heat pump and heating system. Apart from plotting simulation results, reviewing the logged data in a table is also possible. To export the simulation results from IDA ICE throughout the project, the hourly data have been copied from the tables, pasted in Excel, and converted to CSV. The CSV files were then generally imported and post-processed in Python.

3.3.2 Validation metrics

Two metrics that have been proposed by ASHRAE (2002) and others are the coefficient of variation of the root mean square error (CV(RMSE)) and the normalized mean bias error (NMBE).

Normalized Mean Biased Error (NMBE) is a normalized variant of the statistical measure Mean Biased Error(MBE), which is the average error between measured and simulated data (Ruiz & Bandera, 2017). The normalization plays an important role in validating building energy simulations since the data range can vary significantly between hours, days, and months. For example, building heating energy usage ranges can vary between 0-70 kW in the summer and 500-700 kW in winter.

The lower the NMBE is, the better the prediction done by the simulation. Since cancellation errors are possible in NMBE, where negative and positive errors can balance each other out, it shouldn't be used as the only metric. This means that while NMBE provides information on the mean bias, it may not fully capture the magnitude of the errors. Therefore, it's important to use additional metrics like CV(RMSE) to assess a model's accuracy more comprehensively(Ruiz & Bandera, 2017).

NMBE can be calculated with equation 3.1 (Ruiz & Bandera, 2017), where

$$NMBE = \frac{1}{\bar{m}} \cdot \frac{\sum_{i=1}^{n}(m_i - s_i)^2}{(n-p)} \cdot 100 \qquad (\%) \tag{3.1}$$

$\bar{m}$ is the mean value of the measured values, m_i and s_i are the measured and simulated data points at each time instance i, n is the number of measured points, and p is the number of adjustable model parameters (for calibration pruposes proposed to be zero).

The coefficient of variation of the root mean square error, CV(RMSE), indicates the variability between the measured and simulated data. A low CV(RMSE) value indicates low variability and a better prediction of the simulated results. In contrast, a high indicates a higher variability between the measured data and the simulated results. Calculation of CV(RMSE) can be made with the same parameters as NMBE with equation 3.2 (Ruiz & Bandera, 2017).

$$CV(RMSE) = \frac{1}{\bar{m}} \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{(n-p)}} \cdot 100 \qquad (\%) \tag{3.2}$$

(Ruiz & Bandera, 2017).

Using monthly validation data, the following thresholds are proposed for CV(RMSE) 15% and NMBE (+-)5% (ASHRAE, 2002). When hourly data are utilized, the same thresholds are 30% and (+-)10%, respectively.

3.4 Model validation

The initial simulation model provided for the reference building was first analyzed, calibrated, and validated. The following step was to develop and validate the plant model further using the calibration data from the reference building. The following subchapter explains the method of simulations and developments conducted in detail.

3.4.1 Initial simulation model

The initial IDA ICE model was used in the energy calculation of the reference building before being built and could, therefore, be provided by Bengt Dahlgren AB. To simulate the same conditions as in the measured data from 2023, the climate file in the model was changed to represent historical weather from Ulricehamn 2023. The climate file was downloaded at SVEBY (2024) and imported to the model. Energy simulations of the initial model were then made, and the yearly, monthly and hourly results from heating energy were collected. The input data used in the simulation model is presented in Appendix A1. Although BEN standards and guidelines for simulating buildings' energy usage exist, many assumptions and simplifications are still made. Therefore, a safety margin of 20% is usually added to the result to address any insecurities. Following this practice, a safety margin of the same amount was added to the initial model comparison.

3.4.2 Calibration and validation of initial model

Figure 3.2 describes the iterative calibration and validation process. The correctness of the results was determined by comparing with measured and simulated data. Calibration was made mainly by changing the parameters for tenants electricity usage, thermal bridges, heating setpoint, and AHU heating setpoint in iterations until the yearly results matched between simulated and measured.

The main parameter used to validate the initial model was the building's purchased heating energy. The purchased energy consisted of heat delivered to the radiators and AHU heating energy, which was compared and analyzed throughout the calibration process. Domestic hot water (DHW) usage was added to the model based on the measured yearly sums from DHW and hot water circulation (HWC). Since usage patterns were not possible to retrieve from the measured data, the usage was averaged throughout the hours of the year. As the initial model used the basic IDA ICE plant model with district heating, no other calibrations were possible or needed at this stage.

Hourly-, daily-, monthly- and yearly values were used during the calibration process. The aim was to get close to the monthly and yearly results in the final validation. The hourly and daily values were used to find patterns of differences between the simulations and the measured data. The monthly- and yearly values were used for the actual validation.

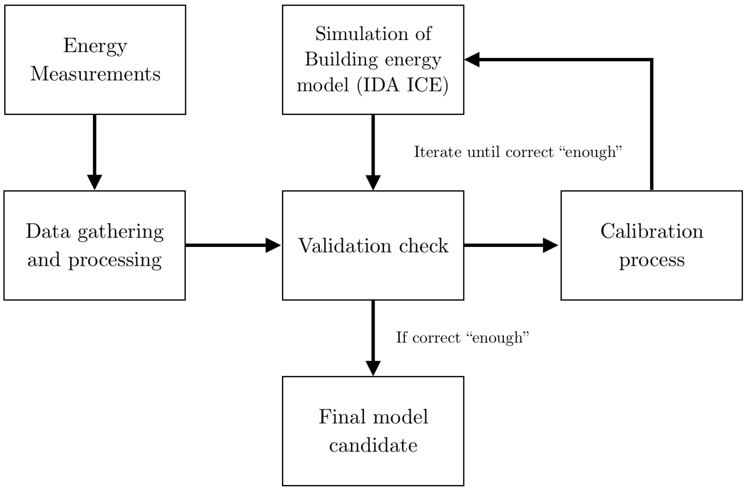

Figure 3.2: The schematic shows the validation and calibration process used to calibrate the existing IDA ICE model towards the measured data.

3.4.3 Tenant electricity use

In the calibration of the initial IDA ICE model, the tenant electricity usage, which refers to electricity for appliances, lighting, stove, fridge, freezer, and computers in their apartments, was modeled using a statistical method based on measured data. Initially, the tenants electricity usage was modeled with the monthly level variation defined by SVEBY (2024). In an attempt to enhance the accuracy of the simulation model's results, and since measured data was available, a statistical approach was taken when predicting daily variations of the tenants' electrical energy usage. As described earlier, full monthly measured data was available for April, September, and December from 2023. By studying and quantifying the statistical electrical energy use for each hour daily based on either weekdays or weekends, two profiles for each month were developed.

In the first step, the monthly mean of each hour of a day, weekday, or weekend was created. Then, the mean value between each hour reflected in the three available months was calculated. Ending up with two profiles, one for weekdays and one for Saturdays and Sundays. After that, the profiles were normalized to a range between 0 and 1.

Before adding the profiles as schedules in IDA ICE, a last step was taken to add the statically established variation described by SVEBY (2024), used initially in the model. This was done by multiplying their monthly factor with the profiles to differentiate between the months. The result was 2 usage profiles each month, a total of 24 profiles, which were then introduced as schedules for tenant electricity use in IDA ICE.

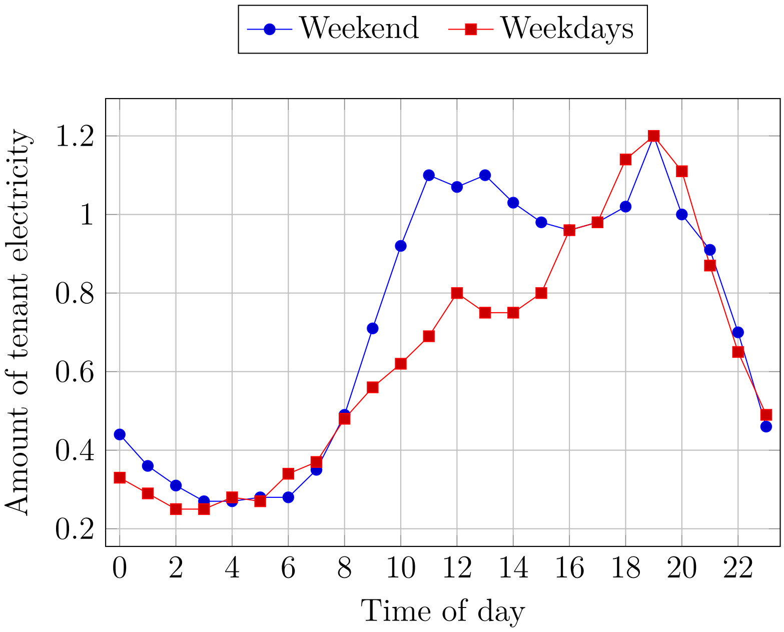

Figure 3.3: Example of the schedules created for representing the tenant's electricity usage in the apartments. Plotted profiles represent December weekdays and weekends/holidays.

An example of the resulting schedules for tenants' electricity in December is presented in figure 3.3. It can be seen that the behavior during weekdays and weekends varies. Weekends tend to have more electricity usage throughout the day, from lunchtime onwards. The overall pattern shows that the tenant's electricity usage is higher in the evenings than during the night and early morning.

These profiles were then coupled to the usage of electric equipment in the apartment zones in the simulation model. The overall electrical power was adjusted to match the measured tenant electricity use. As a result of the calibration process, this level was drastically decreased to match the heating energy usage in the measured data.

3.5 Development of plant model

The plant model was developed in IDA ICE 5.0. Bengt Dahlgren provided the base model, which was then developed during the master's thesis project. The model was built upon an ESBO plant model developed and altered in the software. Figure 3.4 shows a simplified schematic drawing of the plant model. For modeling the boreholes, the built-in borehole model was used; the brine is driven by a pump with a valve to set the mass flow rate of the brine. The heat pump is connected to a split on the supply side and a merge on the return side. These allow for the split between the heating system and DHW supply. The heat pump and heating system are controlled by separate PI-controls, which have one temperature curve each and connect to outdoor temperature sensors. The primary side of both heating and DHW connects to the secondary side with two heat exchangers each. The first heat exchanger allows the available heat from the HP to be exchanged, and the second heat from the top-up boiler/DH. The top-up amount is controlled by the temperature setpoints for the respective part.

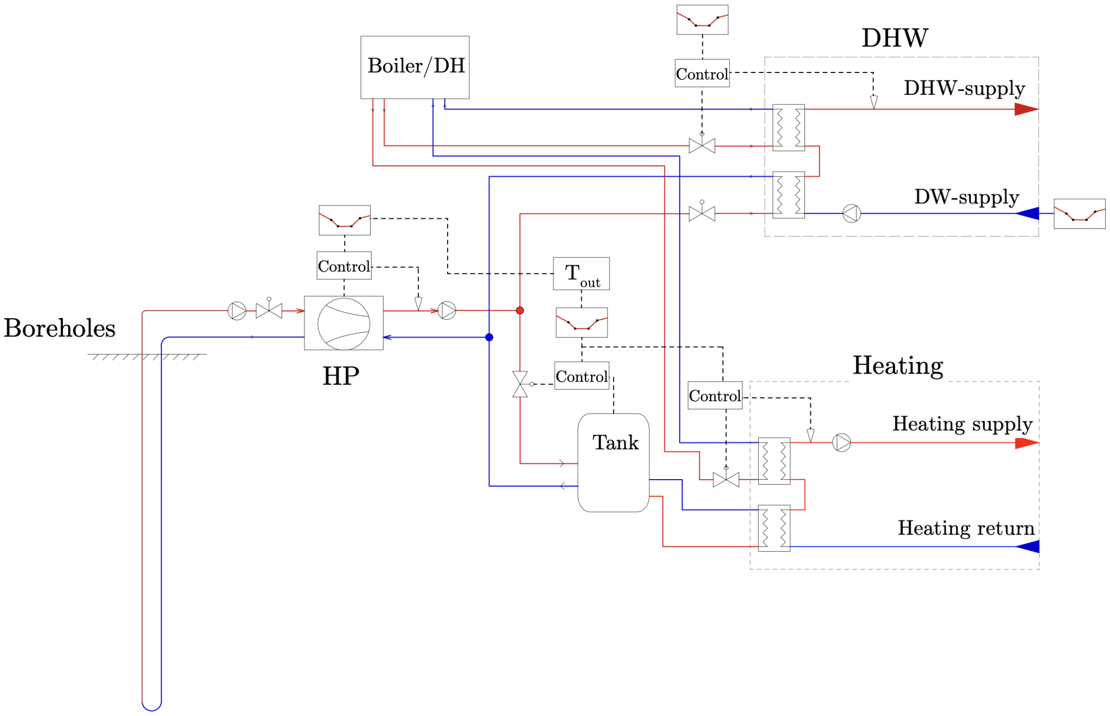

Figure 3.4: Simplified schematics of the plant model developed and validated in IDA ICE.

Other than reflecting the calibration data, the plant model should also be able to utilize control that can mimic a price-governed control system. Therefore, a scheduled binary signal was multiplied with the heat pump control signal to allow for prioritizing one heat carrier. If the signal is 0, the heat pump shuts down, and district heating will get full priority, whilst if the signal is 1, the system will work with both the heat pump and district heating(as top-up) as in normal operation.

3.5.1 Calibration and validation of the GSHP model

The GSHP and DH model was calibrated by comparing simulated results and measured values. This was done in the same manner described in 3.4.2 with the additional development of a Python script that could handle more variables. The main objective was to focus on the energy consumption from heating, DHW, and GSHP to match the available monthly and yearly measurements. This was done using a step-by-step method, first involving calibrating the model based on the heating system's supply temperatures and energy usage. Secondly, the DHW and top-up energy were calibrated. Lastly, the compressor energy for the heat pump was calibrated. The iterative process was the same as in figure 3.2.

Simulation results and measured data based on days, months, and the total year were compared visually and numerically. Lastly, CV(RMSE) and NMBE were used to grasp the calibration's correctness statistically, as proposed by ASHRAE (2002). The thresholds used for CV(RMSE) and NMBE were 15% and 5%, respectively, further described in 3.3.2. Although these thresholds refer to monthly data, they were used to test the validity of the daily results as a last step of the plant validation.

3.5.2 Ground-source heat pump

The ground-source heat pump was modeled with six boreholes, each 300 meters, and the simplified heat pump (HP) model in IDA ICE. The boreholes were set up with single U-tube heat exchangers with ethanol as brine fluid. The effective thermal resistance of the borehole was set to 0.11 $(mK)/W$ and ground thermal resistance to 3.2 $W/(mK)$ as proposed by Arghand (2019).

The simplified HP model includes a limited number of models from various HP manufacturers. The specific model used in the building was not; therefore, the generic HP model was used instead. As a result of the calibration process, the capacity of the HP was set up to 57 kW, while the actual heat pump in the building has a max capacity of 59 kW Thermia (2024). The final COP in the calibrated model was also slightly lower than the specifications, 4.35, instead of 4.5. The deviation from the specified values was necessary to get the compressor energy closer to the yearly heat pump energy usage.

Figure 3.5 shows the temperature curves controlling the plant model's HP. These curves were developed during the calibration process. The main curve is used in all months except March, April, and September. The curves for the three months were added to affect the amount of top-up used for DHW. Although March didn't have complete measured data for the whole month, it was noted that the deviation was so large that it needed to be adjusted anyway.

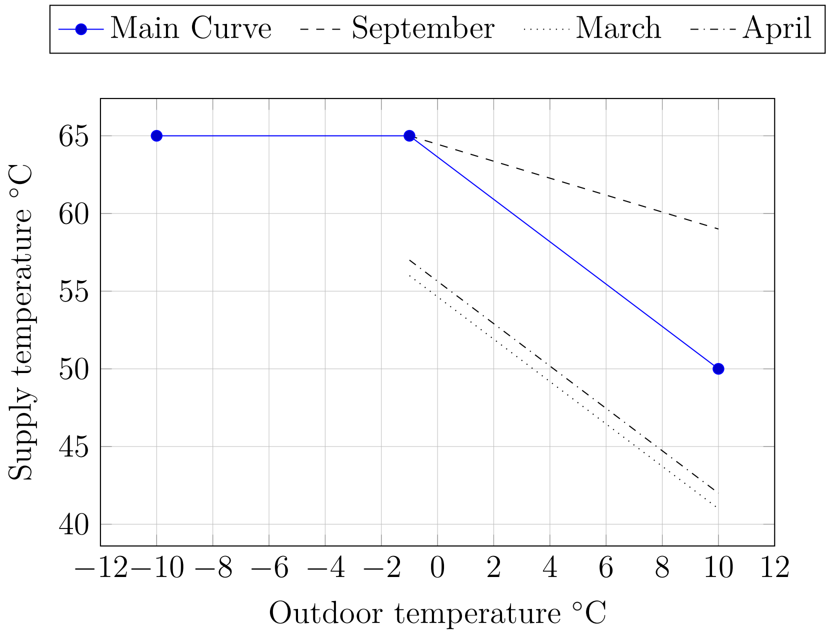

Figure 3.5: The temperature curve used as input for the control of the GSHP in IDA ICE.

3.5.3 Heating system

Firstly, the supply temperatures for the heating system were calibrated. Secondly, the amount of energy used for heating was controlled and documented. Since the heating usage was calibrated towards measured data in the initial validated model, the heating usage with GSHP was the same. The temperature curve shown in figure 3.6 was used to get the calibrated supply temperatures.

It was noted from the measurements that no top-up energy was used for heating in the reference building during 2023. Therefore, the model was calibrated so that nearly no top-up energy was used for heating during regular operation. Nevertheless, the top-up needed to take full precedence if the heat pump was shut down, as this is the scenario when shifting the energy sources. This operation was therefore tested by setting schedules to the heat pump that turned it off for various periods. Energy simulations were then conducted, and checks were made to see that the heating system was still operating with the correct supply and indoor temperatures.

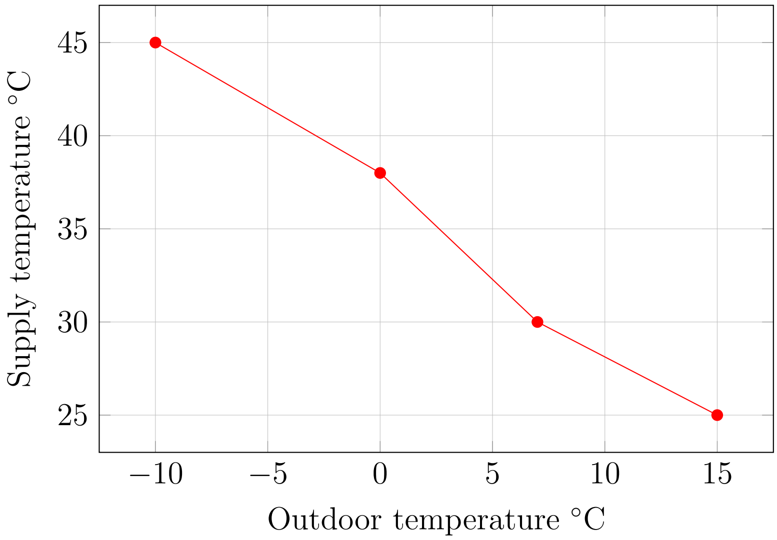

Figure 3.6: Heating supply temperature related to the outdoor temperature used in the plant model.

3.5.4 Domestic Hot-water

As described in 3.4.2, the overall energy demand for DHW was simplified to just using an average demand based on the measured values for DHW and HWC. But since there was top-up energy usage for the DHW the system was calibrated to grab this energy usage. To increase the details impacting DHW top-up, the water temperatures, both for incoming cold water and supply of hot water, were defined by the available measured temperatures for March, April, September, and December. For the rest of the months, temperatures were based on measured temperatures from Stockholm provided by SVEBY (2024). Figure 3.7 and 3.8 shows the temperatures used in the plant model. The variation the temperatures was introduced to ensure that the calibration of top-up for DWH should perform as close to the actual system as possible.

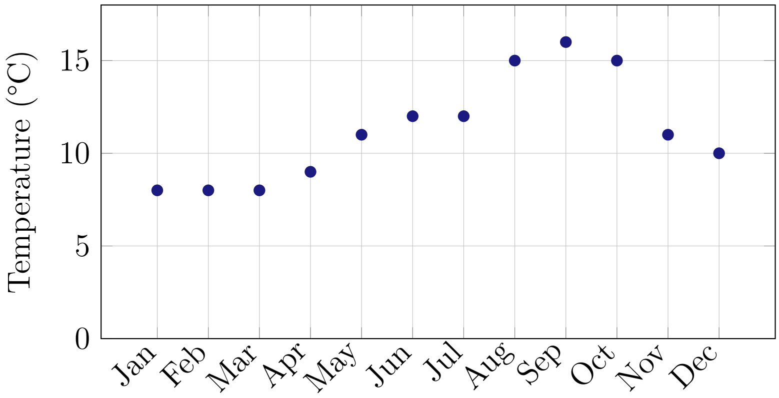

Figure 3.7: Monthly temperature of incoming domestic water used in the model, based on measured data and SVEBY (2024).

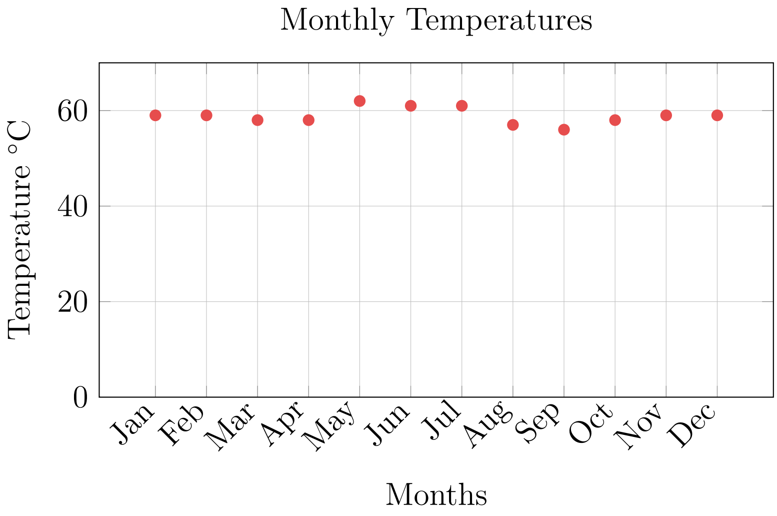

Figure 3.8: Based on measured data, monthly supply temperatures used for the domestic hot water in the plant model.

3.6 Economy

In the economical evaluation the aim was to test how control strategies involving hourly energy prices and power limits on DH impact the yearly energy cost. The location of interest was Gothenburg and the climate file used in validated simulation model was therefore changed to represent the climate in Gothenburg. The simulation model used was the validated plant model coupled with the building from the reference building in Ulricehamn.

The model can shift between GSHP and DH as described in 3.5 but with one side effect. When switching on the GSHP in the control scheme, the top-up would still come from DH. However, when turned off, DH is the only provider, and no electricity is used. Since the top-up generally is quite limited in both power and energy usage during normal operation with GSHP, this has been overseen.

Two sets of scenarios were tested in the economic evaluation of shifting energy sources based on hourly energy prices. The control strategies were based on the following:

1. The lowest price during 3 hours based on electrical prices from 2020-2023
2. The lowest hourly price based on electrical prices from 2022 and 2023, respectively, and an upper bound power limit on the district heating.

These two strategies were then evaluated by using different control signals for each case and simulating them in the developed IDA ICE model. The results for HP energy and DH were then collected, and yearly energy costs for power and energy were calculated. Creating the control signals involves a couple of steps, which will be described in more detail in the following section.

3.6.1 Hourly energy price strategy

An hourly energy price analysis was conducted to analyze how prices can control the hybrid heating system with district heating and ground-source heat pumps. The main idea was to harmonize the hourly prices from DH and Electricity and create a simple algorithm that selects the provider with the lowest price for a defined period. The analysis concentrated on the historical electrical spot prices from 2020-2023 and the DH prices from 2024.

The algoritm was set up as follows:

1. Collect price information for district heating for 2024 and electric-spot prices for 2020-2023
2. Combine the data in Python
3. Add electricity tax and transfer fee to the electricity prices
4. Divide the electricity price by mean COP of the GSHP to make fair comparison to DH prices, (COP = 3.3)
5. Create control signal based on the condition(s)
6. Create .PRN file with control signal, imported to IDA ICE as a schedule controlling the GSHP in the plant model

The result from the simulation was then combined with the price information, and the total cost was calculated and compared. As described in the next chapter (3.6.2), the prices for electricity and DH consist of two parts: one for power transmission and one for used energy. The prices for corporate customers for electric and DH power in Gothenburg include a power tariff (Göteborg Energi, 2024a). (Göteborg Energi, 2024b). The cost of a power subscription is, therefore, a result of the maximum power output from a previous period and needs to be calculated after knowing the maximum power of the month for electricity and with DH. These were, therefore, collected from the simulation results, and the yearly cost for power transmission was calculated for electricity and DH separately. The energy costs are more straightforward and depend on the hourly energy use for electricity and monthly for DH.

Scenarios with DH only, GSHP+top-up(electric), and GSHP+top-up(DH) were also simulated, and yearly energy costs were calculated to serve as references compared to the energy costs for the hybrid system.

Figure 3.9 shows an example of the control signal and the relation to the used energy prices. The jump in DH price represents a change of month. Figure 3.10 shows the energy usage from GSHP and DH during the same period.

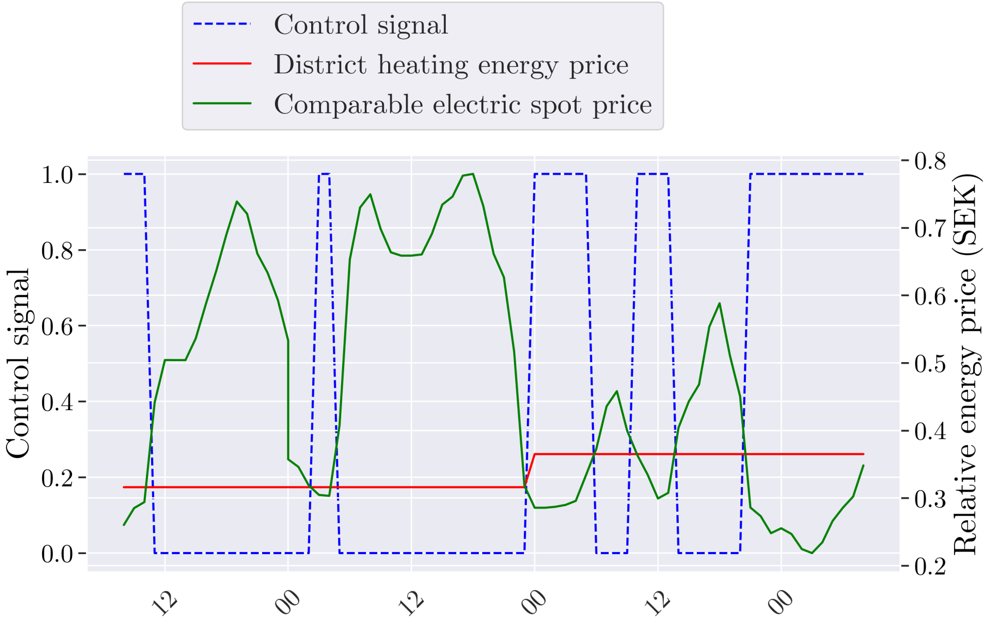

Figure 3.9: Example of the control signal with price dependency from the control algorithm using the lowest price for 3 hours together with the comparable electricity price and DH energy price. Showcasing a 4-day period between 30 of October to 2 of November 2022.

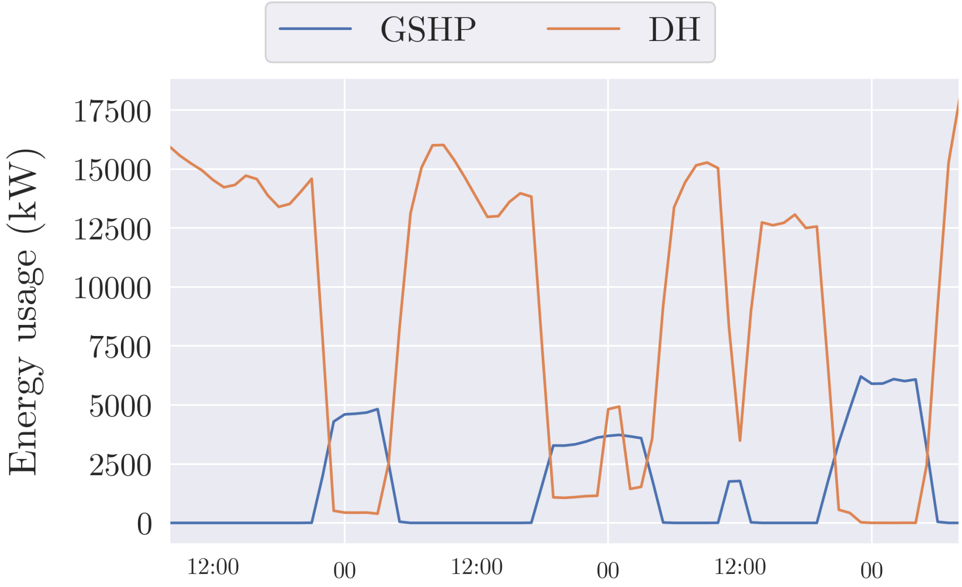

Figure 3.10: Showcasing the shifting of energy from simulation results during the same 4-day period as in figure 3.9.

3.6.2 District heating prices

All energy prices for DH were collected from Göteborg Energi (Göteborg Energi, 2024b). As described in the theory section, the prices consist of two parts: one for the subscription/connection and one for the energy bought. There are two types of subscriptions, which depend on whether DH is used as the only heating provider or if it is combined with a heat pump or something else. Table 3.1 shows the costs for the two types of subscription models. The main difference is the slightly higher rate of the power fee for the subscripted power alternative. The power fee for customers who only use district heating is based on the average of the three highest power outtakes over the year. For subscripted power, it is up to the customer to decide which power they need or want to subscribe to. If additional power is needed during the subscription period, there is an extra fee of 4500 SEK per kW of extension(Göteborg Energi, 2024b). All prices presented in the method exclude VAT.

Figure 3.11 shows the cost for energy (SEK/kWh) for the two different types of subscription models. Customers that use district heating as the only heating source pay slightly more for the energy than the ones with subscripted power.

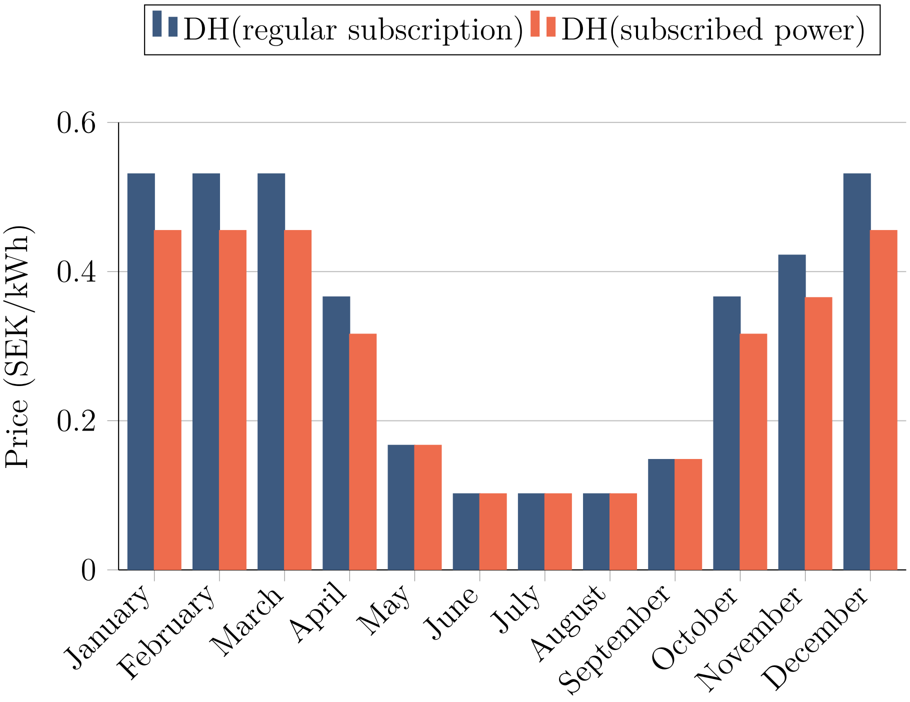

Figure 3.11: Monthly energy tariff for district heating from Göteborg Energi (2024b).

Type of subscription	Fixed price (SEK/Year)	Power fee (SEK/kW, Year)
DH (regular subscription)	10360	1089
Subscripted power	10360	1121

Table 3.1: Subscription prices for district heating valid for the power span 0-100 kW and 2024 (Göteborg Energi, 2024b).

3.6.3 Electricity prices

The electrical spot prices used in the project were downloaded at Energinet (2024), which provide open datasets of up-to-date Elspot prices in Danish kronor and Euro. To convert the price costs to Swedish kronor (SEK), a fixed transfer rate of 11.5 SEK per Euro was used. Historically, the Euro has had a lower transfer rate towards the Swedish kronor(Skatteverket, 2024), but in this study, a fixed transfer rate was chosen to keep consistency in the control algorithm. Figure 3.12 shows the historical spot prices for the price area SE3 from 2020-2023 used in the economic evaluation.

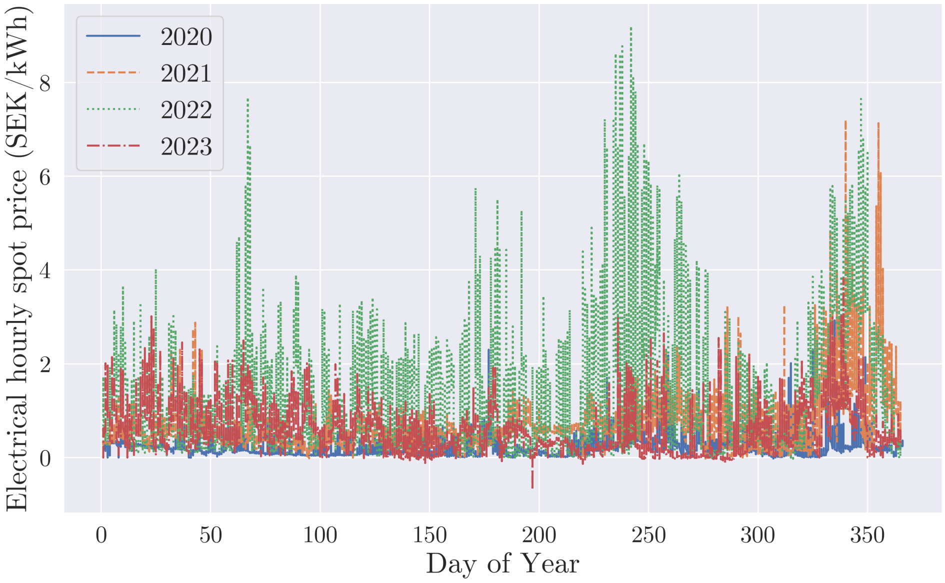

Figure 3.12: Electrical spot prices(SE3) from 2020-2023 in SEK/kWh (Constant Euro exchange rate = 11.5 SEK). Prices origin from (Energinet, 2024).

The fixed costs for electric connection are from Göteborg Energi (2024a) and are presented in table 3.2. Apart from the costs in the figure and table below, there is an additional energy tax of 0,428 SEK/kWh excl. VAT added to the total electrical bill.

As described earlier, all energy-related costs have been added to make the comparison between district heating and electrical prices fair in the control algorithm. As described by equation 3.3, the comparable electrical price, Ep_c, consists of the sum of hourly spot price, transfer fee, and energy tax divided by COP of the GSHP.

$$Ep_c = \frac{Spotprice + Transferfee + Energytax}{COP_{GSHP}} \qquad (SEK/kWh/COP) \qquad (3.3)$$

Size	Fixed (SEK/month)	Transfer fee (SEK/kWh)	Power fee (SEK/kW, month)
Below 63A	125	0,204	35
Above 63A	655	0,113	56.3

Table 3.2: Costs related to the connection for electricity Göteborg Energi (2024a). The power fee is based on the average of the three highest power usages from different monthly occasions.

3.7 AI-tools

The AI tool Chat-GPT has been used and consulted throughout this project, mainly to enhance Python skills and Latex coding. It has also been used to some extent throughout the writing process. Both by proofreading and providing suggestions for minor changes or improvements in the author's written text. The tool has assisted in speeding up processes and increasing the readability and understanding of the project. None of the information, including the theory or interpretation of results, has been created by Chat-GPT or any other such tool. To increase readability, the spelling tool Grammarly has also been used; although there are AI capabilities in the tool, they have not been utilized throughout this project.

4

Results

This chapter presents the results produced throughout the master thesis project. First, the results from calibrating and validating the initial model will be presented. Then, the results from developing the plant model with GSHP and DH will follow. Last, the economic evaluation will study the effects of running the hybrid system with electrical spot prices.

4.1 Measured building energy usage

During the preprocessing of the measured data from the reference building, parts of the building's energy usage were gathered from the categories of most importance for the calibration process. To set an initial baseline, the energy usage from the measurements from 2023 are presented in figure 4.1 and 4.2. The first figure presents the heating energy measured in the hydronic heating system after GSHP and top-up. The second figure shows the measured electric energy used for GSHP, tenants, facility and DHW top-up. The detailed results are also presented in appendix A.

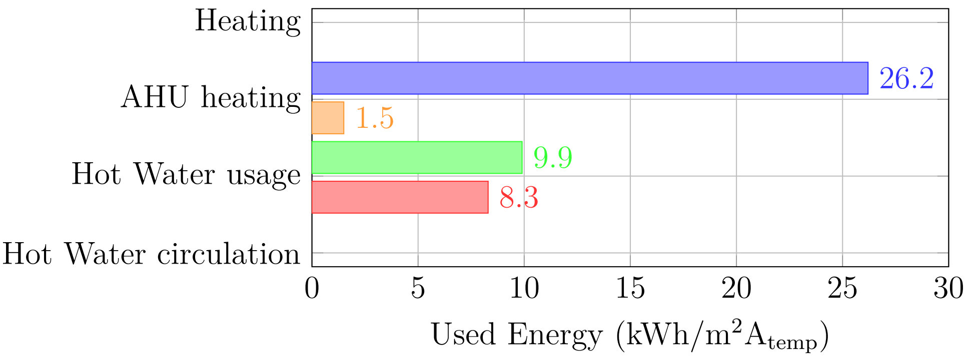

Figure 4.1: Delivered heating energy by the GSHP to the radiators, AHU, DHW and hot water circulation. Measurements carried out after heat pump and top-up.

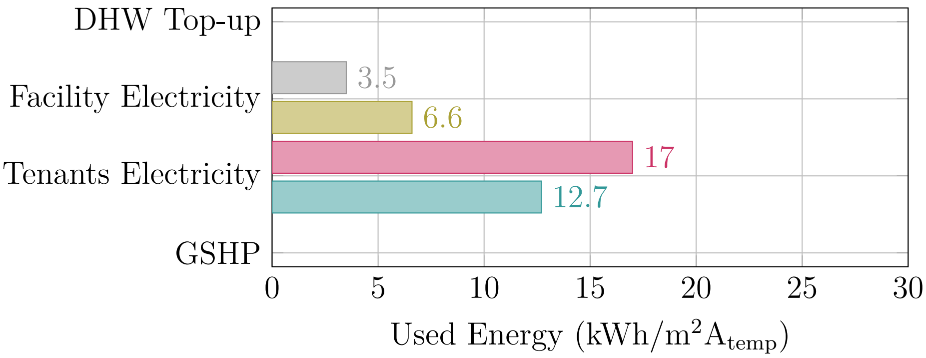

Figure 4.2: Bought electric energy from measured values during 2023. The top-up for heating was zero and, therefore, left out.

4.2 Model validation

This section presents the results from the validations of simulation models conducted throughout the thesis. First, the results of calibrating and validating the initial reference model are presented. Second, the results from validating the developed plant model with GSHP and DH are presented.

4.2.1 Initial simulation model

From the first runs of the initial simulation model provided by Bengt Dahlgren it was noticed that the model had lower heating energy usage than the calibration data showed. There can be many reasons for this difference both in the simulation model and in usage of the building. Assumptions made in the simulation model can be faulty, as can the building itself. Still, to keep to a general calibration situation, the main changes made to the model during the iterations of calibration were the amount of internal heat gains from tenants electricity usage and heating setpoints for both the heating system and the air handling unit. The air handling unit (AHU) heating energy was generally too high initially, and the heating system too low.

Figure 4.3 shows the daily mean energy usage sorted by the outdoor temperature with results from the initial and calibrated models and data from available measurements. The method resembles the one used for determining the energy signature of a building, sometimes used for validating and confirming simulation results (Eriksson et al., 2020). A safety margin of 20% was added to the result from simulating energy usage of the initial uncalibrated model to adjust for uncertainties. The yearly and monthly comparison of delivered heating energy (radiators and AHU) from measured data and simulated results are presented in figure 4.4

The main changes to get the calibrated state of the model were lowering the internal gains from tenants' equipment, increasing the percentage of thermal bridges, and increasing the room heating setpoint. The AHU heating setpoint was also lowered to adjust for overestimating AHU heating energy. A more comprehensive specification of the simulation parameters used in the initial and calibrated models are presented in Appendix B.

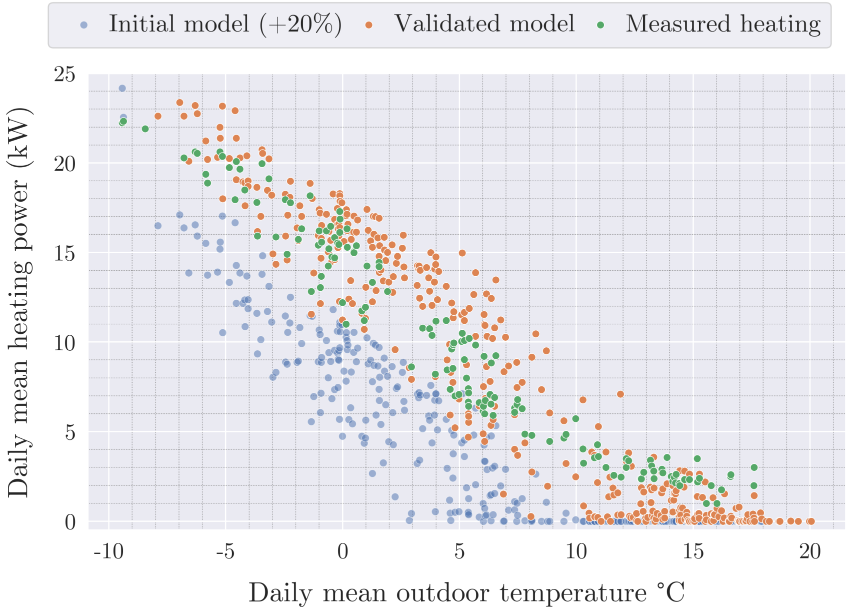

Figure 4.3: Daily mean heating usage as a function of the daily mean outdoor temperature.

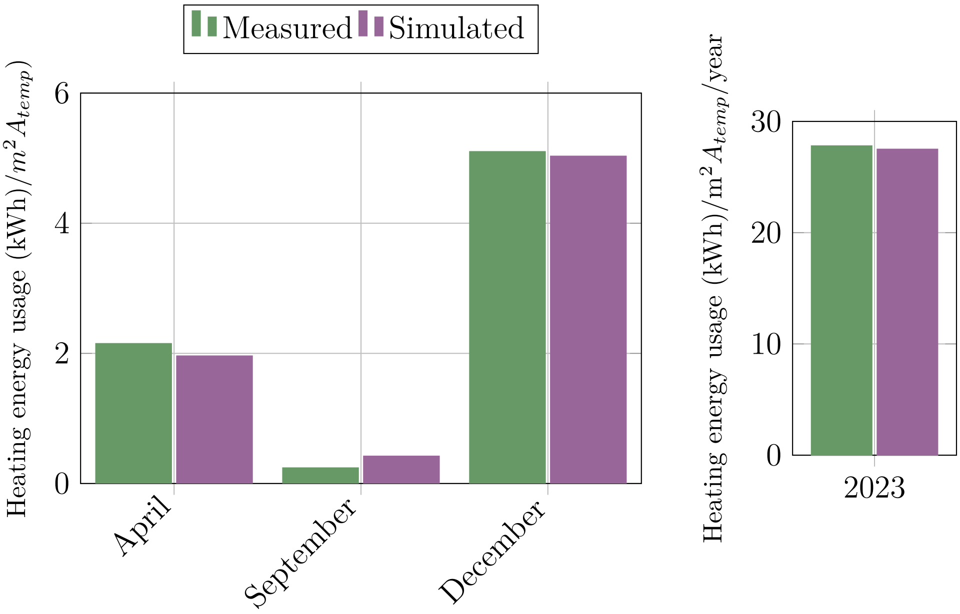

Figure 4.4: The monthly and yearly comparison between measured and simulated for delivered heating energy(radiators and AHU) from the validated initial model.

Figure 4.3 shows that the calibrated model performs closer to the measured values than initially found. Although the measured data does not represent a whole year, there is an indication of better coherence between the calibrated model and measured values after the calibration process. The monthly comparison in figure 4.4 shows that April and September have larger relative differences between the measured and simulated results than December. It was generally more challenging to calibrate the model during the warmer periods of the year than the colder. The yearly total is just off by 1 %, and the accuracy level was enough for the validation.

4.2.2 Validation of plant model

The validation of the plant model involves presenting details of the heat pump, heating system, and DHW. Starting with the heat pump figure 4.5 shows the detailed daily sum of electric energy used for the GSHP from December 2023. The visual confirmation shows a well defined coherence between measured and predicted data. This indication is also verified by the metrics, CV(RMSE) is 10.7%, and the NMBE only -0.4%. Telling that the variations between the predicted and measured data are relatively low, as well as the mean error between the measured and simulated data points. There are, however, some differences in the higher peaks and lows where the prediction either underestimates or overestimates the HP energy usage. Note that daily mean values are used in the comparison and the figure, the hourly differences are therefore smoothened.

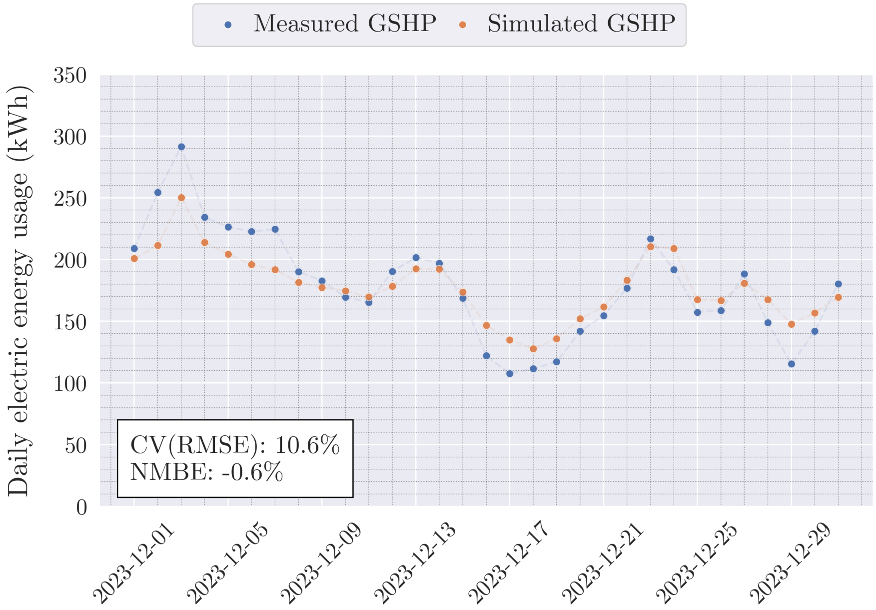

Figure 4.5: Comparison between predicted and measured data for daily sum of heat-pump electricity December 2023.

Figure 4.6 shows the monthly and yearly energy usage for the GSHP. As for the validated initial model (figure 4.4), the monthly results have some variations in April and September but show strong coherence in the colder period in December, as also is verified in figure 4.5. The difference in yearly total is less than 1%.

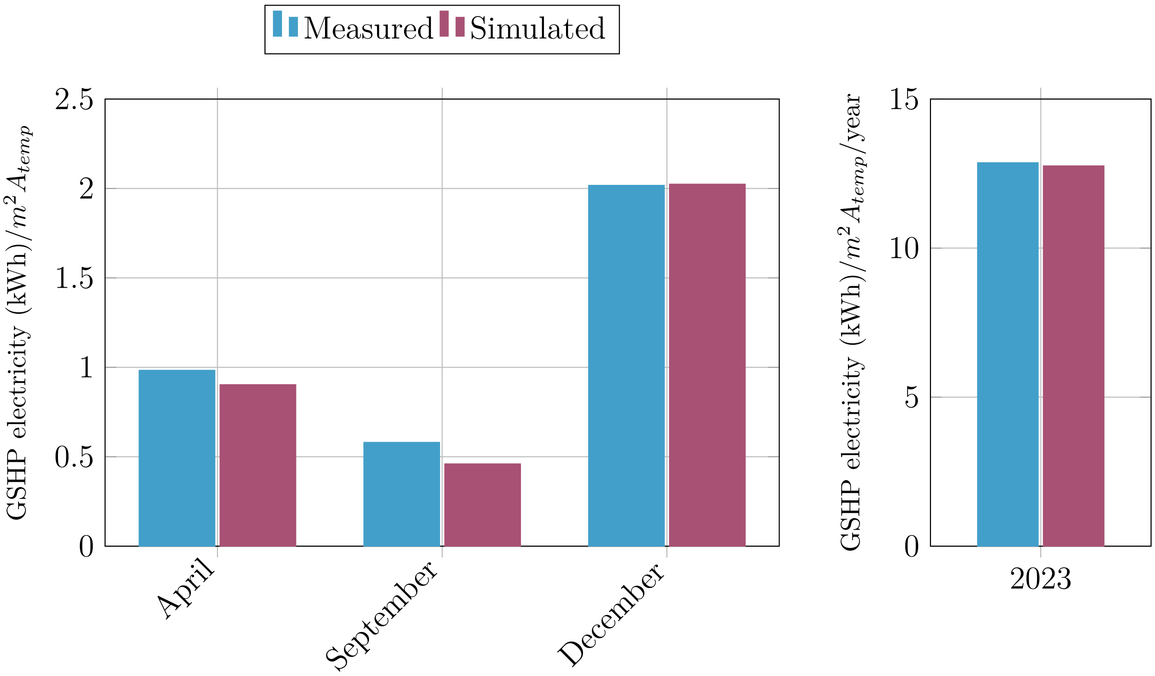

Figure 4.6: The monthly and yearly comparison between measured and simulated GSHP electricity for April, September and December 2023.

4.2.3 Heating system

The temperature curve for the heating system was calibrated to match calibration data at a few outdoor temperatures. Figure 4.7 shows the supply temperature for December, and it can be seen that the fit between measured and predicted values is very consistent.

In figure 4.8, the detailed results of heating energy are presented with a comparison between daily heating energy usage from measured and simulated results. The results show strong coherence with a CV(RMSE) of 12.5% and NMBE of 0-3%. Although there are small differences in both highs and lows, the error is small overall.

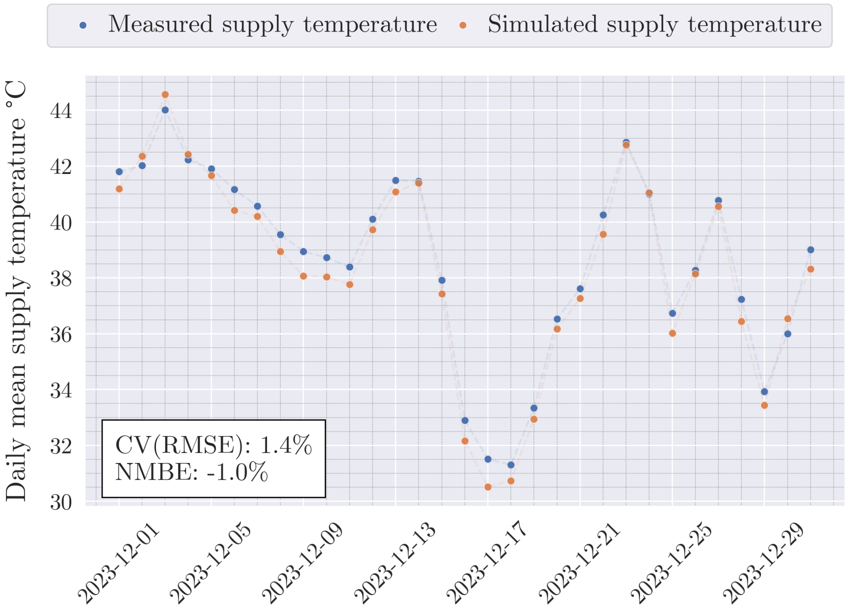

Figure 4.7: Comparison between predicted and measured data of the daily mean heating supply temperatures for December 2023.

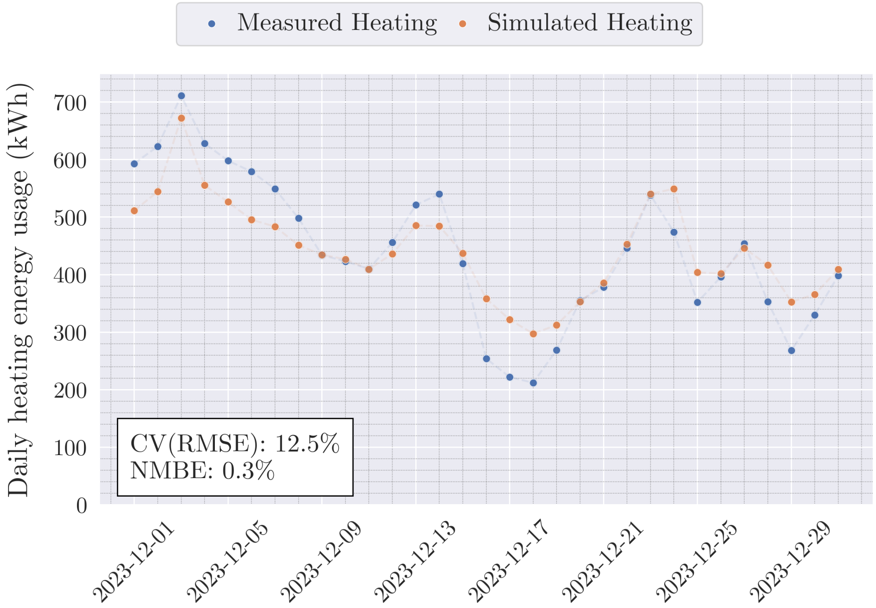

Figure 4.8: Comparison between predicted and measured data of the daily sum of heating energy usage for December 2023.

4.2.4 Domestic hot water

The domestic hot water usage was modeled as an average constant energy usage based on the usage from DHW and HWC presented in figure 4.1 and 4.2. In reality, there are, of course, large variations in usage due to usage patterns. As mentioned in the method (3.4.1), no variations in usage were introduced. The total yearly DHW usage differs only 0.2% between measured and predicted values. The DHW top-up, which represents the electricity or district heating needed to cover hot-water production when GSHP capacity is insufficient, is more interesting since variations will influence GSHP energy usage. Therefore, the actual system's behavior has been carefully studied to produce a similar result to the measured data.

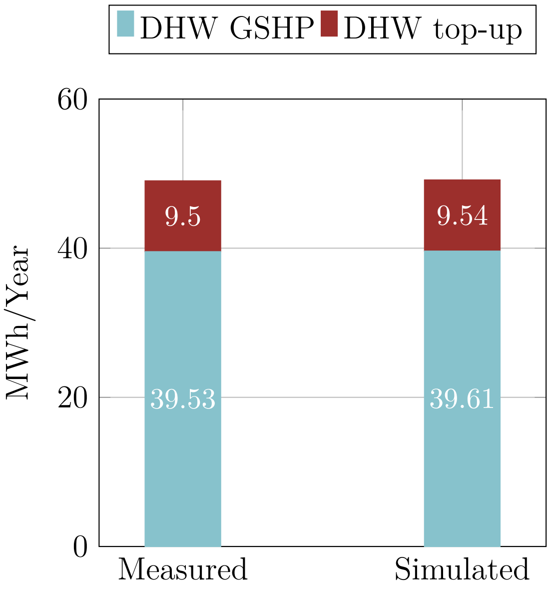

Figure 4.9: DHW from measured and predicted data 2023. Separating the amount of DHW provided by the GSHP from DWH delivered by top-up.

The incoming and outgoing temperatures were adjusted to match the variation during the year. The main reason was to get closer to the measured DHW top-up and get improve the prediction of the GSHP energy. The monthly results in figure 4.10 shows that the top-up is higher during the summer than in the winter. The assumption is that this is a result of the heat pump control. Since less or no heat is needed for the heating of the building during this period, there is probably less utilization of the heat gas heat exchanger in the GSHP, and therefore, more top-up is used. The result shows that the model predicts the monthly and yearly DHW top-up usage very well. To show the results of the assumed top-up consumed throughout the year, all months have been included in this figure.

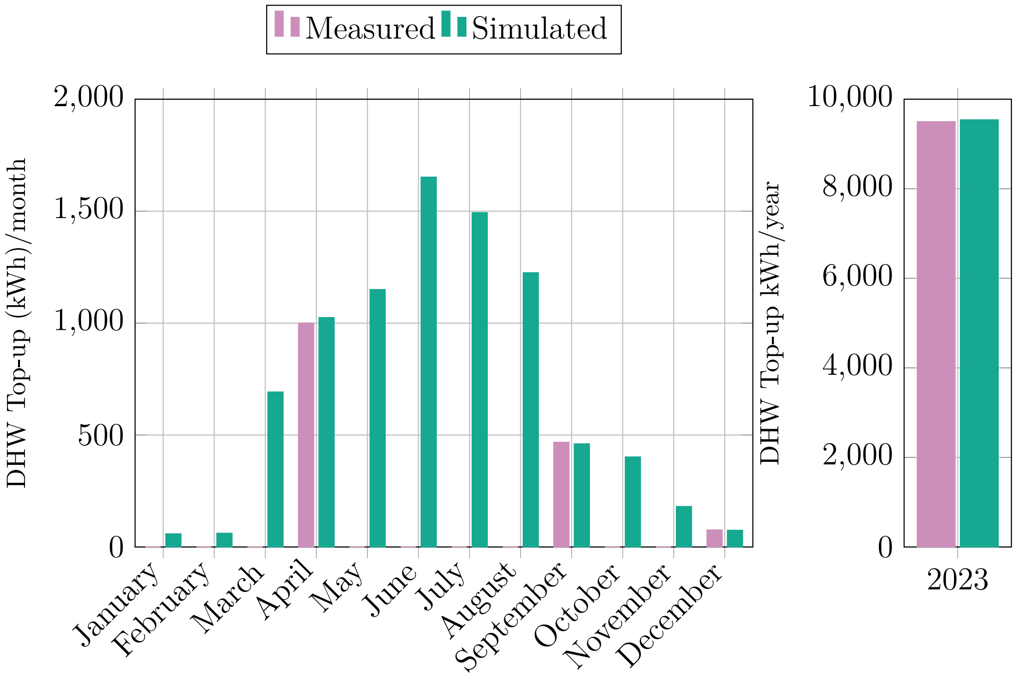

Figure 4.10: DHW top-up from measured data and simulated results.

4.2.5 Model Limitations

Although the plant model has been validated, the finished model is somewhat limited. It is only validated for the heat pump size used in the actual building and the model. If the heat pump model is changed to, for example, a smaller heat pump with less capacity, the results can't be guaranteed without validating the model again. Another limitation is that the hot water usage in the model is based on the yearly mean values. In reality, water usage will vary, resulting in a variable load on the heating system. To oversee this simplification, the decision was taken that the smallest interval for validation of the model would be daily values.

4.3 Economy of shifting energy sources

This chapter presents the results of the economic evaluation. During the evaluation, the reference building, originally located in Ulricehamn, was relocated to Gothenburg using the price market and climate valid there. As described in the method, the electricity prices vary by hour based on the electrical spot prices(SE3) between 2020 and 2023, while the district heating prices used throughout the examined scenarios are from 2024.

4.3.1 Hourly control

Figure 4.11 shows the result of simulations and cost calculation with control based on the lowest energy price during 3 hours. The evaluation is based on comparing the monthly district heating price and hourly electrical spot price with fees divided by COP as described in the method 3.6.1. If one is lower during three hours, that energy carrier will be prioritized.

It should be remembered that the energy usage is the same for all simulations and that the prices and control of the system vary. The total cost is more or less balanced even if the system is hybrid and not controlled by any power limit, at least for 2021 and 2023, which had similar electricity price levels. The pattern shows that when the hourly cost of electric energy is lower, the increased utilization of DH causes such a rise in cost for DH so that the created gap is filled. It seems as if the total cost is almost balanced, independent of the shifting energy source.

Figure 4.12 adds detail by showing the share of bought energy from DH and Electricity. The total amount of bought energy was the lowest for 2020 since the GSHP was prioritized more often due to the lower electricity prices compared to 2021-2023.

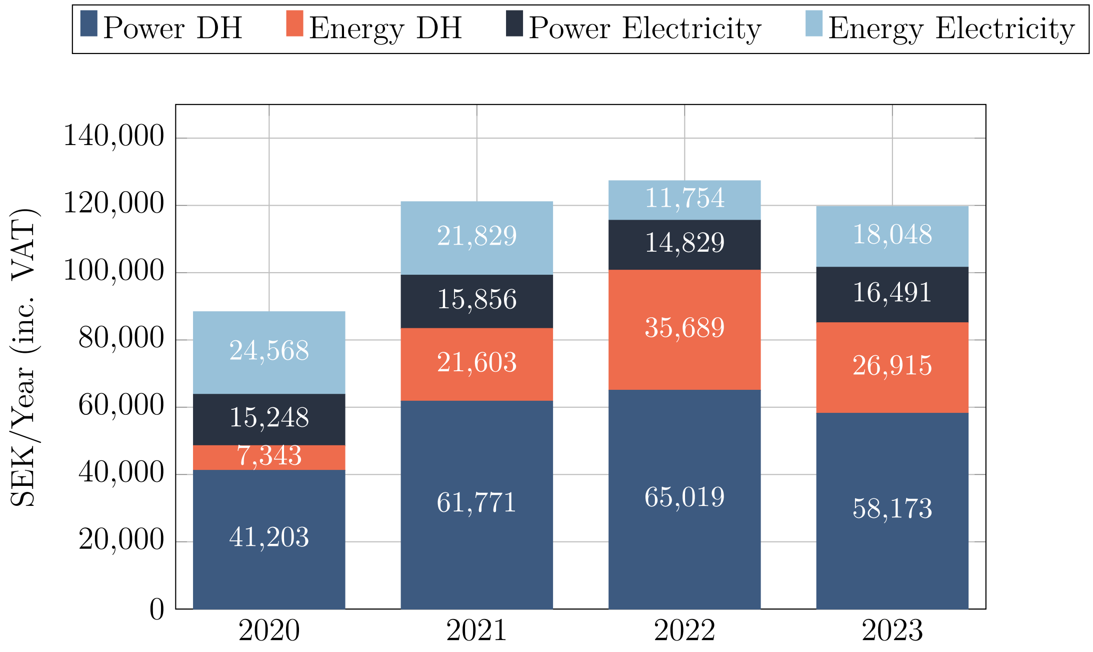

Figure 4.11: Total yearly cost of shifting between DH and HP based on the hourly spot-prices on electricity from 2020-2023 and the DH prices from 2024.

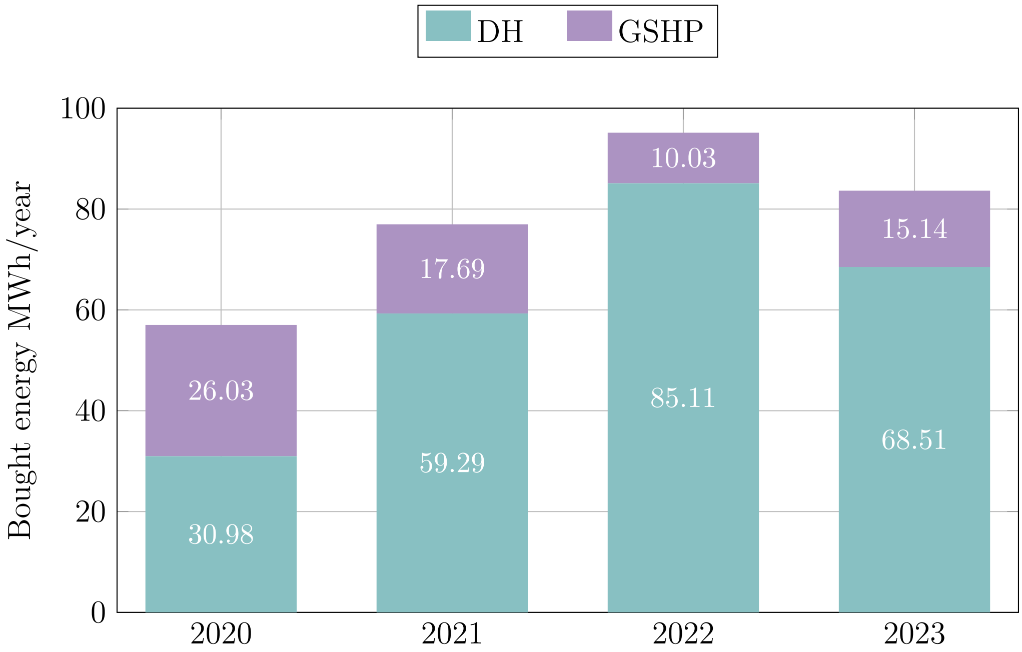

Figure 4.12: The shares of bought energy from DH and Electricity when shifting between DH and GSHP based on the hourly spot prices on electricity from 2020-2023 and the DH prices from 2024.

4.3.2 Hourly control with DH power limit

In figure 4.13 and 4.14, the result of running control based on the electrical spot prices from 2022 and 2023, respectively combined with a power limit on DH are presented. The GSHP has the same capacity throughout the scenarios but will be utilized less when DH is prioritized. The power limit is put on the DH side to indicate how the power-based connection fees impact the total price.

As seen in the figure 4.13, the electrical prices from 2022 create a very even cost situation for all scenarios. Electrical prices were relatively high that year, and this is represented in all the solutions. The different scenarios balance at a total cost that is very close to each other.

Using the electrical prices from 2023 as in figure 4.14 shows that limiting the power impacts the total cost to a higher degree. Another phenomenon that could be noted from both figures is that the cost of a power subscription doesn't dramatically change when power is limited. In the example with price control and 12kW limit, in figure 4.14, it can be noted that the portion for power subscription of DH is 86% of the total cost, while at 31 kW it is 70%.

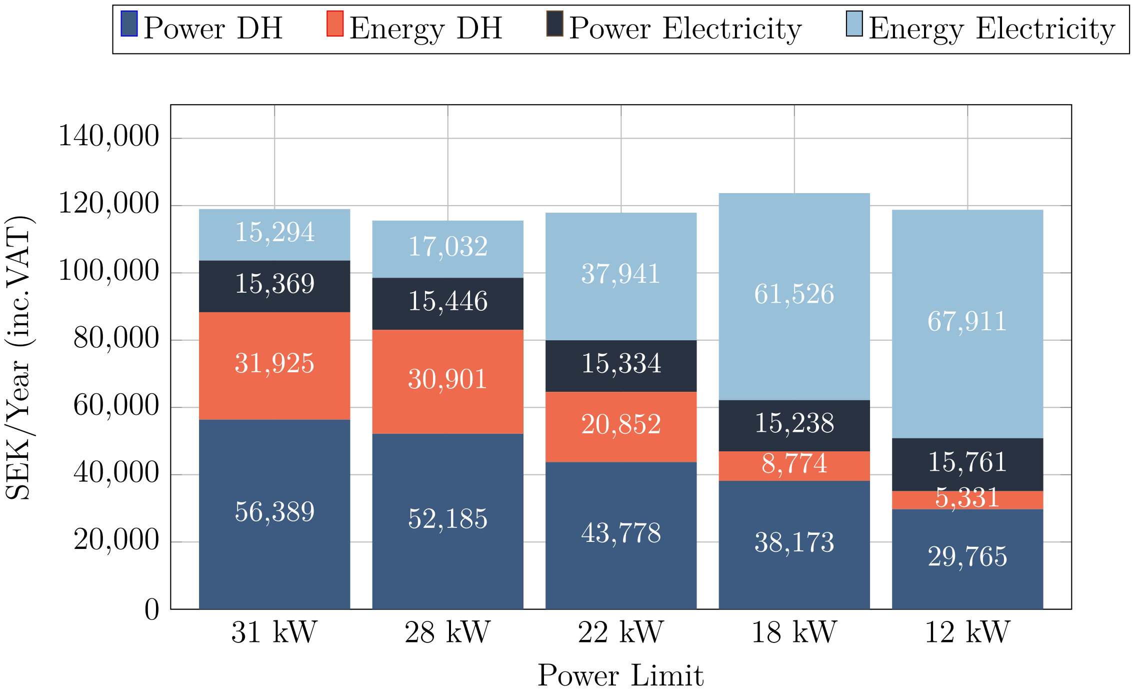

Figure 4.13: Total yearly cost of shifting between DH and HP based on the hourly spot prices on electricity from 2022 and the DH prices from 2024 in combination with a limiting the power on DH.

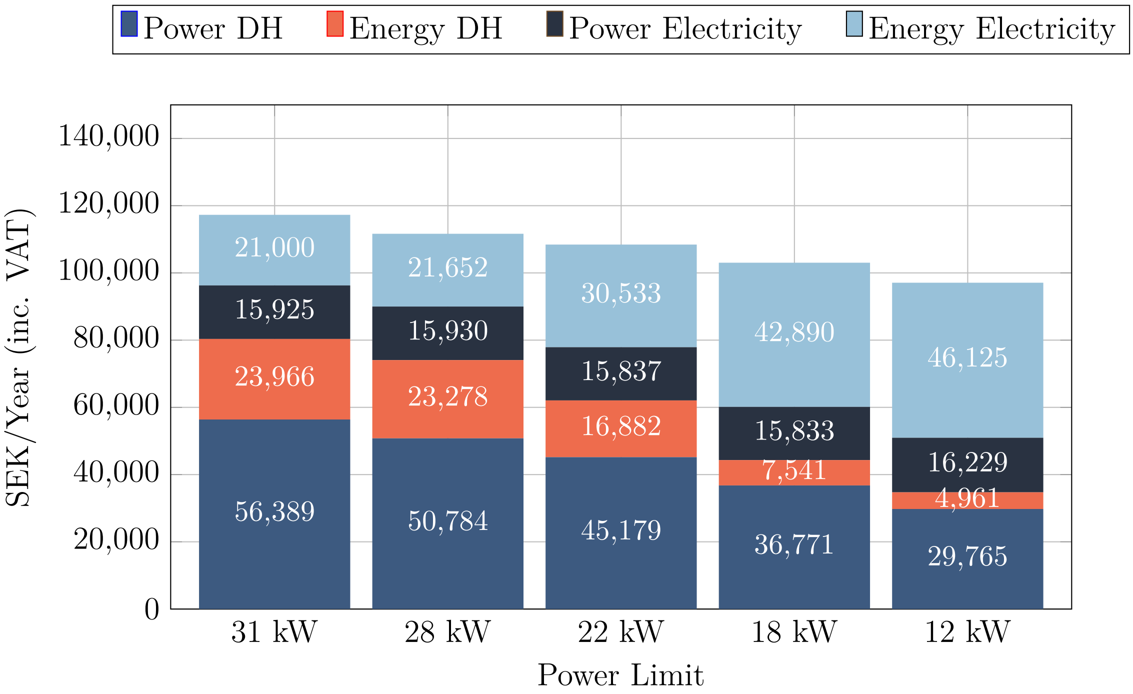

Figure 4.14: Total yearly cost of shifting between DH and HP based on the hourly spot-prices on electricity from 2023 and the DH prices from 2024 in combination with a limiting the power on DH.

4.3.3 Comparison with non-hybrid system

This chapter will compare the results from chapter 4.3.2 to the alternatives of using DH, GSHP with electrical top-up and GSHP with district heating as a top-up. The comparison is done using electrical spot prices from 2022 and 2023. The results are presented in figure 4.15 and 4.16. The pattern recognized in 4.3.1 repeats; it can be seen that the electrical price level influences the yearly outcome to a high degree, although using only DH is the most expensive. With price levels from 2022, the race is still even; the lowest yearly cost is for using GSHP and district heating as a top-up. This alternative limits the power of DH to 5 kW, which is why the power cost for DH is lower than the other alternatives. The fact that 2022 had the highest electrical prices among 2020-2023 is also reflected in the results. Consequently, GSHP and electric top-up as the only heating provider has a much higher share of energy cost from electricity than the one seen for 2023 in figure 4.16.

Turning the focus to the results in figure 4.16, the solution with GSHP and electric top-up is the least expensive of the compared alternatives, based on the electrical prices from 2023. This is followed by the same scenario as above GSHP and a top-up from DH.

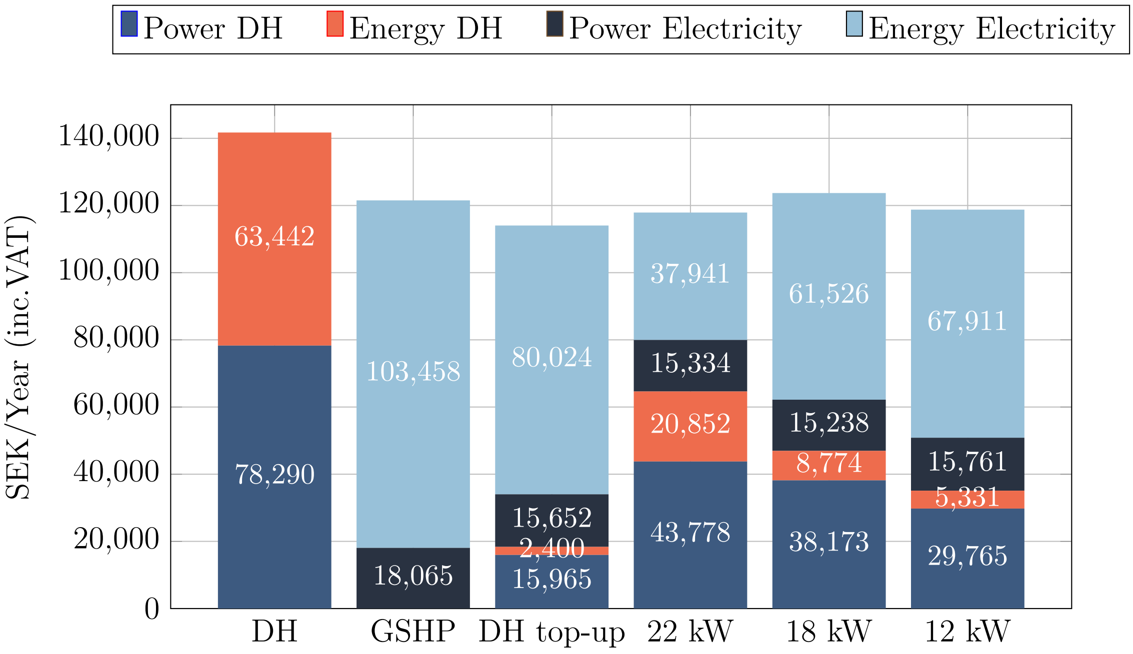

Figure 4.15: Total yearly cost for DH and HP based separately on the hourly spot prices on electricity from 2022 and the DH prices from 2024.

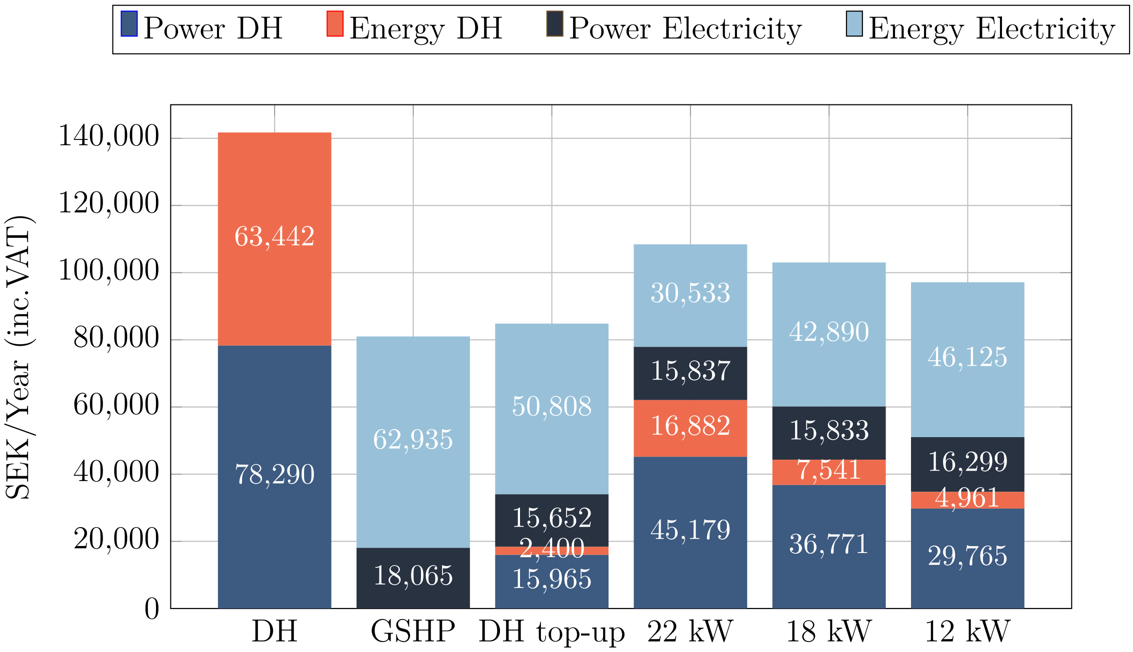

Figure 4.16: Total yearly cost for DH and HP based separately on the hourly spot prices on electricity from 2023 and the DH prices from 2024.

5

Discussion

Due to the nature of the project, the results of this master thesis are branched into two main parts. The first part involves developing and validating the simulation model with a GSHP. The second part holds room for the economic evaluation of shifting energy sources between GSHP and DH based on hourly energy prices and power limits on DH. To enhance the understanding of what is discussed, this chapter will therefore divided into two parts accordingly.

5.1 Validation and simulation

The project's first phase led to the validation of the initial simulation model provided beforehand. Using a step-by-step method, parameters such as setpoints for heating and AHU heating, thermal bridges, occupancy, and tenants' usage of equipment were calibrated to monthly and yearly heating energy usage. The overall results from the validation were very good; the monthly amounts for April and September deviated somewhat, but December had a very good coherence, as did the yearly ones. Since no more detailed calibration data was available for the other months, the decision was taken to move on to developing the plant model with GSHP and DH.

The development of the plant model was of great importance for the total project since the economic evaluation relied on a working simulation model. Several weeks were spent first getting the model to work and later getting all calibration parameters on track for the validation. The development started from an already existing model, which was developed and changed to fit the heating system in the reference building to a higher degree than in the provided plant model. The calibration and validation processes were highly iterative and involved simulations, checking of results, and adjustments of parameters. The validation results show that the plant model works similarly to the actual GSHP in the reference building, which was one of the main aims.

Some differentiations can be recognized for the detailed daily and monthly comparisons made in the validation process. To some extent, these differentiations may depend on the fact that the initial model heating energy, as noted, had some differences. The pattern between heating energy usage and GSHP energy can be reviewed from figure 4.8 and 4.5 in the result section. They show that both quantities have similar patterns, meaning the differences could be caused by the same calibration parameters. Concluding that if the heating energy was calibrated in more detail, the GSHP would likely perform better.

Another aspect that could create some differences, especially in the results from the GSHP, is that the borehole model in IDA ICE hasn't been calibrated or validated to a higher degree. This was, to some extent, outside the scope because solar hybrids interrupt the measured temperatures of the borehole brine. Further studies and improvements to the model might also include this impact by including the solar hybrid.

5.1.1 Limitations

The calibration of the initial IDA ICE model and the development and calibration of the plant model were, to some extent, limited due to missing calibration data. Three months, April, September, and December of 2023 were available. Therefore, a complete analysis of how the building operates is hard to achieve. The available data from 2024 could have been utilized to increase the reliability. However, since no verified weather data is available for 2024, the decision was made to exclude this opportunity. It was possible to retrieve measured outdoor temperatures from the sensors controlling the heating system or inlet temperature of AHU, but since a discrepancy was found between the measured data from 2023 and the weather data provided by SVEBY (2024) for the same period this opportunity was ruled out. It could have been possible to develop a method more reliant on the measured data than the one collected from SVEBY (2024) to oversee this issue. If validation had been the only theme of the thesis, this approach would probably have been tested further.

The developed plant model has been tested with other HP configurations, such as changing the HP model, capacity, and COP. Still, no models other than the ones originally used in the plant have been validated. The time frame of the thesis project does not allow for any more validations towards other buildings, which may be needed to analyze how the changes affect HP's energy usage.

Many factors can influence the energy performance of a building. Errors created during the building implementation and unexpected user patterns are two factors. Catching these unknowns in simulation models is a very complicated task. Therefore, all simulation results throughout this thesis work need to be reviewed with a relevant amount of insecurities in mind. For example, the calibrations done to the initial model can be sprung from reasons other than the adjusted parameters account for.

The model will never be better than the input data available. Still, even if a vast amount of data is available, the conclusion can be drawn that one needs to be humble about the simulation results. They can show you more or less the correct mirror image of the building and its system, but it may also be possible that unknown factors have a larger impact than initially thought.

Reddy et al. (2007) emphasizes that multiple solutions and parameter settings can lead to the same simulation result. This means that turning nobs for different parameters in different ways may lead to the same outcome. Therefore, numerous simulations testing different sets of solutions are encouraged. That approach is, however, not possible to achieve without a programmable connection to the simulation software and an optimization algorithm that takes results from the simulation, compares them with the measured data, and adjusts the parameters for the next simulation in a more randomized way. The point is not to discredit the work done in this thesis project but rather to open the eyes to all possible unknowns and solutions. The method of this project involves keeping to what is known through measurements and adjusting parameters accordingly until the fit between measured and simulated data is good enough. To conclude, there is a risk that this method introduces some insecurities since other multiple sets of simulation parameters could have achieved the same results. However, it is important to remember that most day-to-day simulations are not usually validated. Therefore, the validity goals should be set accordingly at a reasonable level.

5.1.2 Future works

The calibration process used in the project has been based on small adjustments and changes to the models, step by step. This was a straightforward method and detailed enough for this project's scope. Especially for the development of plant models, the use of other methods as parametric simulations is limited due to the risk of instability of the plant models. However, for further studies involving building models and plant validations, it would be relevant and interesting to involve other calibration techniques, such as parametric optimizations, which build on more systematic approaches.

5.2 Economy

During the economic evaluation, the hybrid heating system with GSHP and DH was tested using a few developed control strategies based on hourly energy prices and power limits on DH. The results showed that finding a hybrid solution with lower yearly energy costs could be more challenging than using a GSHP alone in Gothenburg.

Using the historical spot prices for both control and calculation of the yearly energy cost showcases how the yearly cost for hybrid systems vary and depend on the price levels. Introducing power limits on DH and using electrical price levels of 2022(figure 4.13) showed that the price configurations and control strategy created a system with more or less balance, independent of the power limit on DH. The question is, is this a coincidence or a choice made by the DH company? The positive thing is, however, that if price levels from 2022 come again and remain, the configuration of power limits on DH seems unnecessary; the total cost adjusts itself anyway if price control is used.

By comparing the yearly energy cost for the hybrid system when using yearly spot prices from 2020-2023 and DH prices from 2024(figure 4.11) it could be found that the magnitude of electrical spot prices significantly impacted the total yearly cost. The lower spot prices during 2020 resulted in having the lowest yearly cost and more balanced utilization of both heat carriers. Turning to the more extreme year of 2022, where electrical spot prices saw their highest peaks, the yearly cost was the highest of the four years, 44% higher than in 2020. It was also shown that the relatively high spot price level led to a higher utilization rate of DH and, therefore, higher costs for both power subscription and energy.

The comparison between only DH and GSHP systems with prices from 2022(figure 4.15) showed that the hybrid system had a slightly lower cost than the system using only GSHP and electric top-up. The patterns from 2023 are, however, telling another story. Since electrical spot prices have stabilized even further during 2024, focusing on the more normal years might be more important than the extreme. For 2023(figure 4.16), the power limit on DH had more impact, but using only GSHP was still coupled with the lowest yearly energy cost.

The overall results show that there might be a need for other arguments than lowering the yearly energy cost to invest in a hybrid energy system like the one studied. Various design choices or demands can lead to the need for a combination of GSHP and DH. One reason can be that the peak heat load is too large for GSHPs, and they need to rely on DH for top-up at colder periods. Another could be that the borehole design requires charging with heating energy to balance the yearly energy outtake, which could be provided by DH during summer. The search for a heating solution that could lower the CO_2 emissions coupled to the heating energy usage is another potentially important factor for the future.

During this master's thesis, a few discussions have been around systems that already utilize hybrid heating solutions, such as the one studied. A few solutions that include custom pricing models other than the ones available from the normal price models have been brought up by consultants and Jan-Olof Dalenbäck at Chalmers. At least two examples from the regional area of Gothenburg have been discussed. One with a hybrid system with DH and GSHP, which switches energy sources based on a day-a-head price on DH. Thanks to the forecasted price, they can compare it with the electric spot price and decide whether they want to buy DH or electricity the next day. The other example utilizes GSHP for heating and DHW during winter and DH for DWH and charging boreholes during summer. Due to the custom agreements with the DH providers, economic profitability is probably better than this study showcases.

5.2.1 Limitations

The investment cost has not been studied in this thesis project, even though it is an important factor significantly impacting the system choice. While DH might have higher yearly energy costs, the investment costs are expected to be much lower than the ones for a GSHP system with vertical boreholes. Under the assumed circumstances, it is, however, no(or very small) economic savings made to the yearly energy costs. It is, therefore, unnecessary to perform a life-cycle-cost calculation since whichever investment costs are added, no economic gains would be achieved. Bringing in more uncertainties, for example, factors such as environmental impact and greater variations in the used energy prices might increase the relevancy of life-cycle-cost calculations in future works.

One limiting factor during the economic evaluation is that the size of the heat pump has been kept static throughout the different scenarios. This was mainly done for two reasons. First, due to the rising level of insecurities in the simulation model results when changing the capacity of the heat pump model. Second, to limit the number of varying parameters. The results should, therefore, be reviewed accordingly. Limiting the size of the heat pump would influence the maximum capacity and force DH to take some of the power peaks during the colder period of the year, which might influence the yearly energy costs. However, since the investment costs are neglected at this stage, it would have less impact on the result of this study. In conclusion, if the correct sizing of a hybrid system is sought, more studies or other methods are needed.

The use of hybrid systems such as the one described may result in less predictability in power outtake for the DH providers. Since they also need to plan the production, it may have unwanted effects on the production of district heating. This might be one of the reasons why it still is costly to combine two energy carriers.

5.2.2 Future works

The economic evaluation uses historical electric spot prices and present DH prices. Since future prices are challenging to forecast, it might be interesting to investigate how uncertainties, such as increased price fluctuations or fictive price models, impact the economic outcome of a hybrid heating system. Both on yearly energy costs and from a life-cycle-cost perspective. Therefore, there is room for future work to focus on these challenging topics.

As pointed out by Lygnerud et al. (2021), hybrid heating systems may play an important role as demands for lower CO_2-emissions increases. To cope with net-zero goals in coming years, heating systems with the ability to prioritize energy carriers based on emissions rather than cost could have a bright future. Therefore, it is highly relevant to enhance the possibility of studying these kinds of systems and the different environmental gains they can contribute. Further studies could, for example, simulate and analyze how CO_2 emission-based controls of hybrid heating systems impacts the total CO_2 emissions associated with the heating energy usage. The further development of possible business models that create incentives and motivation to diversify the energy market to include more hybrid heating solutions is also encouraged.

6

Conclusion

A hybrid heating system combining GSHP and DH has been simulated and analyzed using the IDA ICE software. The conclusions drawn from the results can be divided into two parts: the first part addresses the simulation outcomes, while the second part focuses on the economic evaluation conducted with the model. Starting with the simulation model, it can be concluded that the developed model performs successfully when validated towards the calibration data from the actual reference building. Through this development and validation, it has been shown that reliable, usable simulation models that utilize GSHP and boreholes can be used further in the analysis of other buildings with the help of the plant model and IDA ICE. There are, however, possibilities for further development and validations, mostly concerning the use of different sizes of heat pumps and multiple heat pumps.

The second set of conclusions concerns the economic evaluation of hourly variations in energy prices and power limits on DH for control. Given the assumptions about the system and the price situation in Gothenburg, it is challenging to find a hybrid solution combining DH and GSHP with lower yearly energy costs than using GSHP alone. The conclusion is that the price models used for DH in Gothenburg do not incentivize utilizing two heat sources, primarily due to the cost of power subscription. Although customers with hybrid solutions may use DH to a small degree or as a backup, they must be willing to pay for it under the current pricing system. To increase the promotion of hybrid solutions in the future, the DH provider's pricing and business models may need to be adjusted to create a win-win situation for both parties.

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A

Appendix A

Energy performance of the reference building:

Table A.1: Delivered heating energy by the GSHP to the radiators, AHU, DHW and hot water circulation. Measurements carried out after heat pump and top-up.

Meter	Energy(kWh/year)	Measured (kWh/$m^2 A_{temp}$/year)
Heating energy, radiators	70 731	26.2
AHU heating energy	4 020	1.5
Hot water	26 660	9.9
Hot water Circulation	22 367	8.3

Table A.2: Bought electric energy 2023

Meter	Measured (kWh/year)	Measured (kWh/$m^2 A_{temp}$/year)
Energy usage GSHP	34 343	12.7
Tenants electricity	45 790	17
Facility electricity	17 931	6.6
Top-up DHW	9 497	3.5
Top-up total heating	0	0

Table A.3: Table with other values

Meter	Value
Calculated yearly COP (GSHP)	3.32

B

Appendix B

Input data for the initial reference IDA ICE model

Heating system	Initial model	Calibrated initial model
Setpoint Apartments (°C)	21	21.4
Setpoint staircase and storage (°C)	18	18

Air handling unit (AHU)	Initial model	Calibrated initial model
Supply airflow rate ($l/s/m^2$)	0.419	0.388
Return airflow rate ($l/s/m^2$)	0.419	0.388
Supply air heating setpoint (°C)	19.5	18.3
Efficiency heat recovery (-)	0.845	0.845

Occupancy	Initial model	Calibrated initial model	Shedule
1 room apartment	1.42	70% utilization	14h home
2 room apartment	1.63	70% utilization	14h home
3 room apartment	2.18	70% utilization	14h home

	Initial model	Calibrated initial model
Equipment (kWh/m^2)	21	16.5
Utilization factor	1.0	0.5
Schedule	Monthly variation	Custom schedule

	Initial model	Calibrated initial model
Building component	U-value (W/m^2K)	
Slab	0.2037	(no change)
External sandwich wall	0.13	(no change)
Roof	0.1	(no change)
Windows	0.9	(no change)
Securety door	1.4	(no change)

Thermal bridges	24%	32.6%
Average U-value	0.2871	0.3234