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The Potential of Flexible Heating for Multi-Family Houses in Sweden

Master's thesis in Sustainable Energy Systems

Per Kleinschmidt & Ida Söderlind

DEPARTMENT OF SPACE, EARTH AND ENVIRONMENT

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Ida Söderlind



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Ida Söderlind

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Supervisor: Joel Bertilsson, Chalmers Space, Earth and Environment Department
Supervisor: Mari-Louise Persson, Riksbyggen
Examiner: Lisa Göransson, Chalmers Space, Earth and Environment Department

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Department of Space, Earth and Environment
Division of Energy Technology
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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Department of Space, Earth and Environment
Chalmers University of Technology

Abstract

The residential and services sector accounted for a significant portion (39%) of the final energy consumption in 2020 in Sweden, with district heating (DH) and electricity as the main heating sources. The choice of heating source varies throughout different types of buildings, and the most common for multi-family houses in Sweden is DH.

When moving towards an energy system with a larger share of renewables, which includes irregularity of production, a flexible demand of electricity will be important to maintain the balance between production and consumption in the power system.

This thesis aims to investigate the potential of flexible heating for multi-family houses in Sweden. The investigation has been made by a model structured in GAMS by using mixed-integer linear programming, to optimize the heating pattern and the installed capacity, with the aim of minimizing the total annual cost (including investment, operational, and maintenance costs). The robustness of the model and results have been assessed by adjusting the input data, such as the district heating power and energy price, the electricity grid price, and the heat pump (HP) lifetime.

The scope of the thesis was to investigate the potential of flexible heating in different regions of Sweden. Luleå, Sundsvall, Gothenburg, and Malmö have been investigated due to their geographical location as they are located in different electricity zones.

The study focused on two buildings built in different eras. This comparison aimed to highlight the differences in results based on the different building characteristics. The thesis is in collaboration together with Riksbyggen (Swedish housing company), which provided the data for the buildings involved in the study.

The results indicate that flexible heating in multi-family houses in Sweden is economical favorable. A wider accepted indoor temperature range (19°C - 25°C) decreases the total heating demand, the necessary installed capacity and the total cost up to 14% compared with a non-flexible indoor temperature range (21°C - 22°C). The most economical favorable heating technology when implementing flexible heating is the heat pump, to make use of the thermal inertia and heating pattern in the most cost-effective way.

Keywords: flexible heating, building, heat pump, district heating, cost, optimization.

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Per Kleinschmidt & Ida Söderlind, Gothenburg, May 2024

List of Acronyms

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

BRF	Housing association (Bostadsrättsförening)
CAPEX	Capital expenditure
CHP	Combined heat and power
COP	Coefficient of performance
DH	District heating
EL	Electricity
GAMS	General Algebraic Modeling System
HP	Heat pump
MILP	Mixed-Integer Linear Programming
OPEX	Operational expenditure
SE(1,2,3,4)	The four different electricity spot price regions in Sweden

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1

Introduction

1.1 Background

In 2020, the residential and services sector accounted for 39% of Sweden's final energy use. District heating (DH) and electricity are the main sources of heating, although differences between one- and two-dwelling houses compared to multi-family houses can be observed. DH covers 18% while electricity claims 51% for one- and two-dwelling houses. Multi-family houses heating shows a different picture as 8% and 90% are covered by electricity and DH respectively [2].

As a household owner, this offers multiple solutions to cover the heat demand. When only looking at the cost development of electricity and DH in Sweden an increase of 17.7% and 7.7% respectively from 2022 to 2023 for household owners can be observed [3]. With increase rates of 1,5% in previous years of DH costs for the customers and a volatile electricity spot price, it poses the question of which heating technology offers the more cost-efficient option for the customers.

From a larger system perspective, further challenges are presented with the energy transition, leading to changes in the electricity and DH systems. The power system needs to be in balance every second of the year to function properly. The balance is between the production and the consumption. Without the balance, the frequency at 50 Hz can't be maintained, and power outages can occur [4].

Sweden has set the target to have a 100% electricity production with fossil-free energy sources by 2040, which will increase the share of production by wind and solar that offer electricity to the lowest cost [5]. As well known, electricity produced by wind and solar is intermittent, and to maintain the balance between the production and demand in the power system, it's more cost-effective (for the system) to have a flexible demand than to curtail the electricity. Flexible demands are such as charging the car, using the dishwasher and heating the building when the power system needs it (i.e. when the demands are too low compared to the production side). The power system will indicate an overproduction of electricity by lowering the electricity spot price.

Two-thirds of the heat supplied by DH relies on biomass and waste. In the future, this could be a problem due to Sweden's aim of zero net greenhouse gas emissions by 2050. This will probably lead to high competition of biomass with other industries,

which will increase the price of biomass [6]. These trends and competitions will influence the cost of heating for all households.

Here, flexible heating refers to heating a building in the most cost-effective way by accepting a larger indoor temperature range and to increase the heating during periods when the energy costs are lower and decreasing heating during times of higher energy costs. As electricity and DH prices differ hourly or monthly, potential savings can be made, and also helping to balance the power system. By allowing a larger range of the acceptable indoor temperature, the heat input can be varied according to fluctuations in energy price.

1.2 Aim

This thesis aims to assess the profitability of flexible heating of multi-family houses for varying locations in Sweden. The study will examine the impact of temperature range variations, taking into account different locations with varying outdoor temperatures, district heating prices and electricity prices while considering investment, operation and maintenance costs. The study will also investigate the most cost-optimal installed capacity of the heating sources.

1.3 Scope

The chosen cities of the four different electricity zones in Sweden which will be investigated are:

- Luleå
- Sundsvall
- Gothenburg
- Malmö

The local considerations from these cities will be the local outdoor temperature, the local solar irradiation and the local spot electricity price. The study will use a yearly time horizon and the reference year will be 2019, and a later investigation of 2050.

The study will investigate the potential of flexible heating for two different types of multi-family houses, one built in 1988 (BRF 1988) and one built in 2018 (BRF 2018) by setting up thermodynamic models to see if the results differ due to different thermal characteristics.

This thesis work is in collaboration with Riksbyggen, which will provide the data for heat consumption, indoor and outdoor temperature of multi-family dwellings that have been used to create the mathematical model of the building. Riksbyggen is a Swedish housing company founded in 1940 owned by the building unions, housing associations (local housing associations) and by other national co-operative associations [7]. Riksbyggen is a service company involved in property and building management as well as residential services.

2

Theory

In this chapter, the background information will be provided to clarify possible uncertainties. Firstly, a building's energy balance equation will be illustrated, and regulations presented. Furthermore, information on heat delivery technologies will be provided and lastly, the DH and electricity market described.

2.1 Energy balance in buildings

To study the behavior of the indoor temperature of a building a mathematical, thermodynamic model can be applied. Ali et al. [8] have constructed a two-capacity building model to determine the hourly indoor temperature of a building. It is dependent on the temperatures of building components, thermal conductivities and thermal capacities, all described in Table 2.1.

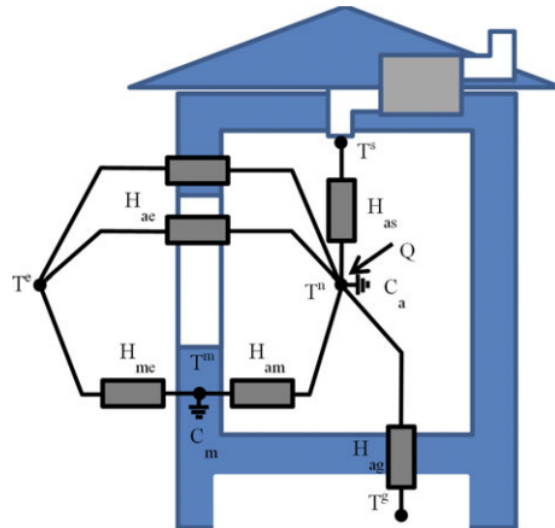


Figure 2.1: Two-capacity building model to determine the hourly indoor temperature

Table 2.1: Nomenclature building properties

T_e	External temperature
T_n	Indoor temperature
T_s	Supply air temperature
T_g	Ground temperature
T_m	Thermal mass temperature
H_{ae}	Thermal conductance summing up infiltration heat capacity flow and window heat capacity
H_{me}	Thermal conductance outdoor air
H_{am}	Thermal conductance indoor air
H_{as}	Ventilation air heat capacity flow
H_{ag}	Thermal conductance ground
C_a	Thermal capacity indoor air
C_m	Thermal capacity building structure mass
Q	Thermal power input

The following equation describes the energy balance for the indoor air node:

$$C_a \cdot \frac{dT_n}{dt} = H_{ae}(T_e - T_n) + H_{am}(T_m - T_n) + H_{ag}(T_g - T_n) + H_{as}(T_s - T_n) + Q \quad (2.1)$$

The temperature differential dT_n and the time differential dt are implemented to later create an hourly model. The mass node point C_m can be calculated as following:

$$C_m \cdot \frac{dT_m}{dt} = H_{am}(T_n - T_m) + H_{me}(T_e - T_m) \quad (2.2)$$

To ensure numerical stability as well as for simplicity an implicit discretization is used leading to:

$$T_{n,t} = \frac{T_{n,t-1} + \frac{\Delta t}{C_a}[H_{am}T_{m,t-1} + H_{ae}T_{e,t} + H_{ag}T_{g,t} + H_{as}T_{s,t} + Q_t]}{1 + \frac{\Delta t}{C_a}(H_{am} + H_{ae} + H_{ag} + H_{as})} \quad (2.3)$$

$$T_{m,t} = \frac{T_{m,t-1} + \frac{\Delta t}{C_m}[H_{am}T_{n,t-1} + H_{me}T_{e,t}]}{1 + \frac{\Delta t}{C_m}(H_{am} + H_{me})} \quad (2.4)$$

Correspondingly, an hourly model of the indoor and thermal mass temperature is formed.

2.2 Building regulations and standards in Sweden

In this section, building regulations in Sweden will be presented and further used in the modelling section.

2.2.1 Temperature range

The operative temperature considers the indoor air temperature and the radiation between the people and the surrounding surfaces (such as windows and walls) and is

a measurement of how the residents experience the indoor temperature. The range can be seen in Table 2.2 and is determined by the Swedish public health authority [9], which differs between a permanent and a short time period during which the operative temperature occurs. The Swedish Work Environment Authority defines a short time period as one week during a heat wave [10],[11].

Table 2.2: Guideline ranges of operative temperatures in Sweden

	Cold period	Summer
Permanently	20 °C - 24 °C	20 °C - 26 °C
Short time period	20 °C - 26 °C	20 °C - 28 °C

2.2.2 Thermal inertia

The thermal inertia of a building is the ability to flatten out and time-shift heat flow fluctuations due to its great amount of thermal mass [12]. The Swedish Standards Institute has determined five classes ranging from very light to very heavy to describe the characteristics of a building's thermal inertia [13] seen in Table 2.3. The listed default values describe measurements for the internal heat inertia for different construction types. It is calculated including the internal surface resistance which corresponds to the area being heated.

Table 2.3: Thermal inertia of different types of buildings

Class	C_m [J/(K*m²)]
Very light	80 000
Light	110 000
Medium	165 000
Heavy	260 000
Very heavy	370 000

2.2.3 U-values

Each construction part of the building transfers heat during steady-state conditions, and this is represented by the construction part's U-value [14]. The Swedish housing agency has determined U-values for the different construction parts [15] (guidelines for 2020), such as the walls and the roof, which can be seen in Table 2.4.

Table 2.4: Guideline of U-values in different construction parts in Sweden new build buildings

Construction part	U-value [W/m²K]
Roof	0,13
Wall	0,18
Floor	0,15
Window	1,2

Statistics that have been used as references for buildings built in the 1980s, and can be seen in Table 2.5 [16].

Table 2.5: Statistics of U-values in different construction parts in Sweden in 1980

Construction part	U-value [W/m^2K]
Roof	0,15
Wall	0,22
Floor	0,26
Window	1,75

2.2.4 Hot water demand

The hot water demand depends on the resident's habits of water usage and tap design. The demand for multi-family houses in Sweden is assumed in this thesis to be 25 kWh/ A_{temp} /year, and has been assumed to be constant every hour throughout the year, where A_{temp} is the heated area [17].

2.3 Heat delivery technologies

The two main technologies of household heating in Sweden are DH or via a heat pump (HP) using electricity and will be presented in this section.

2.3.1 District Heating

Heat supplied by DH is generated and distributed via a network of pipes from a thermal plant [18]. Not only households, but industrial and commercial establishments can receive the produced heat. DH is based on the idea to use local heat or fuel resources that would have been wasted to cover heat demands for customers [19]. Resources for excess heat were traditionally combined heat and power (CHP) plants, industrial processes and waste-to-energy plants. Renewable heat from geothermal wells, biomass fuels and solar collectors have been added to the DH systems. The building, if connected to a DH network, needs to install two heat exchangers to enable hot water heating and space heating.

2.3.2 Ground source heat pump

The technology chosen to deliver heat using electricity in this study is a ground source heat pump. Other types of HPs are air-to-air or water source HPs. Due to the highest and most constant coefficient of performance (COP) will only a ground source HP be considered for this thesis. Ground source HPs use the constant and warm temperature of the ground, compared to the outdoor temperature, and transfer the heat in the ground into the building. The electricity is used to drive a compressor, which increases the pressure and temperature by compressing a fluid in a pipe network. The gained heat is in the next step passed via a heat exchanger to the hot water cylinders, radiators and underfloor heating [20].

2.4 District heating market in Sweden

DH is the most common heating technology in Sweden and is produced centrally by a heat plant or in a central boiler station (as mentioned in subsection 2.3.1) instead of individual heating technologies such as HPs for individual buildings [21].

The heating price and connecting costs depend on the municipality and heat supplier. Prices differ due to the local conditions, density of customers served by the DH company and the fuel used. There is no possibility to switch to a different supplier. Including small DH systems in villages and small towns, there exist about 500 systems in Sweden [19]. The fuel that covers the largest share in Sweden is biomass, which accounts for 62% of the total DH supply [22].

2.4.1 District heating price

The method of determining DH prices is individually decided by each DH company. Different providers have different tariffs to set the price. The studied companies Luleå Energi, Sundsvall Energi, Göteborg Energi and E.ON share the same pattern of forming the final price for the heat. Besides the tax paid by the customer per extracted heat, the three parts defined by the DH companies are:

- Power price
- Energy price
- Flow price

The power price is defined differently for each tariff system. It is mostly calculated by the largest extraction of heat and represents the largest outtake of heat that the customer takes use of. The DH providers measure an average over a defined time period to analyze the household's largest power use. The power price contains a fixed and a variable component and is a yearly cost. The power prices collected from the analyzed cities can be found in Table 2.6 (prices from 2019).

Table 2.6: Yearly power prices consisting of a fix [SEK] and variable (var) [SEK/kW] component for Luleå, Sundsvall, Gothenburg, and Malmö

Range kW	Luleå		Sundsvall		Gothenburg		Malmö	
	Fix SEK/ year	Var SEK/ kW	Fix SEK/ year	Var SEK/ kW	Fix SEK/ year	Var SEK/ kW	Fix SEK/ year	Var SEK/ kW
0 - 25	0	520	0	924	0	879	0	149
26 - 50	750	490	0	924	0	879	0	149
51 - 100	2250	460	0	924	8550	708	0	149
101 - 250	5250	430	7000	854	11888	675	0	149

The energy price varies depending on the season and is dependent on the amount of extracted heat. It represents the cost of producing heat for the DH company. The monthly energy prices of the analyzed tariffs in the studied cities can be seen in Table 2.7.

Table 2.7: Monthly energy prices in SEK/MWh of Luleå, Sundsvall, Gothenburg, and Malmö

	Luleå	Sundsvall	Gothenburg	Malmö
January	312	443	521	520
February	312	443	521	520
March	191	443	521	520
April	191	264	359	175
May	191	264	100	175
June	150	147	100	175
July	150	147	100	175
August	150	147	100	175
September	191	264	100	175
October	191	264	359	175
November	191	443	359	175
December	312	443	521	520

The third part is the flow price. It is based on how many cubic meters of DH water that flow through the heat exchanger of the building [23]. This part of the cost has been added by the heat providers to motivate the customers to have a high efficiency on the heat exchanger, leading to lower temperatures of the return water. The flow price can either be bonus or additional cost depending on the supplying DH company.

There are 86 different tariffs in Sweden, where the distribution of the total cost differs between the energy and power price, which results in different choices of used energy and installed capacity across the country [24].

2.4.2 Future DH market in Sweden

The future of the DH market in Sweden has many possible scenarios and depends on various factors. The demand of DH will depend on the energy efficiency in future buildings as a higher efficiency will lead to a lower DH demand. The flexibility in the DH system will also have a large impact on the market. If it's possible to produce the heat during low energy price hours, and store the heat for later, this will increase the flexibility of the DH system and have an impact on the energy price. Non-technical factors will also have a large impact on the future DH system, such as political decisions, directives from EU etc. It also depends on if the society wants to maintain the centralization of heating systems or prefer the system to be decentralized by stop investing in DH systems. As previously mentioned, the biomass accounts for a large part of the total DH supply and the availability of biomass resources will have a large impact on the future DH market [24].

Regarding the price structure of the future DH market, the trends seem to show towards a more power based structure, i.e. increase the share of the power cost compared with the energy cost [25]. As mentioned in the previous section, there are many price structures of DH suppliers in Sweden, which makes it hard for the

DH consumers to calculate their DH costs. The energy agency in Sweden therefore wants to decrease the number of price tariffs of DH in Sweden to encourage the understanding of the customer's energy usage. Variable price structures also encourage a decreasing energy usage compared to fixed price structures [24].

2.5 Electricity market in Sweden

The three dominant sources of electricity production in Sweden are hydropower, nuclear and wind power, accounting for 40%, 29% and 21% respectively in 2023 [26]. The role of hydropower is hereby not only to provide the largest share of electricity, but also to balance the electricity with an intermittent wind and solar power production [27]. The Swedish electricity market is divided into four bidding areas SE1, SE2, SE3 and SE4 seen in Figure 2.2.

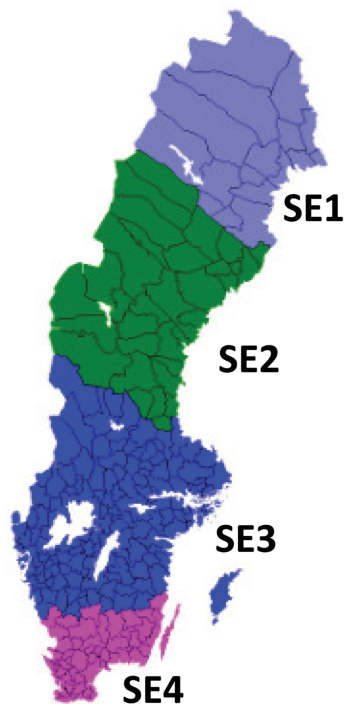


Figure 2.2: Geographical areas of the four electricity bidding zones in Sweden [28]

The division into these four areas occurred in 2011 by the Swedish electricity system operator Svenska Kraftnät. The intention was to improve the control over the electricity transmission between different regions in Sweden. Furthermore, should it encourage the regions with an electricity shortage to construct further power plants and for Svenska Kraftnät to build further transmission capacity. The available potential of hydropower and the lower consumption of electricity are located in the north (SE1, SE2) and due to the higher consumption compared to production there has generally been an electricity deficit in the south (SE3, SE4). Sweden with its four bidding areas is also part of the international power market Nord Pool, which enables cross border trading of electricity [27]. Because of the different spot prices that occur due to the four bidding areas differ the prices. That leads to

lower electricity prices in the north compared to the south due to their relatively higher production and lower consumption of electricity. Heating through electricity therefore offers different potentials in different regions of Sweden.

2.5.1 Electricity price

The electricity price for customers in Sweden depends on the:

- Trade fee
- Grid fee

additionally to the tax paid by the customer [29]. The electricity trade fee is assumed to be equal to the spot price of electricity in the different electricity zones. The spot prices negotiated at Nord Pool are the prices that electricity trading companies have to pay when they buy electricity on behalf of their customers [30]. The electricity grid fee varies on the tariff of different cities and regions and is set by the local grid operator. The investigated grid operators are Luleå Energi Elnät AB, Sundsvall Elnät AB, Göteborg Energi Nät AB, and E.ON Energidistribution AB. How the four analyzed cities' grid operators apply their prices can be seen in Table 2.8. The grid fee represents the cost of transportation, as well as the operation and maintenance costs of the electricity grid [31].

Table 2.8: Cost components electricity grid tariffs for the four examined cities[32], [33], [34], [35]

Luleå	Sundsvall	Gothenburg	Malmö
Luleå Energi Elnät AB	Sundsvall Elnät AB	Göteborg Energi Nät AB	E.ON Energidistribution AB
Grid tariff depending on fixed and variable charge meter fee	Fuse subscription with fixed charge and electricity transmission	Fixed electricity grid contract	Electricity grid subscriptions
Power supply with fixed, power and overdraft charges	Administrative fees	Variable electricity transmission fee	Subscription fees
	Energy tax		Reactive power
			Electricity transmission fee

Due to the irregularities of pricing the grid fee between the cities, the prices from Nils Holgersson report [29] of the 10 largest cities and the cheapest city in Sweden have been investigated and can be seen in Table 2.9

Table 2.9: The grid fees in the 10 largest cities in Sweden [29]

Cities	Grid fee [öre/kWh]
Stockholm	82,30
Gothenburg	62,90
Malmö	119,60
Uppsala	110,70
Linköping	70,30
Örebro	119,60
Västerås	65,00
Helsingborg	75,80
Norrköping	119,60
Jönköping	56,60
Borlänge	51,30

The taxes on electricity in Sweden are given as a price per kWh and are equal in every city, except for some cities in the north, including Luleå [36].

2.5.2 Future electricity system

Sweden has set the target to produce 100% of its electricity production with fossil-free energy sources [5]. Zhong et al. [37] concluded in their study that with a tripling of the current wind power capacity while maintaining the existing hydropower capacity, existing nuclear and thermal power plants could be replaced. However, the study by Zhong et al. did not model with an increasing demand, which would lead to an even larger demand of production capacity. Bergmann et al. [38] predict in their study different potential scenarios for the future electricity consumption. With a current electricity consumption of 130 TWh the most conservative scenario resulted in a total electricity consumption of 150 TWh while the most extreme scenario resulted in 300 TWh. This includes higher shares of wind and solar production, which are dependent on the weather.

The total electricity demand will increase due to the electrification of different operations like processes in the steel industry and the wider usage of electricity following the energy transition. LKAB, a Swedish mining company, estimates an additional 55 TWh for the production of hydrogen [39]. With more intermittent electricity production and more requirements on the electricity system, the flexibility measures will need to increase to use the capacities available.

To engage the customers to spread out their electricity will all local grid suppliers introduce a price model with a power charge latest the 1st of January 2027 [40]. The new model will be divided into a yearly subscription based on the largest out-take respectively the maximum coverage needed. Furthermore, will incentives on an hourly perspective be added to engage customers to use low electricity prices and avoid higher price periods. The expansion of electrical infrastructure is needed to increase the transmission capacity. Investments in new power lines and other parts

of the electrical infrastructure will be made [41]. Trends of the last years which are expected to continue show a rise of the network tariff grids to maintain and increase the capacity of the electricity grid [42].

3

Method

The method section describes the procedure of designing a thermodynamic model for two existing buildings, the implementation of historic data into the modelling tool GAMS and a description of the studied scenarios. The development of the model was based on data from the year 2019. This is due to the later examined scenario of used future electricity and DH prices, which were based on the weather data, electricity, and heat demand of 2019.

3.1 Description of existing multi-family houses

Models for multi-family houses were built upon two existing buildings. Two unrelated buildings were considered to represent different types of buildings and construction styles that were built at different times. A multi-family dwelling located in Västra Götalands county, in this study called BRF 2018, represents a modern building style as well as a modern heating system combining heat delivered by radiators and heat recovery by a ventilation system. Furthermore, to examine different characteristics of an older building, a multi-family dwelling located in Jönköping county, in this study called BRF 1988, was analyzed. Both buildings are using DH as their heating technology. The choice for the listed buildings was made due to the existing data for heat demand, indoor and outdoor temperature provided by Riksbyggen. For anonymity reasons were the names of the actual BRFs excluded.

3.1.1 New building BRF 2018

The first selected multi-family house to examine the potential of flexible heating is located in Västra Götaland county, constructed in 2018. The building association is maintained by Riksbyggen. It consists of 50 dwellings divided in three terraced house blocks. A_{temp} describes the floor area on which the primary energy performance of the building is calculated on. It defines the heated area per floor level, independent of the ceiling height [43]. q_{vent} describes the projected ventilation rate. Both A_{temp} and q_{vent} were obtained by the energy declaration of the building.

Table 3.1: Input data of BRF 2018

Input data	Value	Unit
No. residents	72	-
A_{temp}	5413	m^2
q_{vent}	0,35	L/sm^2

3.1.2 Old building BRF 1988

The second multi-family dwelling located in Jönköping county was built in 1988 and is maintained by Riksbyggen. 30 dwellings are separated over two buildings with an A_{temp} and q_{vent} that can be seen in Table 3.2.

Table 3.2: Input data of BRF 1988

Input data	Value	Unit
No. residents	44	-
A_{temp}	2320	m^2
q_{vent}	0,35	L/sm^2

3.2 Modelling the heat balance of a multi-family house

The aim of this part was to model the indoor temperature together with measured data such as heat supplied by the DH and the outdoor temperature and then compare it with the measured indoor temperature. The basis of the set up equations was the model by Ali et al. [8]. Simplifications and assumptions of input data needed to be done due to missing input data such as: The hourly thermal mass temperature was not looked at for the set up model due to missing information on wall temperature and material. Furthermore, was the thermal conductance of the inside air not considered because of the assumption that the indoor air temperature and wall temperature on the inside are equal. The heat balance was then described as in Equation 3.1:

$$T_{in}(t+1) = T_{in}(t) + \frac{Q_{supply}(t) - Q_{loss}(t)}{C_m} \quad (3.1)$$

where C_m is the thermal inertia of the building, which will be described later in this section. The heat supply (Q_{supply}) is described as in Equation 3.2:

$$Q_{supply}(t) = Q_{DH}(t) + Q_{solar}(t) + Q_{residents}(t) \quad (3.2)$$

As previously mentioned, the extracted heat data from DH was provided by Riksbyggen. The heat gain from the sun is calculated by data of global horizontal irradiance [W/m²] provided by Sveby [44]. To simulate the heat generated by residents, it has been assumed that the residents stay at home from 17:00 to 08:00 for non-weekend days and during the whole weekends. According to Sveby, it's assumed that the generated heat by residents is 80 W per person [45]. Every resident's present hour was described through a profile during the year and added to the model as a heat gain. The heat losses are described as in Equation 3.3:

$$Q_{loss}(t) = \sum Q_{transmission}(t) + Q_{vent}(t) \quad (3.3)$$

where the sum of $Q_{transmission}$ includes the transmission losses through the walls, roof, ground, and the windows as in Equation 3.4:

$$\sum Q_{transmission}(t) = (T_{in}(t) - T_{out}(t)) \cdot \sum_{constructionparts} (U \cdot A) \quad (3.4)$$

To achieve the correct U-values and thermal inertia for the two case studies, it has been an iterative process to get the results, but the starting values have been the recommended values for the construction parts from when the building was built, see subsection 2.2.3. The construction part's areas were captured by construction plan drawings provided by Riksbyggen.

The second term Q_{vent} of Equation 3.3 represents the heat losses through ventilation. These losses depend on the ventilation rate, q_{vent} , provided in the energy declaration of each property, as well as the temperature difference between the indoor and outdoor temperatures. It was given in the energy declaration of the two buildings that the ventilation system has a heat recovery which reduces the heat losses through the ventilation system, since the heat in the outgoing ventilation is being reused. The efficiency of the heat recovery, η_{vent} , has been assumed to be in between 40-50% for the two buildings. The heat losses due to the ventilation have been described in Equation 3.5 [46], where ρ_{air} represents the density of air and $c_{p,air}$ represents the heat capacity of air.

$$Q_{vent} = (T_{in}(t) - T_{out}(t)) \cdot (\rho_{air} \cdot c_{p,air} \cdot q_{vent}) \cdot \eta_{vent} \quad (3.5)$$

3.2.1 Modelling the heat balance of BRF 2018

With the heat balance equation (described in Equation 3.1) set up, the next step was to evaluate the building properties. As data for the heat demand, indoor and outdoor temperature were available, but no building characteristics except the drawings, the U-values needed to be assessed via a thermodynamic model. As the indoor temperature was given, the aim was to set up the heat balance by inserting the outdoor temperature and heat demand and to achieve a similar development of the indoor temperature. This was done by an iterative process to identify the U-values and the thermal inertia of the building. If the actual and simulated indoor temperature are equal, it can assume that the estimated, modelled house properties correspond to the actual house properties. During the summer, when the outdoor temperature exceeds the indoor temperature, it's assumed that the residents will either ventilate by opening a window or using solar shading, which will decrease the solar radiation. This has been modeled by decreasing the heat gain through the solar irradiance during high outdoor temperature hours. These assumptions were made to increase the reliability of the study and harmonize the measured and modelled indoor temperature.

The model has also been tested with input data from 2020, to see how the model behaves at a different year, but still with the same building parameters.

3.2.2 Modelling the heat balance of BRF 1988

To model the indoor temperature of BRF 1988, the input data was extracted from 2021 and 2023. Due to lack of data, it wasn't possible to extract the data from 2019 and 2020 as in the BRF 2018 case study. The data for the years 2021 and

2023 were missing singular hourly data, but have been used and assumed to be presentable for the house. Likewise to the BRF 2018 case, a modeling of the indoor temperature was needed to assess the properties of the building, as these were not given. By modeling a similar indoor temperature to the actual, we can assume that the assessed U-values and thermal inertia are close to the actual values that are needed to describe the building's behavior.

3.3 Optimization model in GAMS

To minimize the total annual heating cost, the General Algebraic Modeling System (GAMS) is used. GAMS is a modelling tool for optimization purposes and mathematical programming. The optimization is based on perfect foresight, determining a global optimum after optimizing all variables over the whole time frame in a single run [47]. With the building characteristics found in the modelling part (see Table 4.3 and Table 4.1), the two buildings have been transferred into GAMS to optimize the heating pattern with the aim to minimize the total cost over the year (both the annualized investment cost and running cost).

3.4 Input data in GAMS

This section contains the chosen input data for the GAMS model.

3.4.1 Outdoor conditions

The outdoor conditions implemented were obtained by Sveby which collect and present standardized and verified energy performance data of buildings [44]. The hourly outdoor temperatures of 2019 for the four analyzed cities were extracted and inserted into the GAMS model and can be seen in Figure 3.1. Furthermore, was the hourly solar data obtained and adjusted as described in subsection 3.2.1.

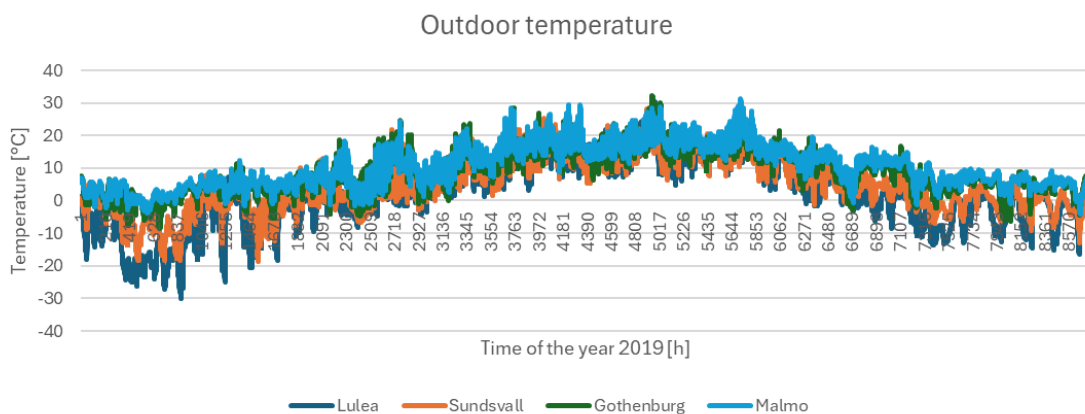


Figure 3.1: Outdoor temperature 2019

3.4.2 District heating prices

The DH prices consist of the power, energy, and flow price as described in section 2.4. The flow prices are neglected due to their low influence on the total price. The power and energy prices are set by each DH company individually. As the aim of this study was to investigate the different costs of using DH or electricity for heating while not being locally settled, the results would not be trustworthy by using the local prices provided by the local DH company. As the companies have different ways of setting the power and energy prices, the decision was made to use the averages of the four examined cities Luleå, Sundsvall, Gothenburg, and Malmö. The average values are classified in this study as base.

The power price sets a yearly cost for DH, containing a fix and a variable part, as described in subsection 2.4.1. A base, minimum and maximum scenario was investigated and can be seen in Table 3.3. The base scenario represents the average of the investigated cities in that range (kW). Minimum and maximum cases describe the the lowest and largest cost components.

Table 3.3: Yearly power prices consisting of a fix [SEK] and variable (var) [SEK/kW] component of the minimum, base and maximum scenario

Range kW	Minimum		Base		Maximum	
	Fix SEK/ year	Var SEK/ kW	Fix SEK/ year	Var SEK/ kW	Fix SEK/ year	Var SEK/ kW
0 - 25	0	149	0	618	0	924
26 - 50	0	149	187,5	610,8	750	924
51 - 100	0	149	2700	560,25	8550	924
101 - 250	0	149	6034,5	527	11888	854

To better understand the price setting, an example is used for clarification: If the GAMS optimization code develops the most efficient capacity using DH of 40 kW for the base scenario, it results in the range of 26-50 kW. The annual fixed component is therefore 187,5 SEK. The variable component is:

$$40 \text{ kW} \cdot 610,8 \text{ SEK/kW} = 24432 \text{ SEK} \quad (3.6)$$

Together the outtake leads to a total annual power price of 24619,5 SEK.

When calculating the DH energy base price, the base scenario is the monthly average price of the investigated cities, and the same method for the monthly minimum and maximum scenarios, seen in Table 3.4.

Table 3.4: Minimum, Base, and Maximum monthly energy prices in SEK/MWh

	Minimum	Base	Maximum
January	312	449	521
February	312	449	521
March	191	418,75	521
April	175	247,25	359
May	100	182,5	264
June	100	143	175
July	100	143	175
August	100	143	175
September	100	182,5	264
October	175	247,25	359
November	175	292	443
December	312	449	521

3.4.3 Electricity prices

As described before in section 2.5, the electricity price consists of the spot price, grid tariff, and the electricity tax. The spot price differs for each city as Luleå, Sundsvall, Gothenburg, and Malmö were chosen to represent the four electricity zones, and will therefore be locally bounded to the cities.

The grid tariff is set by the local electricity grid provider. The electricity grid providers set the prices individually and are therefore difficult to compare. To make the prices more comparable, the values provided by the Nils Holgersson report have been used, which present the total electricity grid tariff of each provider [48]. Equally to the energy and power prices of DH should the electricity grid tariffs be locally independent. Therefore, a minimum, average and maximum price was taken to examine the influence of this price factor. As small municipalities need to cover the cost of fewer people, their electricity grid tariff might not be representative. Therefore are the chosen municipalities Borlänge for the lowest and Malmö for the highest price [48]. The base value for the electricity grid tariff is the average of the 10 largest cities of Sweden (Stockholm, Gothenburg, Malmö, Uppsala, Linköping, Örebro, Västerås, Helsingborg, Norrköping, Jönköping). The used prices are:

- Minimum: 51,30 Öre/kWh
- Base: 88,24 Öre/kWh
- Maximum: 119,60 Öre/kWh

3.4.4 Investment and operational costs

The investment cost and lifetimes for the HPs and DH were obtained by the Danish Energy Agency [49], which publishes and updates data for individual heating for several technologies including HPs and DH for new and old apartment complexes.

Multiple HP technologies are listed as air-air or air-water HPs, but for this examination, ground source HPs data was used. As current installation prices can differ largely depending on region and future costs are difficult to predict, the actual values shouldn't be taken as a specific, exhaustive collection of data but imply trends.

3.4.4.1 BRF 2018

The input data is based on the assumption of a new building which invests in a heating system [49].

Table 3.5: Input data of capital and operational costs as well as respective lifetime of heat pump and DH installations to GAMS in 2020 for a new installation

Input data	Value	Unit
HP CAPEX ₂₀₂₀	731 250	Euro/MW
HP fixed O&M ₂₀₂₀	9644	Euro/MW _{,year}
HP Lifetime	20	Years
HP COP ₂₀₂₀	2.9	-
DH CAPEX ₂₀₂₀	53 125	Euro/MW _{installed}
DH fixed O&M ₂₀₂₀	481	Euro/MW _{,year}
DH Lifetime	25	Years
DH COP ₂₀₂₀	1	-

3.4.4.2 BRF 1988

The input data is based on the assumption of the cost of retrofitting a heating system [49].

Table 3.6: Input data to GAMS for a retrofit solution of a DH or HP installation in 2020

Input data	Value	Unit
HP CAPEX ₂₀₂₀	640 938	Euro/MW _{installed}
HP fixed O&M ₂₀₂₀	6700	Euro/MW _{,year}
HP Lifetime	20	Years
HP COP ₂₀₂₀	3.2	-
DH CAPEX ₂₀₂₀	30 800	Euro/MW _{installed}
DH fixed O&M ₂₀₂₀	222	Euro/MW _{,year}
DH Lifetime	25	Years
DH COP ₂₀₂₀	1	-

3.5 Scenarios

To see and understand the influence of the different components, multiple scenarios will be investigated. The concept of the model is that in the first step, the year

is chosen which is being examined with its respective prices. Secondly, the building is chosen which differs in properties and characteristics. In the next step, the geographical location is defined. After these three parameters have been decided, the temperature range, DH energy and power price as well as the grid tariff of the electricity price get defined. As the aim is to see the individual influences, only one parameter gets changed while the other remain with their base value. The graphic in Figure 3.2 describes the model options.

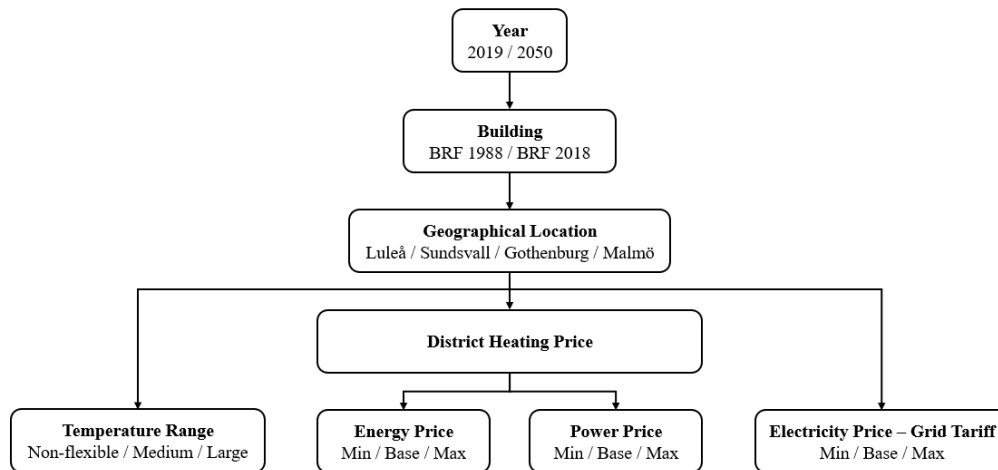


Figure 3.2: Flowchart of the different scenarios

3.5.1 Scenario with varying geographical location

The first scenario will be the influence of the geographical location. To be able to compare the cities, with no dependency of locally set DH prices and electricity grid prices, the base price profiles will be used in all the cities. Since the spot prices are locally bounded to each electricity zone, will these be locally set. The aim is to see the impact of the geographical location changes the most cost-effective method to heat up the building. The indoor temperature range is set to 20 °C to 24 °C (medium).

Table 3.7: Used values for geographical location scenario

	T_{in} range	Outdoor conditions		DH price		EL price	
		T_{out}	I_{solar}	Energy	Power	Spot	Grid
Luleå	Medium	Local	Local	Base	Base	Local	Base
Sundsvall	Medium	Local	Local	Base	Base	Local	Base
Gothenburg	Medium	Local	Local	Base	Base	Local	Base
Malmö	Medium	Local	Local	Base	Base	Local	Base

3.5.2 Scenario with varying indoor temperature range

The second scenario will investigate the influence of the indoor temperature range in the four studied cities. It has been assumed that the indoor temperature range

of multi-family houses is between 21 and 22 °C today (which will be called non-flexible temperature range in the results). A medium temperature range will then be investigated, which is an indoor temperature range between 20 and 24 °C. The third indoor temperature range will be the large one, which is between 19 and 25 °C. The temperature ranges will have a higher allowed maximum indoor temperature during the summer (June, July, and August). Due to the aim of the project, a cooling system hasn't been implemented in the buildings. The indoor temperature ranges and values chosen for the scenario of differentiating the temperature range can be seen in Table 3.8 and Table 3.9.

Table 3.8: Indoor temperature limits for the three ranges non-flexible, medium and large in °C

	Non-flexible (Non)	Medium (M)	Large (L)
Lower limit	21	20	19
Upper limit	22	24	25
Upper limit summer	23	26	26

Table 3.9: Used values to analyse the influence of the indoor temperature range

	T_{in} range	Outdoor conditions		DH price		EL price	
		T_{out}	I_{solar}	Energy	Power	Spot	Grid
Luleå	Non/M/L	Local	Local	Base	Base	Local	Base
Sundsvall	Non/M/L	Local	Local	Base	Base	Local	Base
Gothenburg	Non/M/L	Local	Local	Base	Base	Local	Base
Malmö	Non/M/L	Local	Local	Base	Base	Local	Base

3.5.3 Scenario with varying district heating power price

As mentioned in subsection 2.4.1, the DH price depends on the power price and energy price. In this scenario, the DH power price will be investigated, by using a minimum and maximum scenario as described in Table 3.3. The other parameters stay as base, and the temperature range will be in the medium range, 20 to 24 °C. The setup of the scenario can be seen in Table 3.10.

Table 3.10: Used values DH price scenario - influence power price

	T_{in} range	Outdoor conditions		DH price		EL price	
		T_{out}	I_{solar}	Energy	Power	Spot	Grid
Luleå	Medium	Local	Local	Base	Max/Min	Local	Base
Sundsvall	Medium	Local	Local	Base	Max/Min	Local	Base
Gothenburg	Medium	Local	Local	Base	Max/Min	Local	Base
Malmö	Medium	Local	Local	Base	Max/Min	Local	Base

3.5.4 Scenario with varying district heating energy price

In this scenario, the DH energy price will be investigated by using a maximum and minimum scenario, which were presented in Table 3.4. The set-up in the scenario can be seen in Table 3.11, where the energy price changes, the rest remains as base or local and the indoor temperature range stays at medium.

Table 3.11: Used values DH price scenario - influence energy price

	T_{in} range	Outdoor conditions		DH price		EL price	
		T_{out}	I_{solar}	Energy	Power	Spot	Grid
Luleå	Medium	Local	Local	Max/Min	Base	Local	Base
Sundsvall	Medium	Local	Local	Max/Min	Base	Local	Base
Gothenburg	Medium	Local	Local	Max/Min	Base	Local	Base
Malmö	Medium	Local	Local	Max/Min	Base	Local	Base

3.5.5 Scenario with varying electricity price

Lastly, the impact of the electricity price will be looked at. The values of the outdoor conditions and DH are local and base, respectively. As described before will the local spot prices be used, but for the grid tariffs the maximum and minimum prices in Sweden will be used.

Table 3.12: Used values for electricity price scenario

	T_{in} range	Outdoor conditions		DH price		EL price	
		T_{out}	I_{solar}	Energy	Power	Spot	Grid
Luleå	Medium	Local	Local	Base	Base	Local	Max/Min
Sundsvall	Medium	Local	Local	Base	Base	Local	Max/Min
Gothenburg	Medium	Local	Local	Base	Base	Local	Max/Min
Malmö	Medium	Local	Local	Base	Base	Local	Max/Min

3.6 Future 2050 scenario

The final part of this study are to examine the potential of flexible heating in multi-family houses in Sweden in 2050. The aim was to see if the forecasted future system shows changes in the result of the preferred heating technology. The forecasted trends are described in subsection 2.4.2 and subsection 2.5.2 and the method of the implementation will be described in this section.

Firstly, it is assumed that the building characteristics are unchanged. The input data of outdoor temperature and solar irradiance will remain constant from 2019, due to the marginal cost of DH and electricity in 2050 (which were based on outdoor data from 2019). The CAPEX and fixed OPEX of DH and HP installations can be obtained in Table 3.13 and Table 3.14, and are a prediction from the Danish Energy Agency [49].

Table 3.13: Input data to GAMS for a new installation in 2050 (BRF 2018)

Input data	Value	Unit
HP CAPEX ₂₀₅₀	528 750	Euro/MW
HP fixed O&M ₂₀₅₀	8881	Euro/MW _{,year}
HP Lifetime	20	Years
HP COP	3.4	-
DH CAPEX ₂₀₅₀	45 688	Euro/MW _{installed}
DH fixed O&M ₂₀₅₀	456	Euro/MW _{,year}
DH Lifetime	25	Years
DH COP	1	-

Table 3.14: Input data to GAMS for a retrofit solution of a DH or HP installation in 2050 (BRF Huskarnahus)

Input data	Value	Unit
HP CAPEX ₂₀₅₀	463 094	Euro/MW _{installed}
HP fixed O&M ₂₀₅₀	6322	Euro/MW _{,year}
HP Lifetime	20	Years
HP COP	3.6	-
DH CAPEX ₂₀₅₀	26 500	Euro/MW _{installed}
DH fixed O&M ₂₀₅₀	208	Euro/MW _{,year}
DH Lifetime	25	Years
DH COP	1	-

The tax on both DH and electricity is assumed to be equal to the 2019 values. The DH prices other components that define the final cost for the customers are the energy and power price. The marginal cost of DH in 2050 [50], based on 2019 weather, electricity, and heat demand data, has been used and assumed to be equal to the DH energy price. Likewise to the analysis of the 2019 scenarios, local independence wanted to be assured. An average of the hourly marginal costs of the four cities was therefore formed, which could decrease the DH energy price fluctuations but was done to be able to compare the results with the reference year of 2019.

The assumption of the change in DH power price is due to the theory (see subsection 2.4.2) about the future DH market. The implementation of the DH power price has been done, even if the DH energy price (marginal price of heat) already contains a power component, since it is assumed that the DH companies will charge the customers for the power outtake as well (similarly to 2019 scenario). The new DH power price was developed in an iterative process by running the model and increasing the price of the power price with the aim of achieving a larger DH power share in the total price compared with the 2019 scenario. The prices of 2019 have been hereby used as guidelines. The new distribution of DH costs can be seen in Figure 3.3, where the DH power (both fixed and variable) share increases from the distribution in 2019 and the DH energy share decreases. The total cost of DH increases with 10% and is used when comparing with the HP costs.

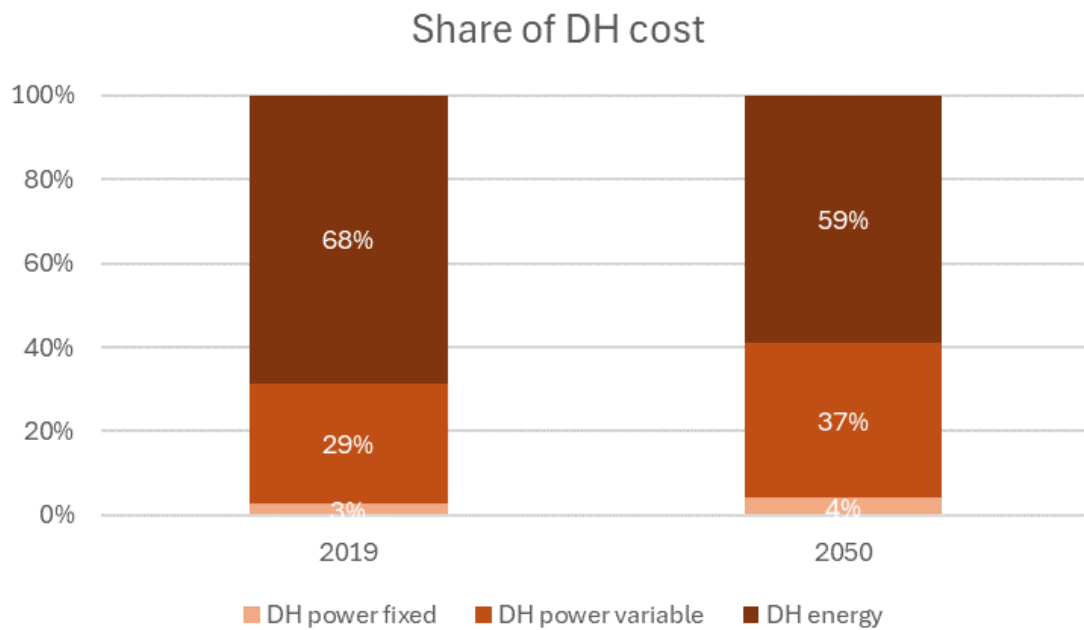


Figure 3.3: The DH cost structure change

The HP costs depend on the electricity spot price, grid fee, and tax. The marginal cost of electricity in 2050 has been used as the spot price. The grid fee has then been changed to achieve a higher share of the total electricity costs than in the 2019 scenario. The grid fee has been divided into “spot grid fee” and “power-based grid fee”.

The first part is dependent on the spot price (“spot grid fee”). During low spot prices a low spot grid tariff and for high spot prices a high grid spot tariff occur. Between those lower and upper limits, there is a grid spot tariff based on the 2019 used base value.

The second part is called “power-based grid fee”. Likewise to the DH power price, which is based on the largest outtake of heat over the year, the power-based grid fee for the electricity is based on the largest available outtake, which here is based on the installed capacity of the HP. Different ranges of capacity were formed for which a yearly cost is added, with the ranges getting more expensive the larger the installed capacity. Table 3.15 illustrates the ranges of installed capacity. In the first column, “Electricity output ranges”, the maximum electrical output ranges are presented. For instance, in the 0-10 range, for BRF 1988 (a retrofit) with an HP COP value of 3.6, the HP capacity range is between 0 and 36. Similarly, for BRF 2018 (a new investment) with an HP COP of 3.4, the HP capacity range in the same 0-10 range is between 0 and 34.

Table 3.15: The maximum power outage ranges

Electrical output ranges kW_{el}	BRF 1988 kW_{HP}	BRF 2018 kW_{HP}
0-10	0-36	0-34
10-20	36-72	34-68
20-30	72-108	68-102
>40	>108	>102

A cost comparison between the grid tariff used for 2019 which was based on the electricity consumed and the 2050 model which was split is difficult, but it was assumed that the total annual cost increased with 9% (compared with the DH total annual cost which increased with 10%). The final share of the HP running cost can be seen in Figure 3.4.

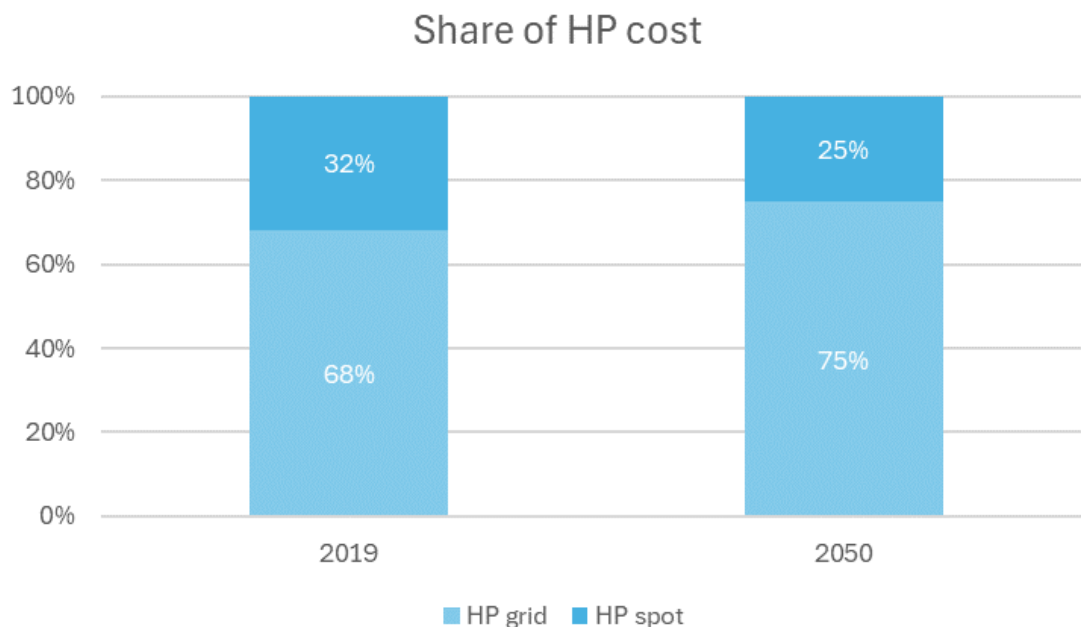
**Figure 3.4:** The HP cost structure change

Figure 3.4 shows an increase of the HP grid price and a decrease of the HP spot price.

The aim with the 2050 scenario was to see how the model responds on the new cost structure. To make it reasonable, the total cost of DH and HP has approximately increased by 10%, similar to the power share of the both technologies. The scenario is based on future trends, and the exact values need to be used carefully.

3.7 The mathematical model for cost optimization

Indices

t	Index for time step
t_{summer}	Index for time step during the summer
h	Index for heating technology
b	Index for building
c	Index for city
cp	Index for construction parts

Sets

T	Set of hours of the year: $\{1:8760\}$
T_{summer}	Set of hours of the summer : $\{3625:5831\}$
H	Set of heating technologies: $\{DH, HP\}$
B	Set of building: $\{BRF 1988, BRF 2018\}$
C	Set of city: $\{Luleå, Sundsvall, Gothenburg \text{ and } Malmö\}$
CP	Set of construction parts: $\{Wall, Window, Roof \text{ and } Floor\}$

Parameters

$Q_{solar_{c,t}}$	Solar irradiation profile for each city c every hour t of the year
$Q_{resi_{b,t}}$	The heat gain profile from the residents in each building b every hour t
$T_{out_{c,t}}$	The outdoor temperature profile for each city c every hour t of the year
$U_{value_{b,cp}}$	The U-value of each construction part in each building b
$Area_{b,cp}$	The area of each construction part in each building b
eta_{vent_b}	The heat recovery efficiency of the ventilation system in each building b
Cm_b	The thermal inertia of each building b
$VentRate_b$	The ventilation rate in each building b
$COP_{b,h}$	The efficiency of the heating technology in each building b
$CAPEX_{b,h}$	The investment cost of the heating technology h in each building b
$OPEX_{b,h}$	The operational cost of the heating technology h in each building b
$Lifetime_{b,h}$	The lifetime of the heating technology h in each building b
$DHenergy_t$	The general DH energy price profile every hour t of the year
$DHpowerVar_b$	The variable DH power price for each building b
$DHpowerFix_b$	The fixed DH power price for each building b

$ELspot_{c,t}$	The EL spot price profile for each city every hour t of the year
$ELgrid$	The EL grid price
tax	Energy tax in Sweden on electricity and DH
a_h	Annuity factor for each heating technology h
$TinMin$	The minimum allowed indoor temperature
$TinMax$	The maximum allowed indoor temperature
$TinMaxS$	The maximum allowed indoor temperature during the summer
$HotWaterdeliv_b$	Constant hot water delivered of the heating technology h to each building b

Variables

$TotCost_b$	Total annual heating cost for each building
$Capacity_{b,h}$	Installed capacity of each heating technology for each building
$Heatdeliv_{b,h,t}$	Heat delivered to each building, from each heating technology every hour
$Tin_{b,t}$	Indoor temperature in each building every hour
$Qsupply_{b,t}$	The total heat supply in each building every hour
$Qloss_{b,t}$	The total heat losses in each building every hour
$Qneg_{b,t}$	The total irregular heat losses in each building every hour
$TotHeatSupply_{b,h,t}$	The total heat demand including heating and hot water for every hour

Objective function

$$\begin{aligned}
\text{minimize } TotCost_b = & Capacity_{b,DH} \cdot DHpowerVar_b + DHpowerFix_b \\
& Capacity_{b,DH} \cdot (CAPEX_{b,DH} \cdot a_h + OPEX_{b,DH}) + \\
& \sum_t (DHenergy_t + tax) \cdot \frac{TotHeatSupply_{b,DH,t}}{COP_{b,DH}} + \\
& Capacity_{b,HP} \cdot (CAPEX_{b,HP} \cdot a_h + OPEX_{b,HP}) + \\
& \sum_t ((ELspot_{c,t} + ELgrid_t + tax_t) \cdot \frac{TotHeatSupply_{b,HP,t}}{COP_{b,HP}}
\end{aligned} \tag{3.7}$$

Constraints

The indoor temperature needs to be within the temperature range (in each building) and is controlled through the following constraints, which need to be fulfilled during every hour of the year, except during the summer, when the indoor temperature has a higher upper limit as described in Equation 3.10.

$$Tin_{b,t} \geq TinMin \tag{3.8}$$

$$Tin_{b,t \setminus t_{summer}} \leq TinMax \tag{3.9}$$

$$Tin_{b,t_{summer}} \leq TinMaxS \tag{3.10}$$

3. Method

The hourly transmission losses depend on the indoor temperature, outdoor temperature and the construction part's U-values and areas, which is described in Equation 3.11.

$$Q_{transloss_{b,t}} = (Tin_{b,t} - Tout_{c,t}) \cdot \sum_{cp} Uvalue_{b,cp} \cdot Area_{b,cp} \quad (3.11)$$

The hourly heat losses through the ventilation depend on the indoor temperature, outdoor temperature, the ventilation rate and the efficiency of the heat recovery of the ventilation system, which is described in Equation 3.12.

$$Q_{ventloss_{b,t}} = (Tin_{b,t} - Tout_{c,t}) \cdot VentRate_b \cdot \eta_{avent_b} \cdot Cp_{air} \cdot \rho_{air} \quad (3.12)$$

The total hourly heat supplies and losses are described in the following equation, where no losses of heat delivery were assumed (i.e. the heat demand is equal to the actual heat supplied):

$$Q_{supply_{b,t}} = \left(\sum_h Heatdeliv_{b,h,t} \right) + Q_{solar_{c,t}} + Q_{resi_{b,t}} \quad (3.13)$$

$$Q_{loss_{b,t}} = Q_{transloss_{b,t}} + Q_{ventloss_{b,t}} \quad (3.14)$$

The indoor temperature then depends on the balance between the heat supply and losses. To be able to describe aspects of natural ventilation and solar shading (i.e. an irregular heat loss), the variable Q_{neg} is inserted into the constraints to achieve the temperature ranges (described in Equation 3.9, 3.8 and 3.10). Without this variable, the buildings would overheat (and the model infeasible). All supplied and lost heat needs to be divided by the thermal inertia Cm_b of the buildings.

$$Tin_{b,t+1} = Tin_{b,t} + (Q_{supply_{b,t}} - Q_{neg_t} - Q_{loss_{b,t}}) / Cm_b \quad (3.15)$$

$Q_{supply_{b,t}}$, can be seen in Equation 3.13, is divided into the heat delivered by the heating technology as well as the solar heat and heat generated by residents. Furthermore, the heating technology is also responsible for heating the water in the building. The total needed heat demand is divided into the heat delivered to heat the indoor environment and for heating the water for the different household processes. The hot water is constant throughout every hour of the year and depends on the amount of heated area in the building, see subsection 2.2.4.

$$TotHeatSupply_{b,h,t} = Heatdeliv_{b,h,t} + HotWaterdeliv_b \quad (3.16)$$

However, it needs to be assured, that the installed capacity of the heating technologies can provide both heating of the indoor temperature and water. The capacity therefore needs to be greater than the combined hourly demand of both heating requirements.

$$Capacity_{b,h} \geq Heatdeliv_{b,h,t} + HotWaterdeliv_b \quad (3.17)$$

The last constraint concerns the actual feasibility to not invest in a very small capacity of one technology to a small amount of money, which was defined as seen in Equation 3.18. The lower limit of the invested capacity was set to be at least equal or greater than the hot water demand (which is 10-20% of the total demand)

or zero. It is important to mention that only the capacity of the installed capacity is 0, equal or larger than the hot water demand. An equal capacity to the hot water demand does not correspondent to that technology only covering this demand. That will still be decided by the cost-minimal solution.

$$Capacity_{b,h} = \begin{cases} 0 & \text{if } Capacity_{b,h} < HotWaterdeliv_b \\ Capacity_{b,h} & \text{if } Capacity_{b,h} \geq HotWaterdeliv_b \end{cases} \quad (3.18)$$

4

Results

The results provide the findings of the cases examined. First, the results of the for the BRF 1988 implementation will be shown before displaying the BRF 2018 results. Lastly, the future 2050 case will be presented and its findings displayed.

4.1 BRF 1988

This chapter contains the results of BRF 1988 with the data of 2019 where the geographical location results will be shown first. The results of different geographical locations will then be compared when changing parameters such as indoor temperature range, DH power price, DH energy price, electricity grid price and HP lifetime.

4.1.1 Building characteristics

The results of the temperature profile for 2021 can be seen in Figure 4.1 and results for 2023 can be seen in Figure 4.2.

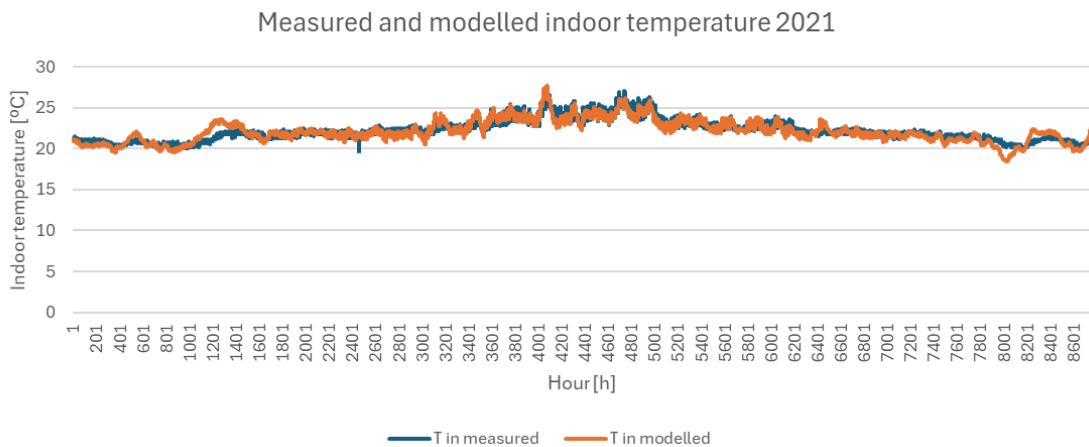


Figure 4.1: Measured and modeled indoor temperature 2021 at BRF 1988

4. Results

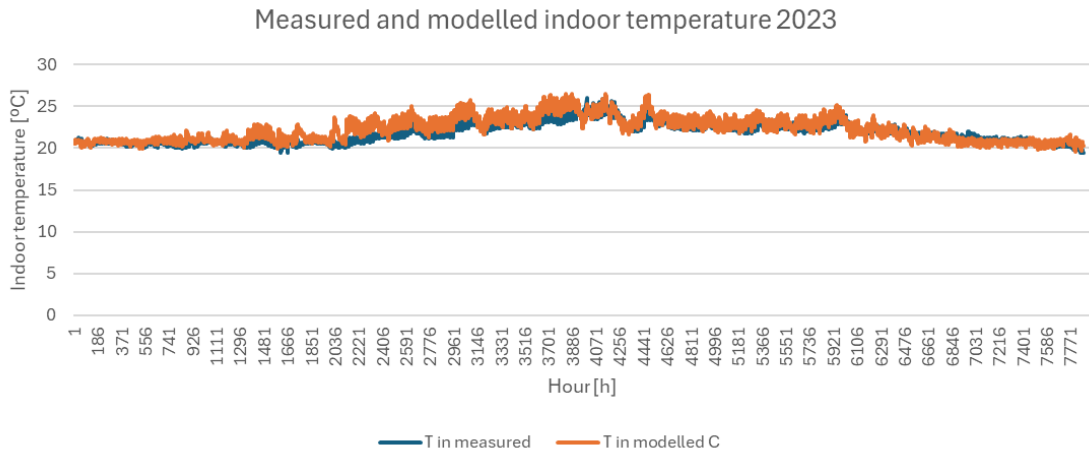


Figure 4.2: Measured and modeled indoor temperature 2023 at BRF 1988

With these results for 2021 and 2023 applying an iterative process, using the data of subsection 2.2.3 and subsection 2.2.2, the results of the U-values and thermal inertia can be seen in Table 4.1.

Table 4.1: Building characteristics' data of BRF 1988

Building characteristics'	Value	Unit
U-value wall	0,2	W/m ² K
U-value roof	0,18	W/m ² K
U-value floor	0,25	W/m ² K
U-value window	2,5	W/m ² K
Thermal inertia	0,23	MJ/m ² K

4.1.2 Geographical location

The results in Figure 4.3 and Figure 4.4 show that Luleå has the highest heating demand and the longest heating season, which can be explained due to its geographical location, up north in Sweden. The share between the hot water consumption and the space heating are also shown in the figure.

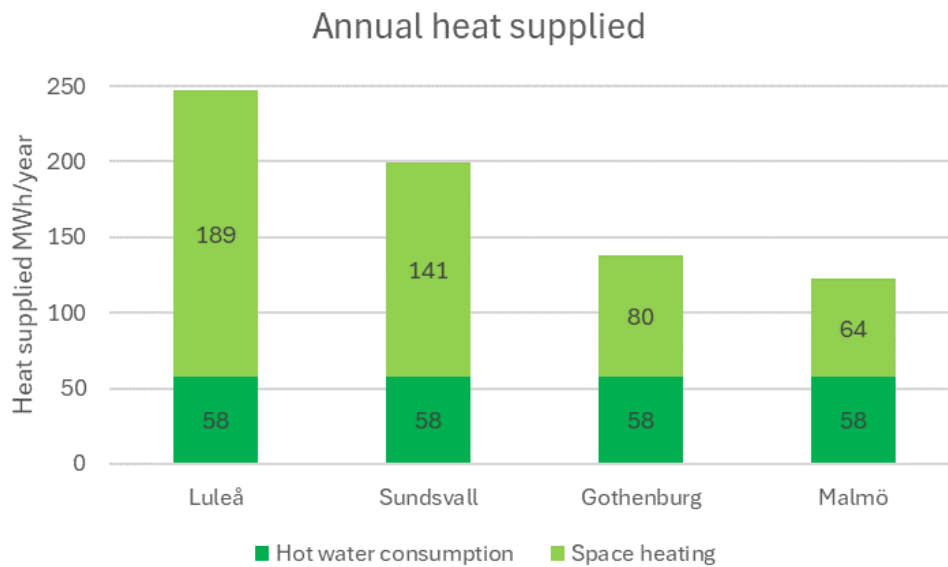


Figure 4.3: Total heat supplied of BRF 1988 in different geographical locations

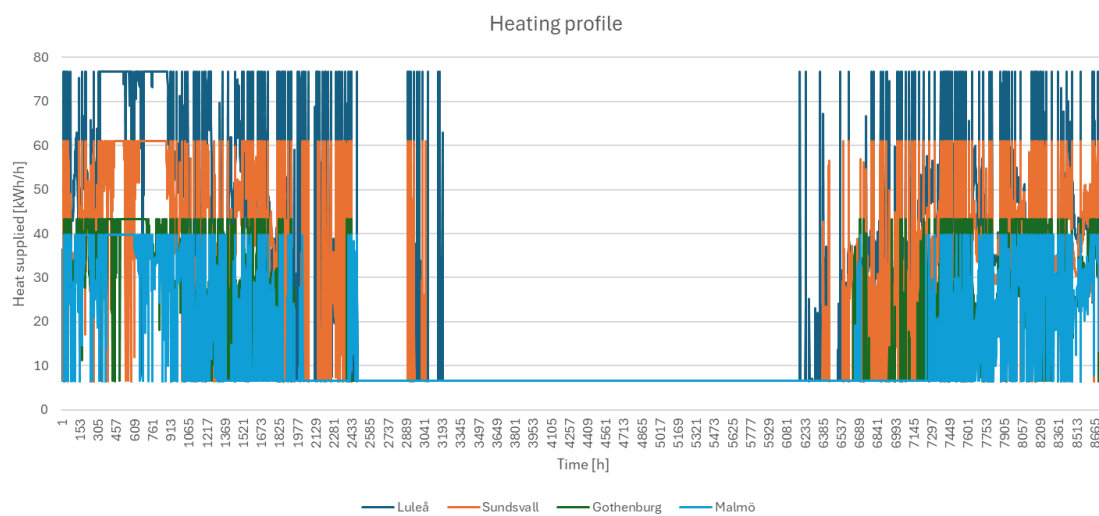


Figure 4.4: Heating profile of BRF 1988 of the different cities

The results of the annual heating cost can be seen in Figure 4.5, which is highly related to the results regarding the total installed capacity (Figure 4.6) and the total heat supplied (Figure 4.3) as a larger installed capacity leads to higher capital costs and more heat supplied that causes higher running costs.

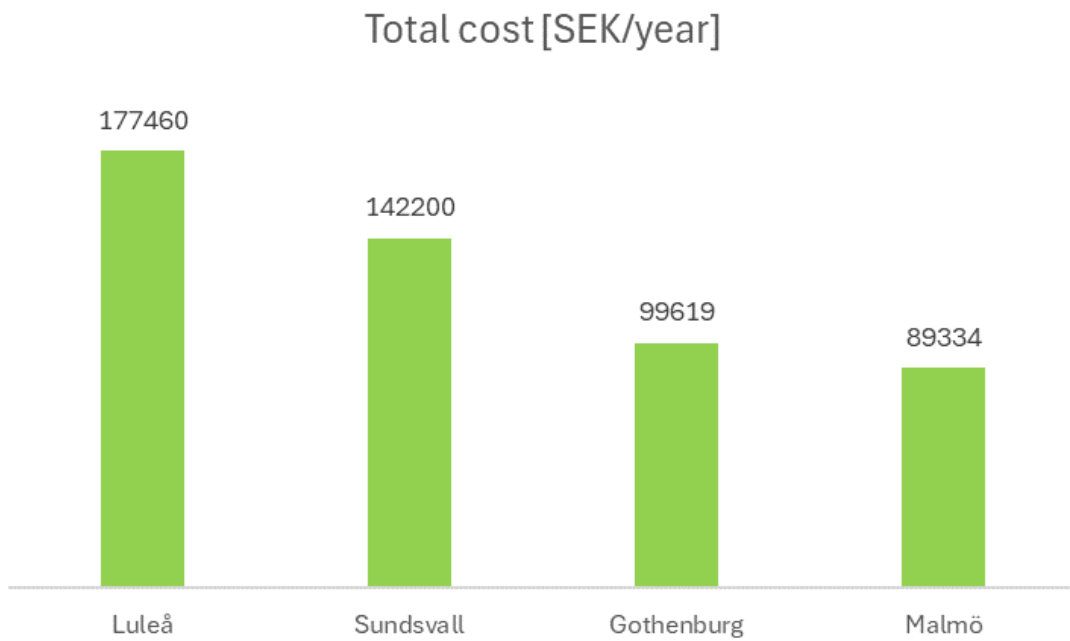


Figure 4.5: Total annual cost of BRF 1988 in different geographical location

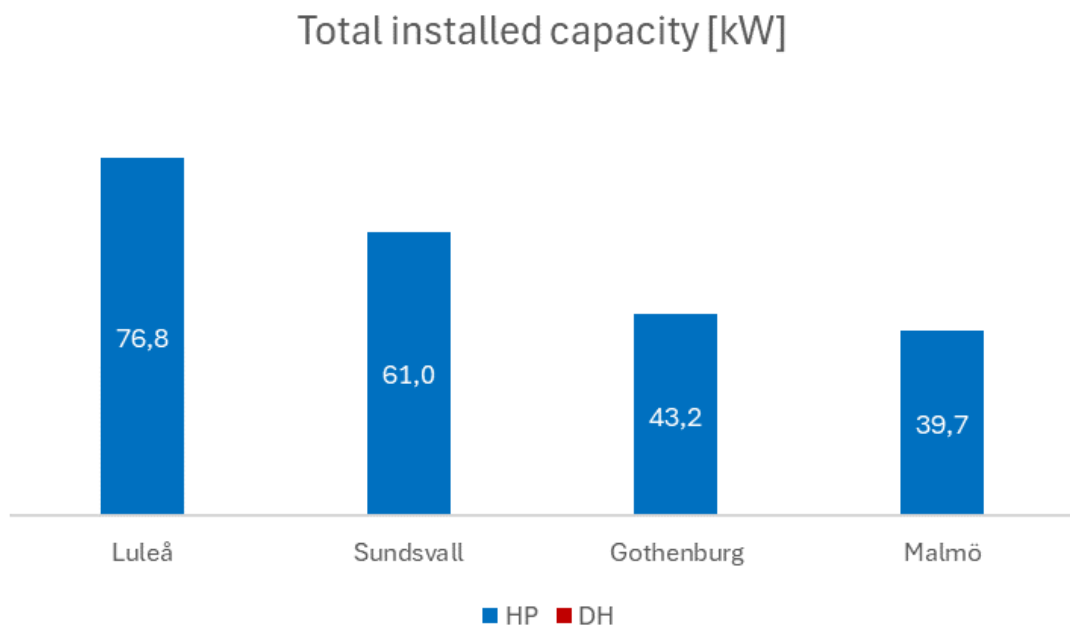


Figure 4.6: Total installed capacity of BRF 1988 in different geographical location

The share between installed capacity of HP and DH can be seen in Figure 4.6, where the most cost-effective capacity for all the cities is with a 100% share of HP.

When zooming in on one week in January, in Sundsvall, the correlation between the heat supplied and electricity price can be seen in Figure 4.7. The results show

that the building uses the fluctuating electricity prices by decreasing the supplied heat during high-cost electricity hours. But it's also seen that BRF 1988 only uses a few hours at full capacity and then drops down the supplied heat.

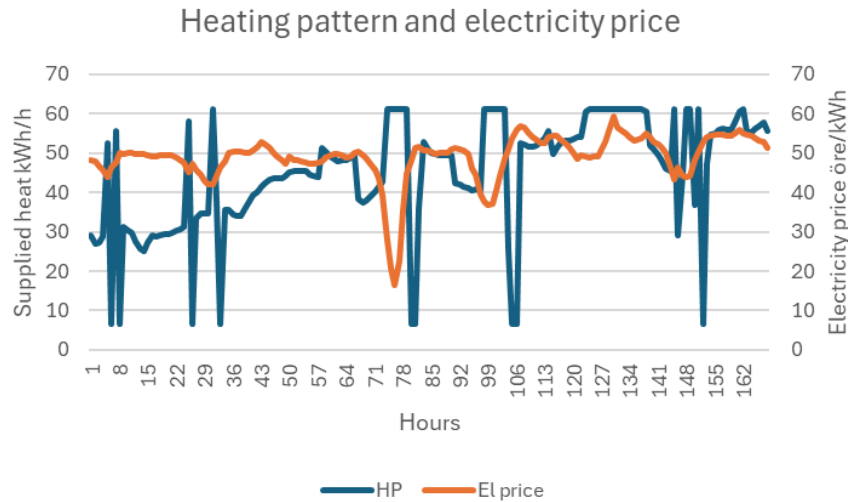


Figure 4.7: Heat supplied and electricity price one week in January 2019 for BRF 1988

4.1.3 Indoor temperature range

For the next case, a varying temperature range was studied. A non-flexible, medium and large indoor temperature span were given as constraints. The allowed indoor temperatures can be seen in Table 3.8. When looking at the total annual heat supplied change, which can be seen in Figure 4.8, similar patterns can be obtained for all four cities. A larger indoor temperature range leads to a lower demand of heat supplied.

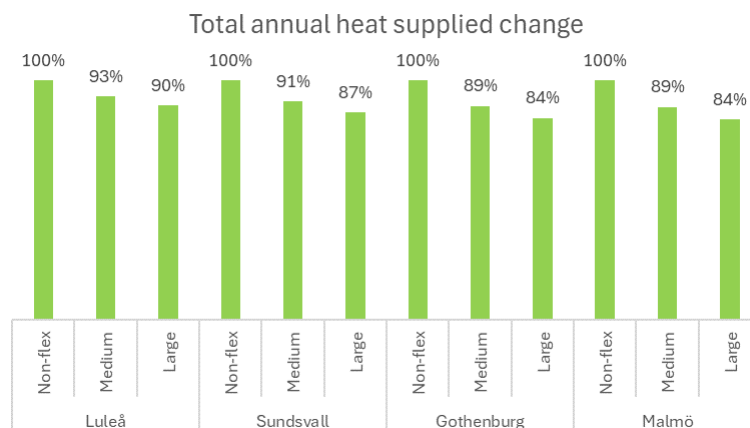


Figure 4.8: Total annual heat supplied difference of BRF 1988 for different temperature ranges

How the constraints of the temperature range influence the actual indoor temperature can be seen in Figure 4.9. The non-flexible restriction leads to a constant movement of the indoor temperature between 21 and 22 °C. The medium temperature range leads to many hours at the lower limit of 20 °C, but during summer hours a temperature of 24 °C is also reached regularly, which are presumably described by the higher outdoor temperatures (see Figure 3.1) rather than using the flexibility of the electricity. The same trends can be seen for the large range with its lower and upper limit of 19 and 25 °C respectively.

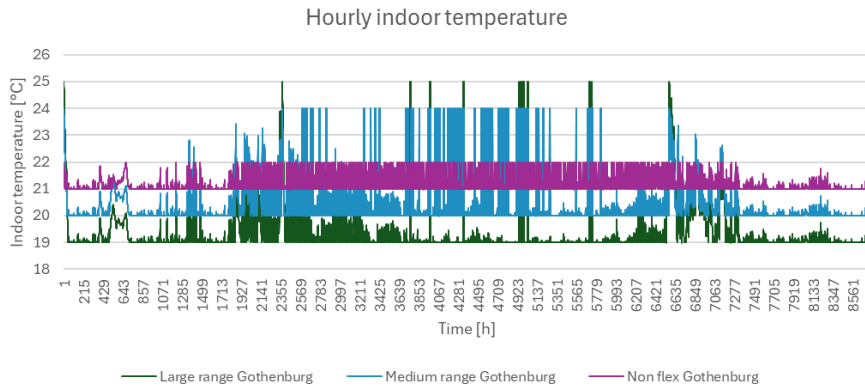


Figure 4.9: Hourly indoor temperature of BRF 1988 in Gothenburg for a non-flexible, small and large temperature range

The change of total cost when varying the temperature ranges can be seen in Figure 4.10. The main reason behind a decreased total annual cost is due to the lower energy demand since the model rather uses a lower temperature than using the flexibility of the electricity price. The average temperature, seen in Table 4.2, indicates on this as-well, since the average temperature are close to the minimum acceptable temperature in each case.

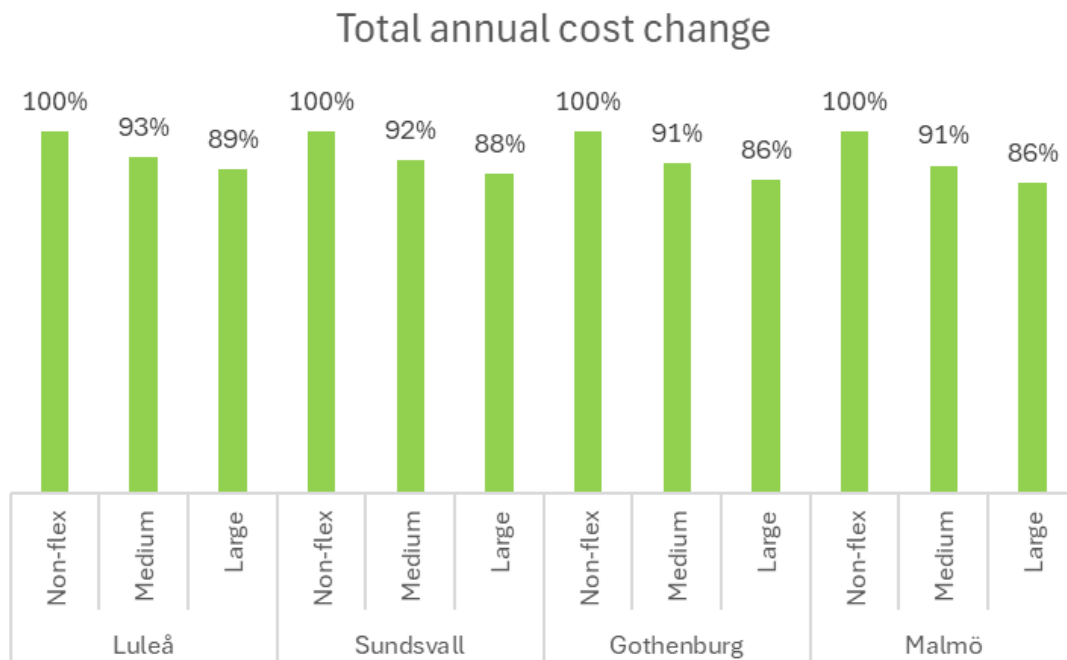


Figure 4.10: Total annual cost difference of BRF 1988 for different temperature ranges

Table 4.2: Average indoor temperature for a non-flexible, medium and large temperature range for BRF 1988

Non-flex	Medium	Large
21.2	20.5	19.4

Lastly, the installed capacity was examined. A larger indoor temperature range leads to a lower demand of installed capacity (Figure 4.11). This trend can be seen for each examined city, and similar shifts when increasing the range can be obtained. The share of installed capacity delivers other trends. For each city, independent of the installed capacity or temperature range, HP is the most cost-efficient option.

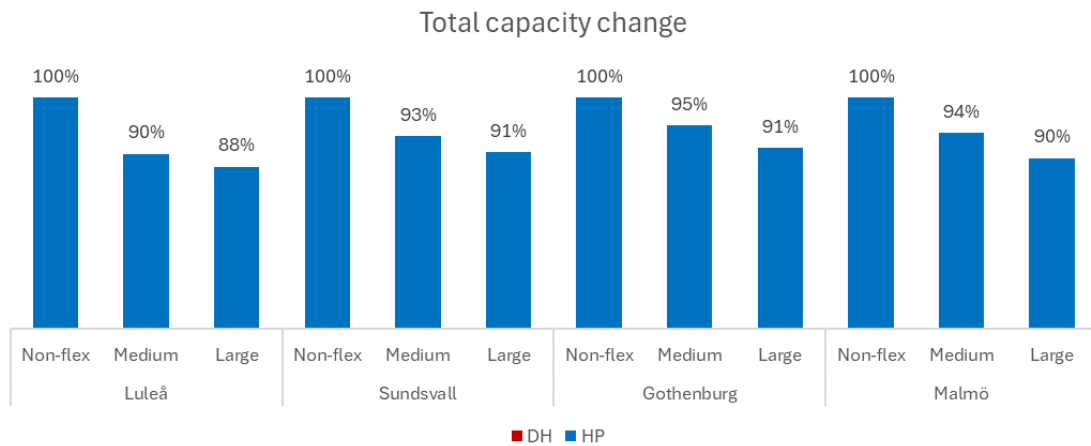


Figure 4.11: Total capacity change of BRF 1988 for different temperature ranges

4.1.4 District heating power price

The total cost change can be seen in Figure 4.12, where the minimum and maximum scenarios are compared with the base scenario in every city. The trend of the decreasing total annual cost for the minimum case occurs for every city in the minimum scenario.

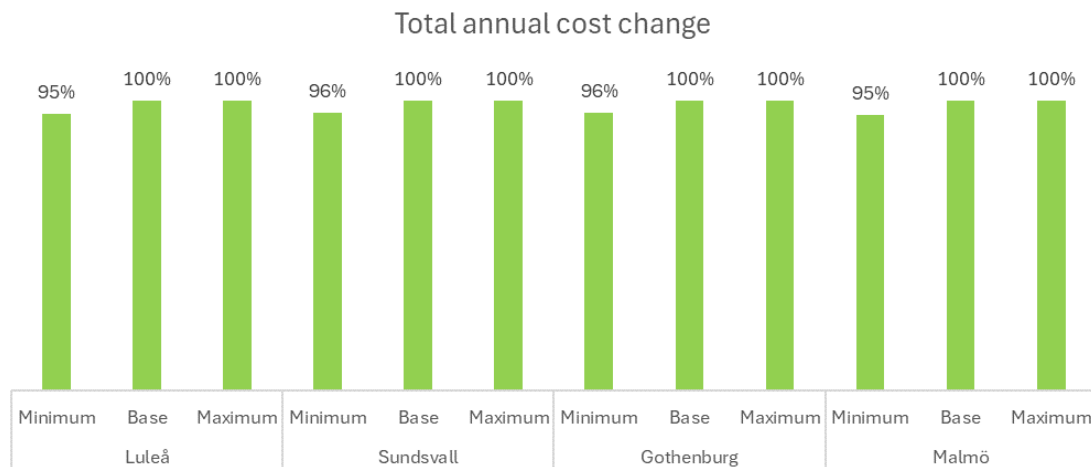


Figure 4.12: The total annual cost change of BRF 1988 with different DH power price

The total installed capacity nearly remains constant (increase of 2% for all cities) when decreasing the DH power price, and stays constant in the maximum scenario, similar trends can be obtained throughout Sweden. Figure 4.13 describes the share of DH and HP in every scenario and city. As mentioned above, the base and maximum scenario stays constant, which is due to the 100% HP share, so the distribution is not affected of increasing the DH price. When using the lowest DH power price in Sweden (scenario minimum), the share of DH increases and similar trends are obtained in all the cities.

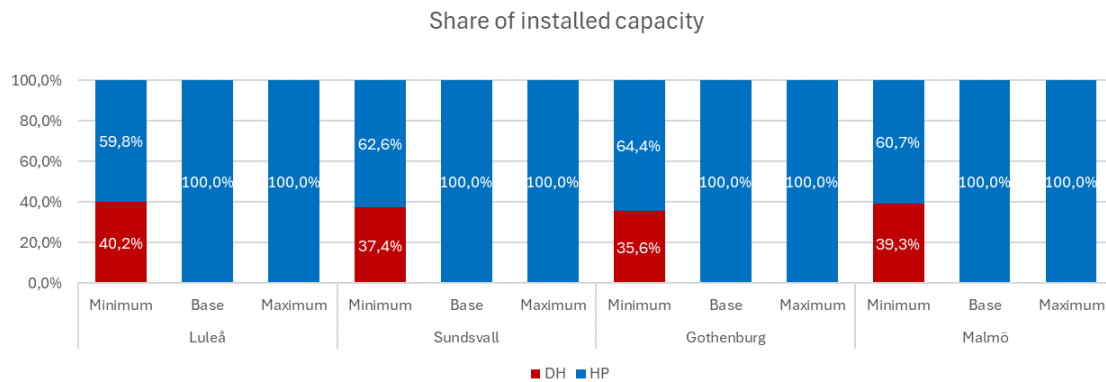


Figure 4.13: The share of installed capacity of DH and HP of BRF 1988 with different DH power price

4.1.5 District heating energy price

When changing the DH energy price (a variable operational cost), the total annual cost seems to stay constant in the minimum and maximum scenarios in all the cities (changes lower than 1%), compared with the base scenario. The total installed capacity also remains unchanged in all scenarios. The results are not affected of the price increase since only HP is being implemented. But when decreasing the DH energy price, a slight increase of the installed DH share occurs. As mentioned in the GAMS code description, there is a constraint of the invested capacity that it at least has to be equal or greater than the constant hot water consumption if installed, to make the model realistically feasible. That is what happens here for the minimum scenario in every city. The shares differ due to the varying total heat demands with equal hot water demands in each city.

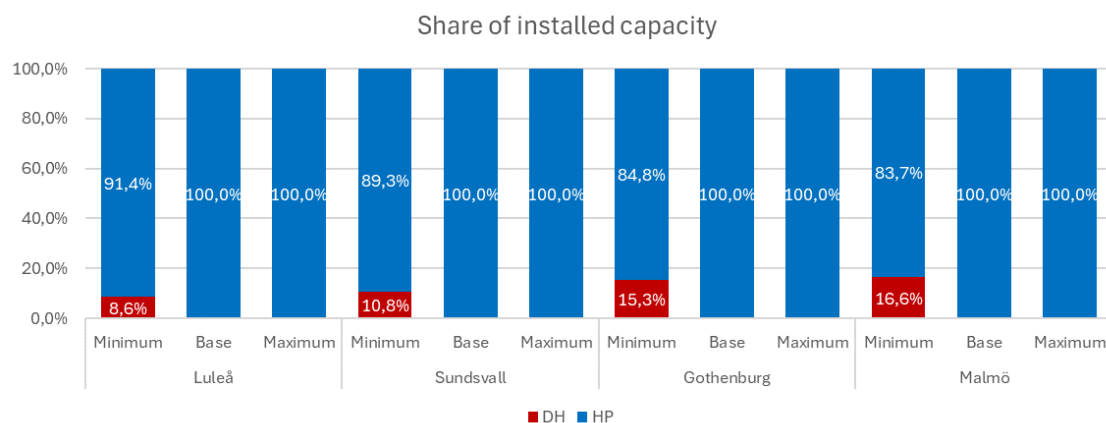


Figure 4.14: The share of installed capacity of DH and HP of BRF 1988 with different DH energy price

4.1.6 Electricity price

For this scenario, a varying electricity price, more specifically the electricity grid tariff, will be examined. Looking at the total annual cost change seen in Figure 4.15, a lower grid tariff leads to lower total annual costs, while higher grid tariffs lead to a higher total annual cost. This applies to all four cities. Interestingly, the margins between base to minimum or maximum are quite alike, even though the difference between base and minimum grid tariff is larger than between base and maximum grid tariff (see subsection 3.4.3). The potential of savings is equally distributed and not geographically driven.

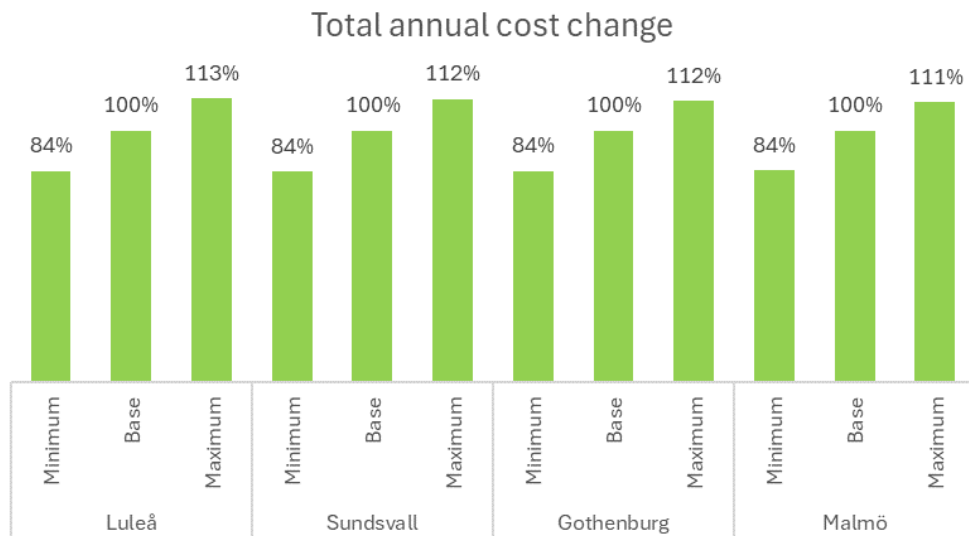


Figure 4.15: Total annual cost change of BRF 1988 for different electricity grid tariffs

The results showed that the total installed capacity remains constant when changing the grid fee. When looking at the share of installed capacity of DH and HPs similar patterns can be detected for all four cities. A lower or base grid tariff will lead to a domination of HP with it only being installed. For the maximum grid tariff, an implementation of DH is cost-efficient and covers between 9% in Luleå and 17% in Malmö of the total capacity. The shares of DH correspond to the hot water demand. The different shares of heating technologies can be seen in Figure 4.16.

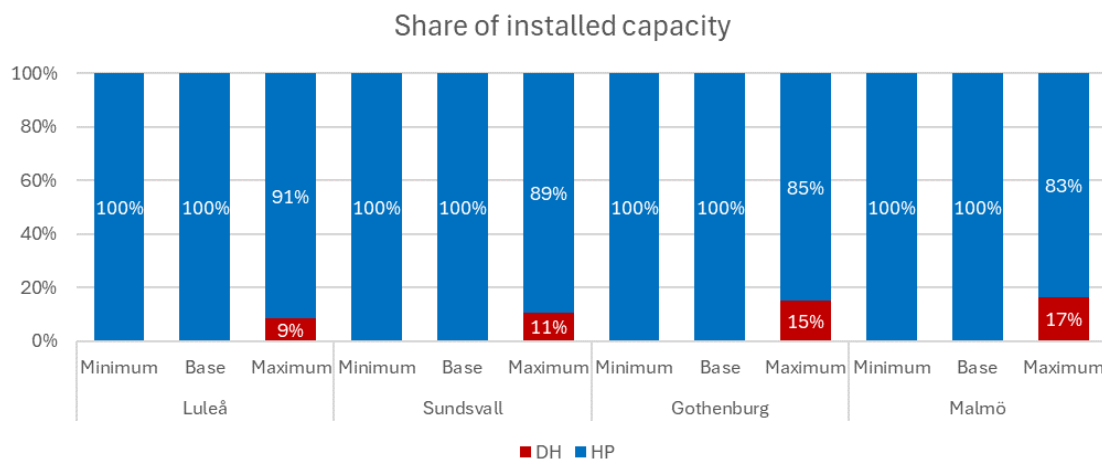


Figure 4.16: The share of installed capacity of DH and HP of BRF 1988 with different electricity grid tariffs

4.1.7 Heat pump lifetime

The last case that will be examined is the impact of the HP lifetime. A lifetime of 20 years has been used as the “base” lifetime and used in the previous results. The share of total installed capacity changes when decreasing the HP lifetime, which can be seen in Figure 4.17. The share of DH slightly increases when decreasing the HP lifetime due to an increased annual CAPEX of the HP.

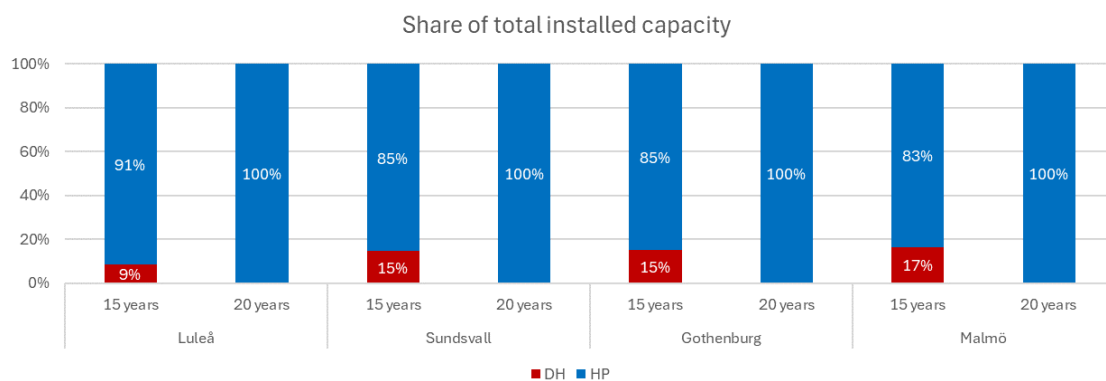


Figure 4.17: The share of total installed capacity of DH and HP of BRF 1988 with different HP lifetimes

As mentioned previously, the total cost will increase when decreasing the lifetime due to an increase of the annuity factor, see Figure 4.18.

4. Results

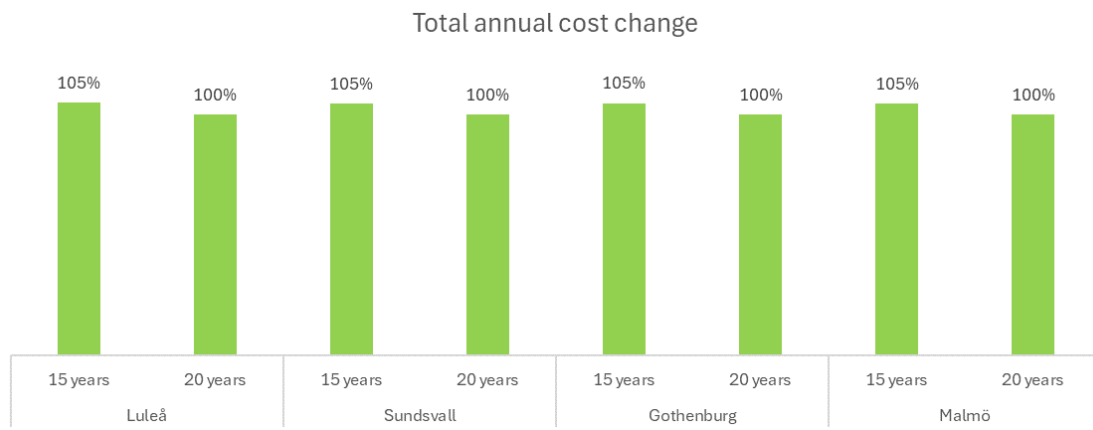


Figure 4.18: The total annual cost of BRF 1988 with different HP lifetimes

4.2 BRF 2018

This chapter contains the results of BRF 2018 with the data of 2019, where the geographical location results will be shown first. The results of different geographical locations will then be compared when changing factors such as indoor temperature range, DH power price, DH energy price, electricity grid price and HP lifetime.

4.2.1 Building properties

The result of the modeled temperature in 2019 can be seen in Figure 4.19.

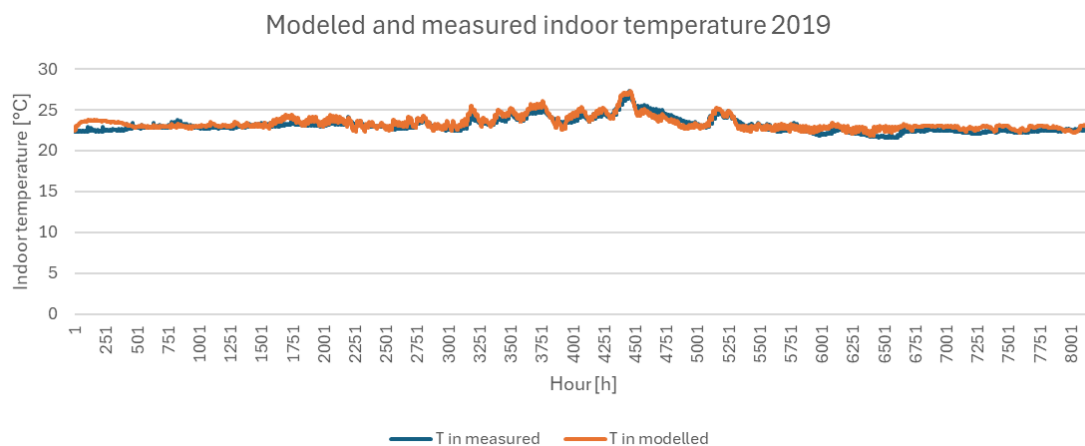


Figure 4.19: Measured and modelled indoor temperature for 2019 at BRF 2018

As seen in Figure 4.19, the two temperature developments look similar, and the modeled temperature follows the pattern of the measured indoor temperature.

The results of the verification year 2020 can be seen in Figure 4.20. When comparing the results of 2019 and 2020, it can be seen that the model seems to work for 2020 as well, however, clearer contrasts of the two temperature patterns can be seen. Since 2019 is the reference year and the year which the model was designed for, the assumptions about ventilation and solar shade values and patterns were accepted.

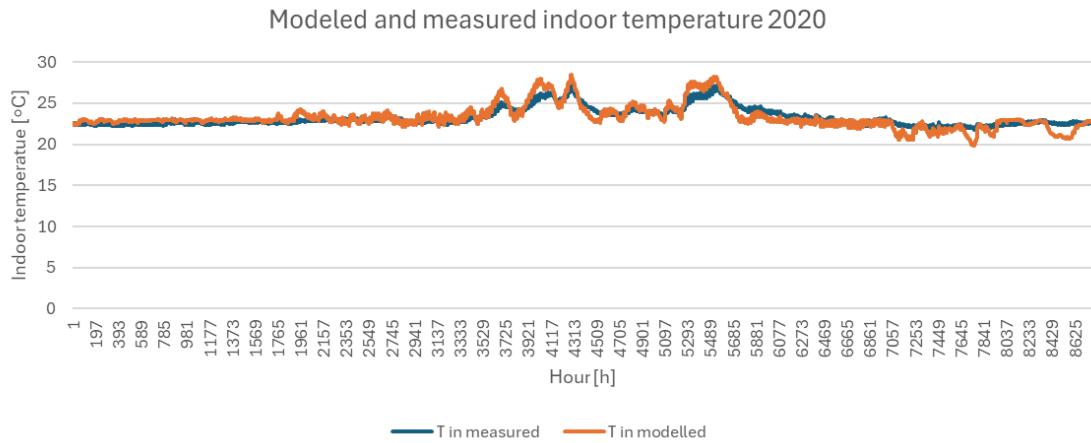


Figure 4.20: Measured and modelled indoor temperature for 2020 at BRF 2018

With the results of 2019 and 2020, the determination of the U-values and thermal inertia was concluded and can be seen in Table 4.3. The U-values were obtained in an iterative process using [51], [52] and guidelines described in subsection 2.2.3. The thermal inertia was assessed on the basis described in subsection 2.2.2.

Table 4.3: Building characteristics' data of BRF 2018

Building characteristics	Value	Unit
U-value wall	0,18	W/m ² K
U-value roof	0,13	W/m ² K
U-value floor	0,15	W/m ² K
U-value window	0,9	W/m ² K
Thermal inertia	0,25	MJ/m ² K

4.2.2 Geographical location

The total annual heat supplied can be seen in Figure 4.21. The results show the same trends as in the result for BRF 1988 (Figure 4.3), a higher heating demand in the north in Sweden, compared to the south of Sweden. The share between the heat supplied to space heating and hot water can also be seen in Figure 4.3.

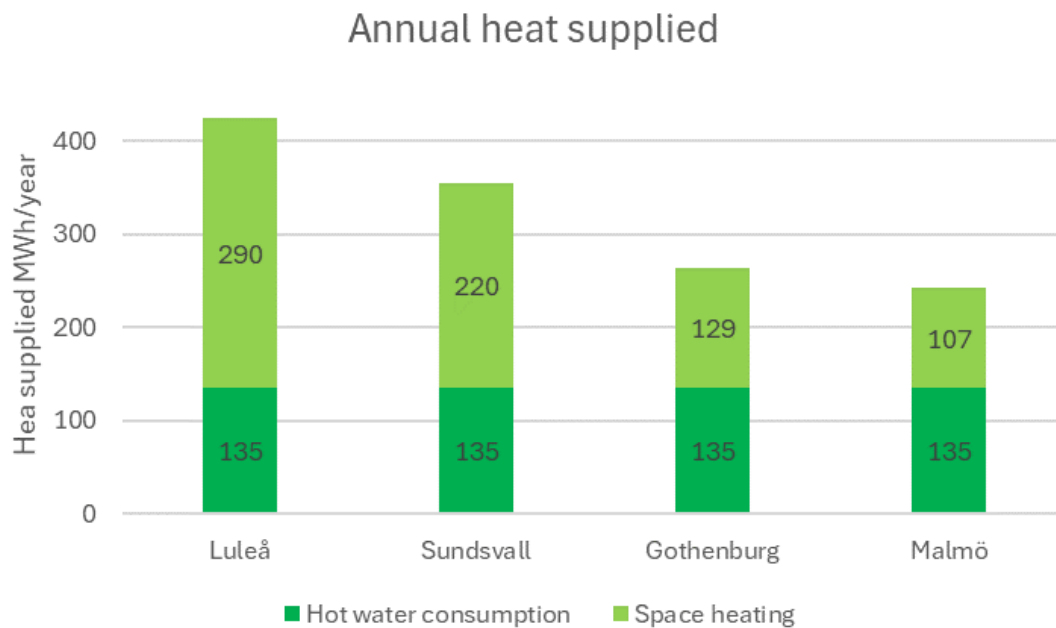


Figure 4.21: The annual heat supplied to BRF 2018 in different geographical locations

The heating profile throughout the year for BRF 2018 in different cities can be seen in Figure 4.22. The result shows similar patterns as the result for BRF 1988, that Luleå and Sundsvall have a longer heating period during the spring than the cities in the south of Sweden, which is due to the lower outdoor temperatures and smaller solar heat gains. The constant heat supplied, during the summer as well, represents the hot water consumption, which was set to constant throughout the year.

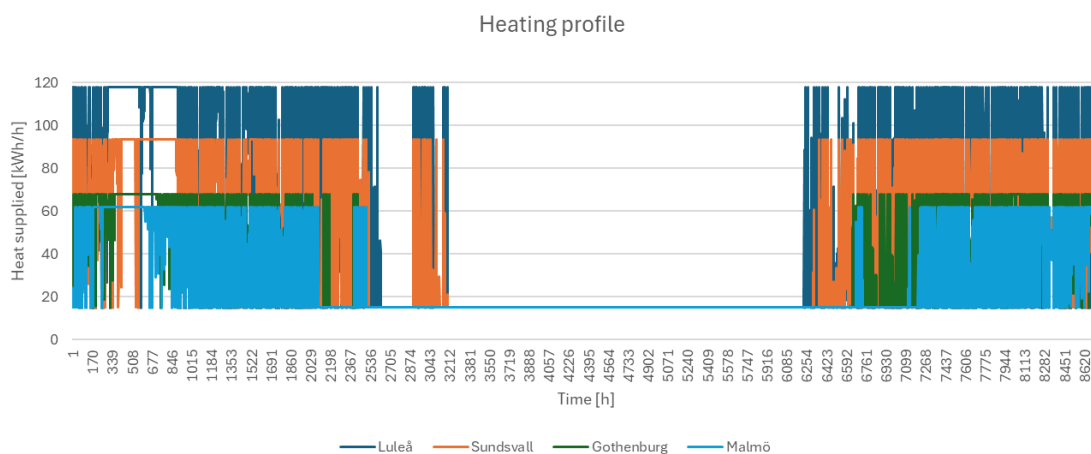


Figure 4.22: Heating profile of BRF 2018 in different geographical locations

The total annual cost can be seen in Figure 4.23 for the different cities, which shows the similar trends as the heat supplied in Figure 4.21.

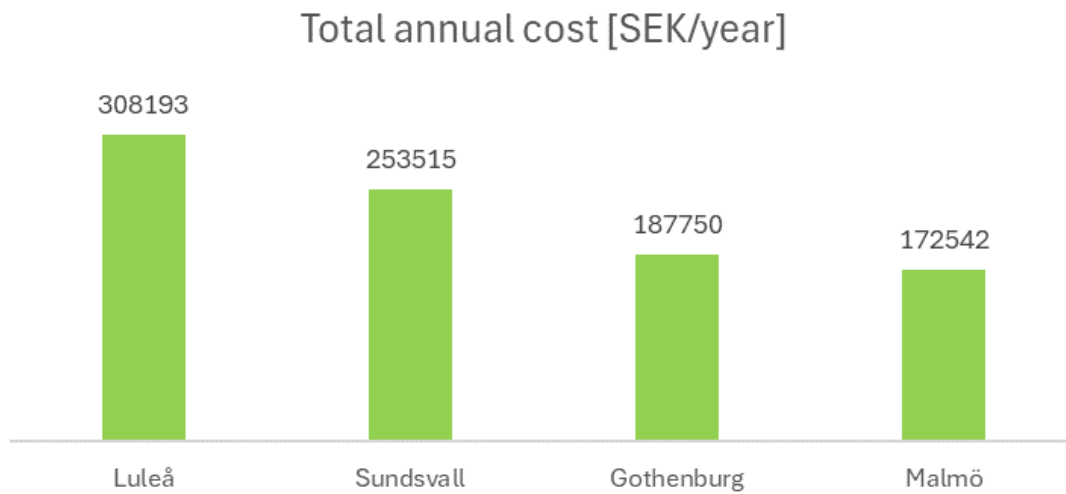


Figure 4.23: The total annual cost of BRF 2018 in different geographical locations

The total installed capacities follow the previous results and are shown in Figure 4.24, and the most cost-effective heating technology seems to be the HP in all of the investigated cities.

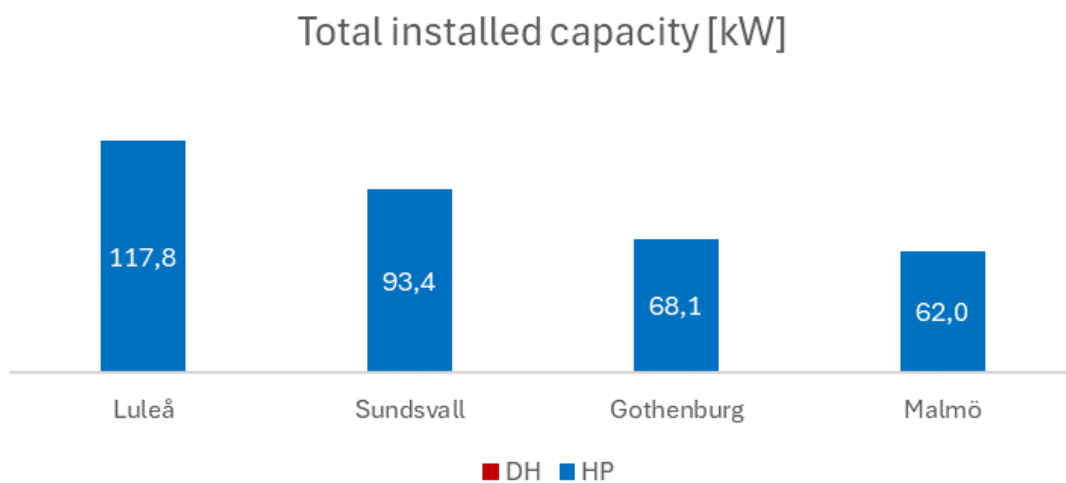


Figure 4.24: The total installed capacity of DH and HP of BRF 2018 in different geographical locations

When zooming in on one week in January, in Sundsvall, the correlation between the heat supplied and electricity price can be seen in Figure 4.25. The results show that the building uses the flexibility of the electricity price, to some extent. During more expensive electricity hours, the used heat decreases. But the results show that this stays for a few couple of hours before it needs to supply heat again.

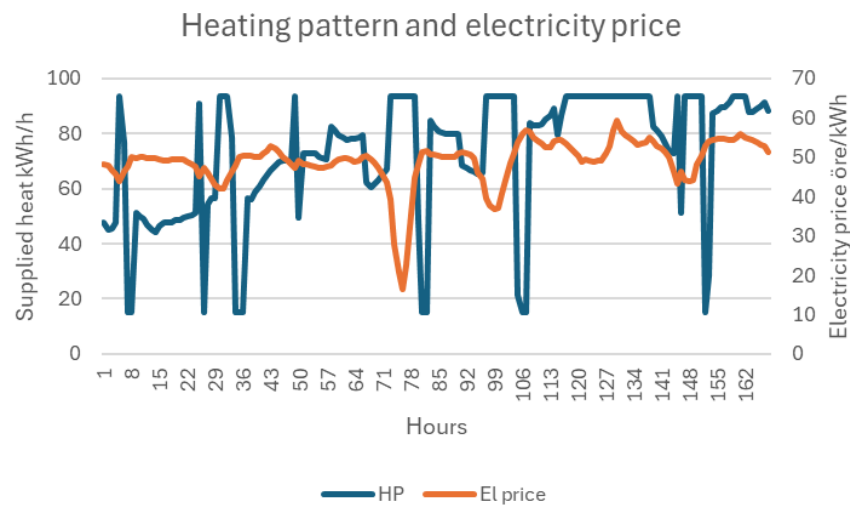


Figure 4.25: Heating pattern and electricity price in Sundsvall in BRF 2018

4.2.3 Indoor temperature range

Looking at the change of the total annual heat supplied, the same trends as for the BRF 1988 can be seen. A larger indoor temperature range will lead to a lower amount of heat supplied. The trends occur independently of geographical location and can be seen in Figure 4.26.

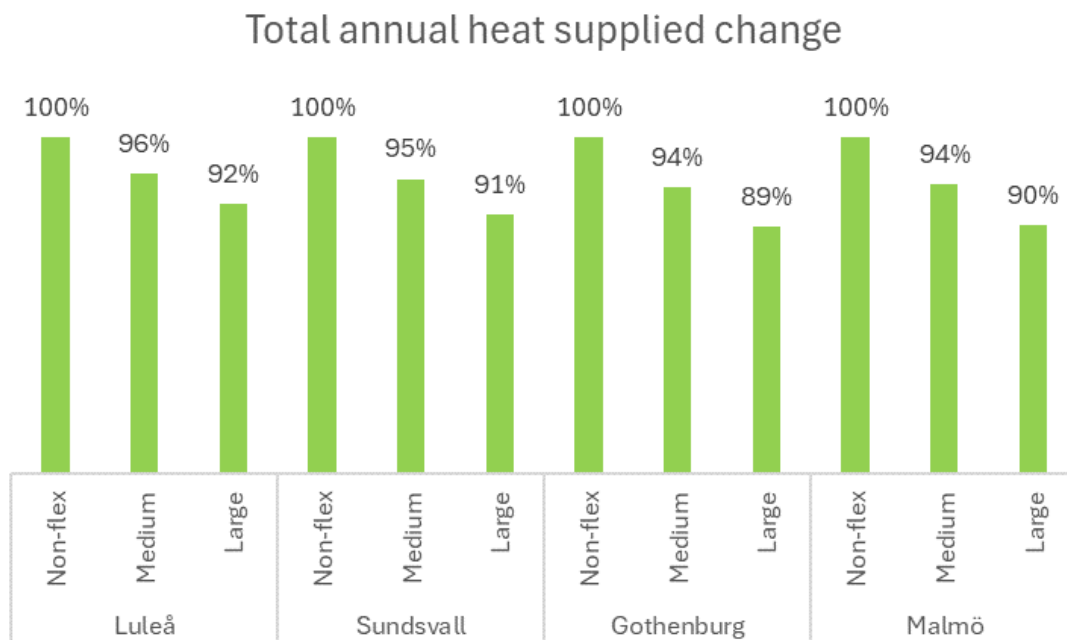


Figure 4.26: Total annual heat supplied difference of BRF 2018 for different temperature ranges

The hourly indoor temperature for BRF 2018 in Gothenburg can be seen in Fig-

ure 4.27. The constraints force the temperature to stay in the respective span for the three ranges. It can be seen that the temperatures for many hours of the year remain at their lower limit, with some hours of exceptions at which all ranges react similarly.

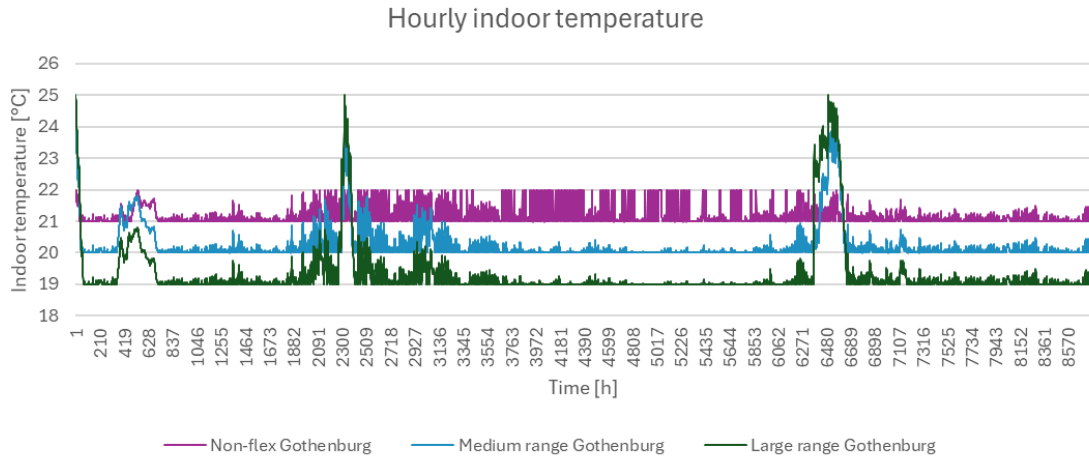


Figure 4.27: Hourly indoor temperature of BRF 2018 in Gothenburg for a non-flexible, small and large temperature range

The average of the indoor temperature in Gothenburg for all of the three ranges can be seen in Table 4.4.

Table 4.4: Average indoor temperature for a non-flexible, medium and large temperature range for BRF 2018

Non-flex	Medium	Large
21.2	20.2	19.3

When looking at the change of the total annual cost, a larger indoor temperature range will lead to lower total costs. As for the BRF 1988 case is the potential of saving similar for all four locations. The results can be seen in Figure 4.28. The reduction of total annual costs can be argued through the lower allowed indoor temperatures as the average indoor temperatures only are slightly higher.

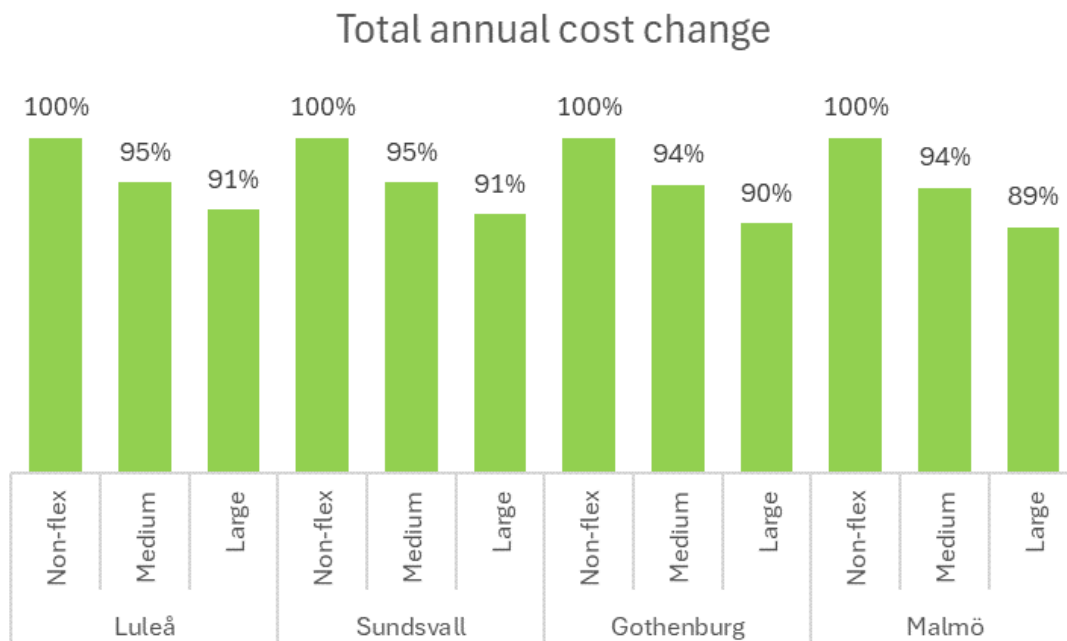


Figure 4.28: Total annual cost difference of BRF 2018 for different temperature ranges

The installed capacity decreases with a higher indoor temperature range, and can be seen in Figure 4.29. The geographical location makes no difference for the installed capacity.

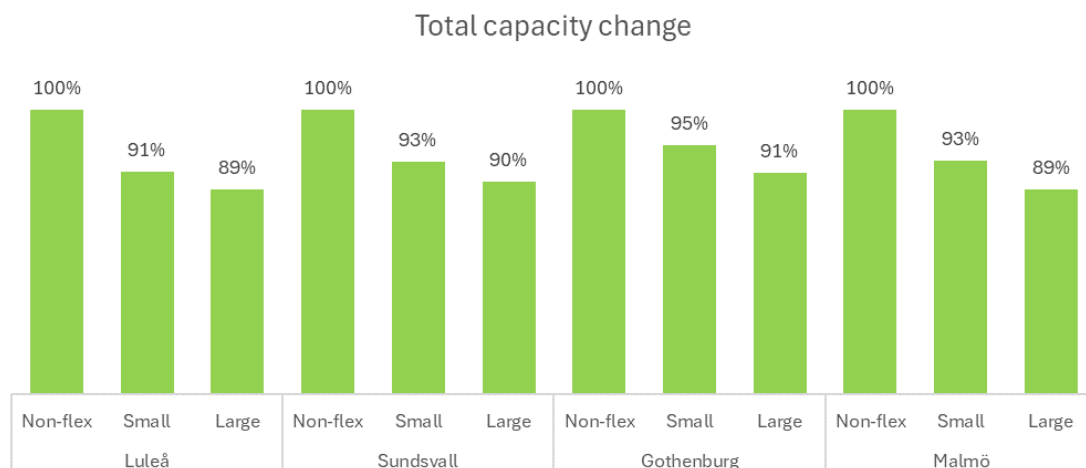


Figure 4.29: Total capacity change of BRF 2018 for different temperature ranges

When analyzing the share of installed capacity, a difference in location can be obtained. For Gothenburg and Malmö an installation of DH is not cost-efficient and therefore will only HP be implemented independently of the temperature range. For Luleå and Sundsvall is an installation of DH the cheaper option for a non-flexible indoor temperature range with 12% and 15% respectively of the total capacity, which

4. Results

correspond to the share of hot water demand. For the medium and large range, only a 100% coverage of HP is again more cost-efficient. All distributions can be seen in Figure 4.30.

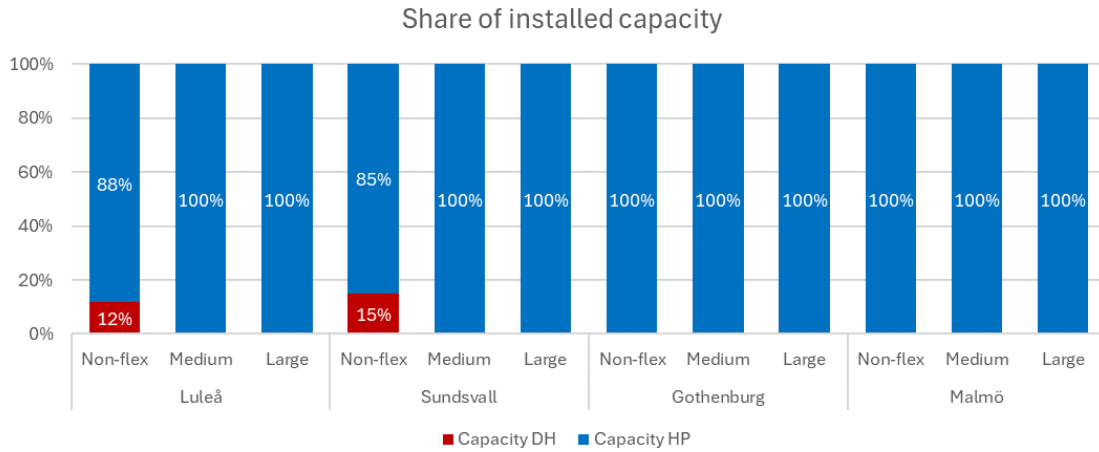


Figure 4.30: Share of installed capacity of BRF 2018 for different temperature ranges

The heating pattern of the two heating technologies in Luleå for the first 1000 h of the year can be seen in Figure 4.31. Similar results were obtained in Sundsvall. The results shows that the DH are being used during a few hours to fulfill the extended demand, which especially occur during the winter.

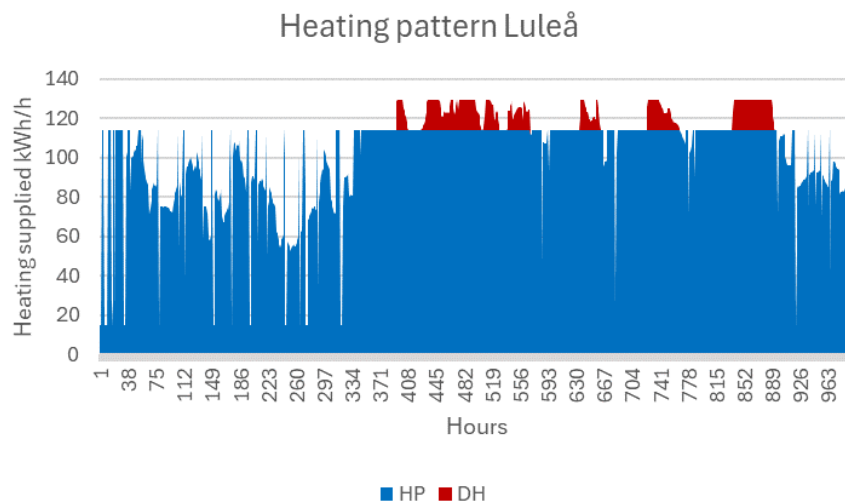


Figure 4.31: Heating pattern of Luleå in BRF 2018

4.2.4 District heating power price

The total annual cost change can be seen in Figure 4.32. As described in previous results, an increase of the DH power price doesn't affect the maximum scenario due

to the 100% share of HP for both base and maximum values. The minimum scenario seems to affect the different cities similarly.

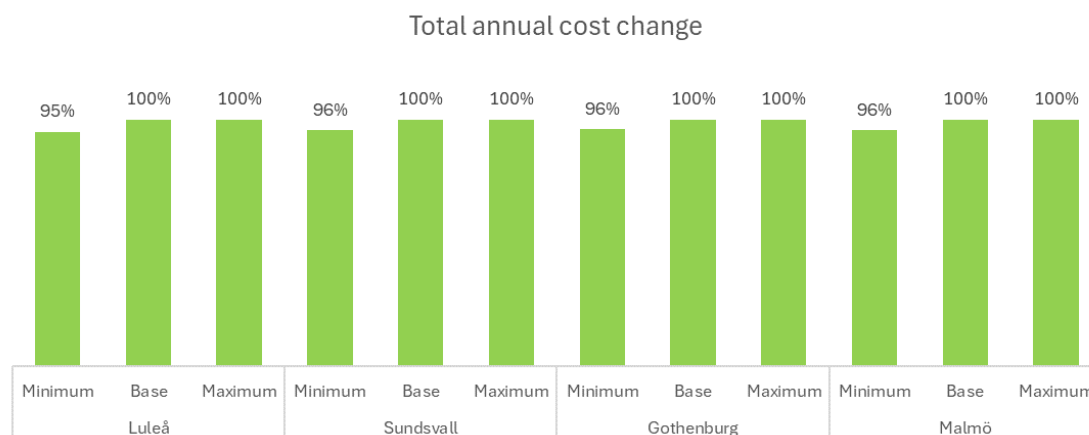


Figure 4.32: The total annual cost change of BRF 2018 for different DH power prices

The total capacity shows no changes between base and maximum DH power price as DH is not being implemented. A slight increase of total capacity can be obtained for the minimum case with larger capacities of added 2-3% compared to the base case. It can be seen that an increase of the DH power price doesn't affect the share of DH and HP compared to the base case (seen in Figure 4.33). A decrease of the DH power price affects the result by increasing the share of DH of the total installed capacity.

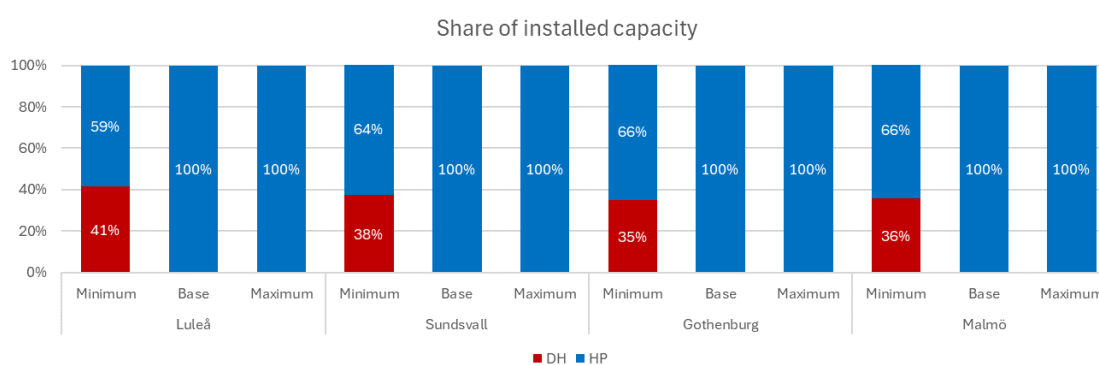


Figure 4.33: The share of installed capacity of BRF 2018 for different DH power prices

4.2.5 District heating energy price

Looking at the influence of the district heating energy price slight differences can be obtained when decreasing or increasing the energy price. The total annual cost was reduced by 1-2% for the minimum case in comparison to the base case. There was no difference of total cost obtained for the maximum DH energy price. The total

capacity showed no notable differences (total capacity change of under 1% for the minimum case) for the different DH energy prices. That no changes occur between the base and maximum case can be explained with the share of installed capacity. The share of the total installed capacity can be seen in Figure 4.34. Compared to when changing the DH effect price, the shares of the DH increase are smaller here (when changing the energy price). This could be described due to the low variable running cost of an HP. When decreasing the DH energy price, the DH gets more cost competitive to the HP than before, but less in comparison to changing the DH power price. It is worth noticing that in Gothenburg and Malmö the DH covers the hot water demand, while in Luleå and Sundsvall DH covers a larger share than just for the hot water. This will be discussed later.

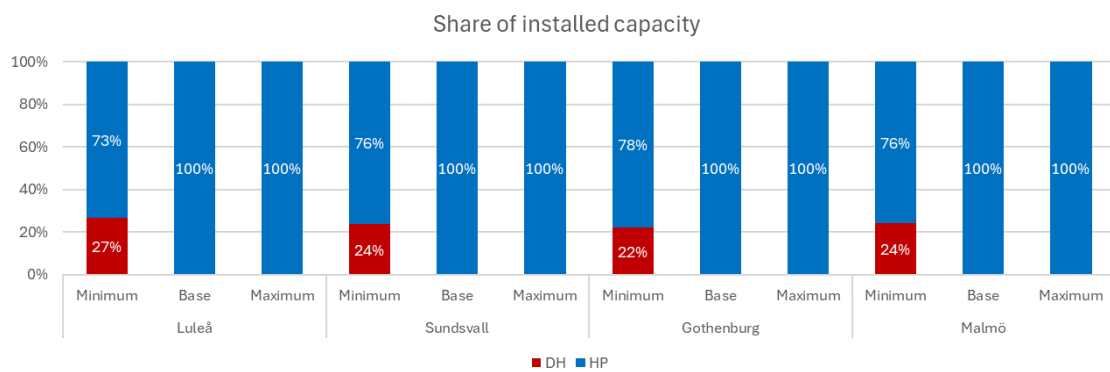


Figure 4.34: The share of installed capacity change of BRF 2018 for different DH energy prices

4.2.6 Electricity price

The influence of a varying electricity price for the BRF 2018 building will be assessed in this section. For the total annual costs it can be seen that a lower electricity grid tariff leads to lower total annual costs and a higher grid tariff produces a higher total cost, see Figure 4.35.

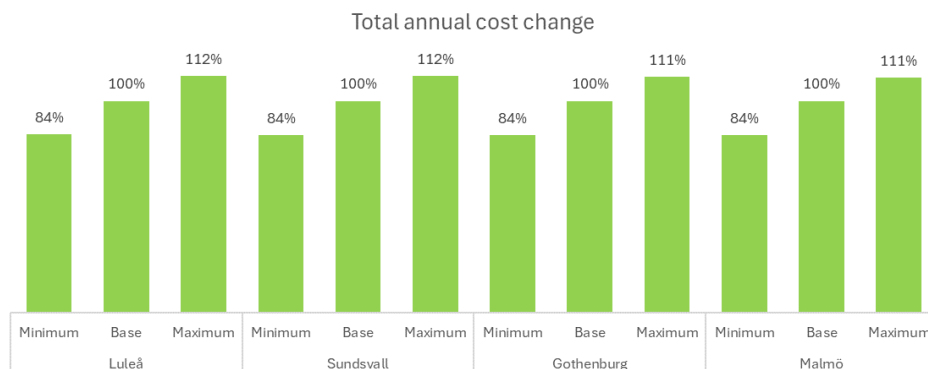


Figure 4.35: Total annual cost change for BRF 2018 for different electricity grid tariffs

A change in the total capacity can't be obtained for varying grid tariffs. The share of installed capacity for BRF 2018 shows similar trends for all four locations: With a maximum grid tariff, an installation of DH is cost-efficient and will be implemented with coverage between 17% in Sundsvall and 24% in Malmö. Likewise to when changing the DH energy price covers the DH in Gothenburg and Malmö the hot water demand while higher capacities for DH are implemented in Luleå and Sundsvall. For a minimum or base-level electricity grid tariff will an implementation of DH not be the most cost-effective option. Therefore, for those cases, only HP will be installed. All distributions can be seen in Figure 4.36.

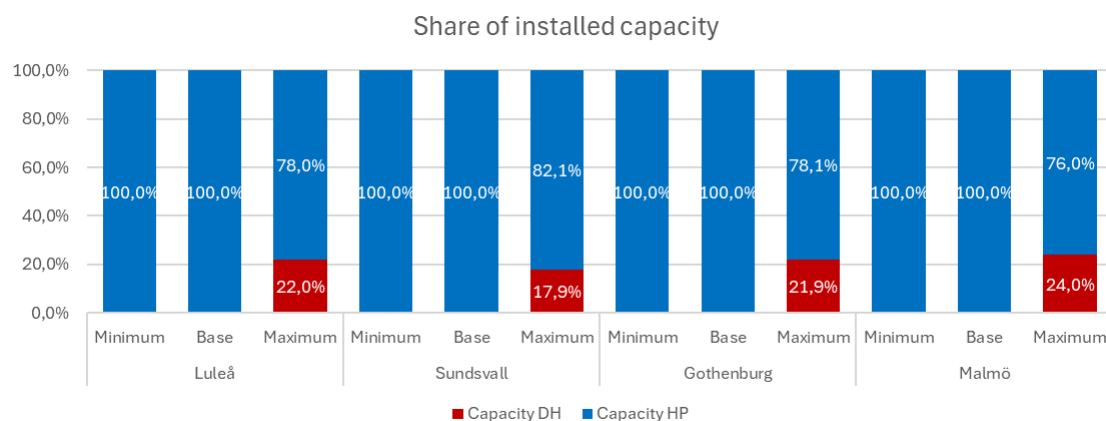


Figure 4.36: The share of installed capacity of DH and HP of BRF 2018 with different electricity grid tariffs

4.2.7 Heat pump lifetime

The results of decreasing the HP lifetime to 15 years instead of 20 years (which is used in the previous results for BRF 2018) can be seen in Figure 4.37. As mentioned in the BRF 1988 results, the annuity factor increases when decreasing the lifetime of the technology. This will have a larger effect on BRF 2018 due to a larger installed capacity (i.e. greater CAPEX).

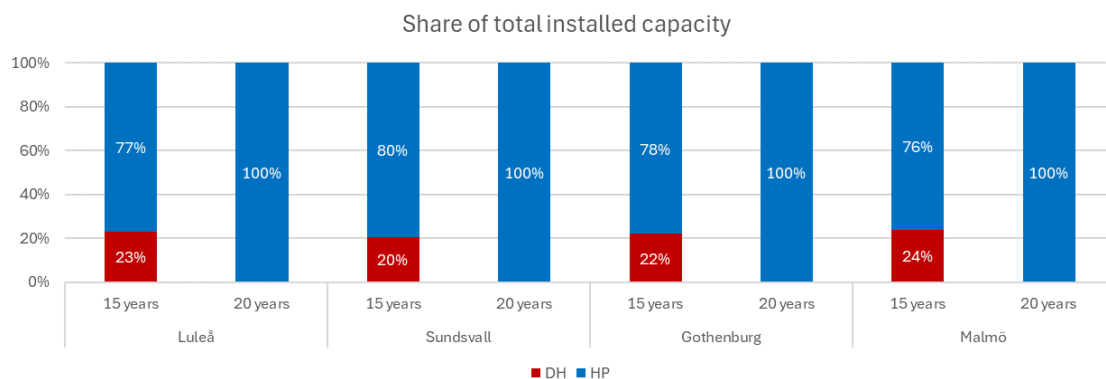


Figure 4.37: The share of the total installed capacity of DH and HP of BRF 2018 with different HP lifetime

By installing a 20-24% share of DH, the total cost only increases by 4%, see Figure 4.38.

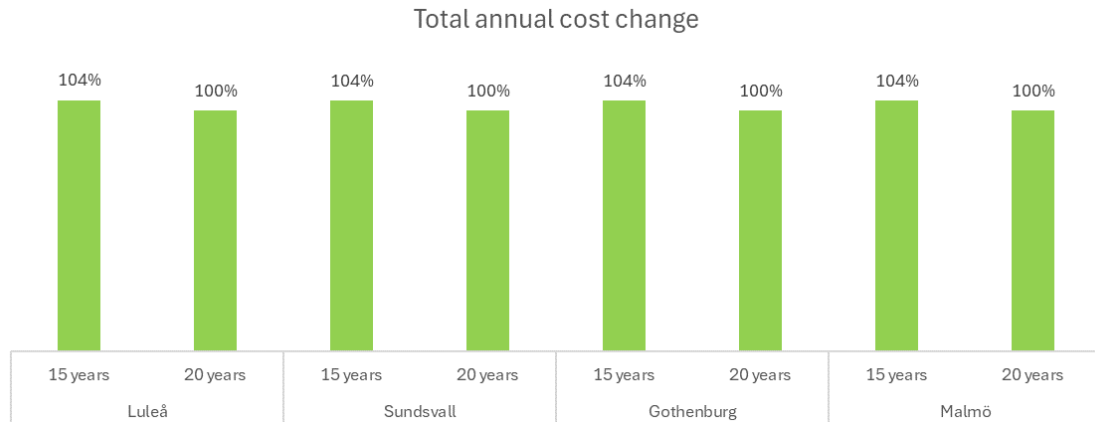


Figure 4.38: The share of the total installed capacity of DH and HP of BRF 2018 with different HP lifetime

4.3 Future 2050 case

This section contains the results of a hypothetical future scenario in 2050. Several things have been changed and described in section 3.6, such as the price structure of DH and electricity (larger share of power costs, both in DH and HP), investment costs, and operational costs. All results of the 2050 scenario contain a large temperature range.

4.3.1 BRF 1988

The change of installed capacity of the DH and HP between 2019 and 2050 can be seen in Figure 4.39. The larger share of DH in Sundsvall is due to the grid fee capacity ranges, described in Table 3.15. It is more cost-efficient to stay in the 0-36 kW range, than to invest in 59 kW in HP (36-72 kW range). The results observed in Gothenburg and Malmö are due to the consistent hot water heat demand of 7 kW/hour, as well as the constraint of either not installing DH or installing with a capacity of 7 kW and above (see Equation 3.18).

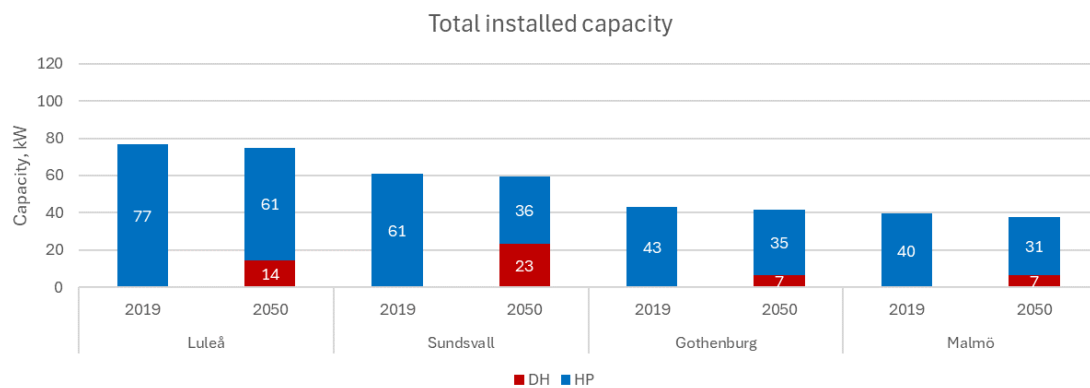


Figure 4.39: The share of installed capacity of DH and HP of BRF 1988 for 2019 and 2050

The load duration curve of 2019 (only using HP) and 2050 (using both HP and DH) can be seen in Figure 4.40. For 2050, it can be seen that the total installed capacity (75kW), which are the hours at which the full capacity of HP and DH are running, is used only 500 hours a year, meanwhile 2019 uses the total installed capacity 800 hours a year. When comparing full load hours between the years, 2019 has 3215 FLH and 2050 has 3237 FLH.

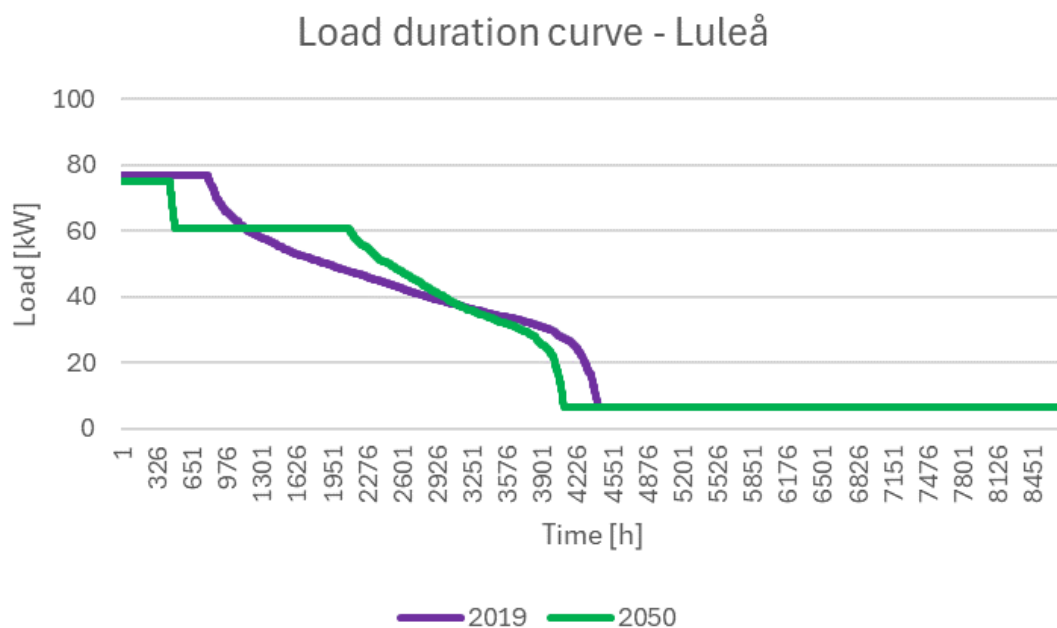


Figure 4.40: Comparison of 2019 and 2050 load duration curves, in BRF 1988

When comparing the heating patterns between 2019 and 2050, it can be seen that 2050 has a lower annual heating demand (due to a larger temperature range), but it can be seen, during a few hours a year, it uses the same capacity as 2019, which is where the DH is being used.

4. Results

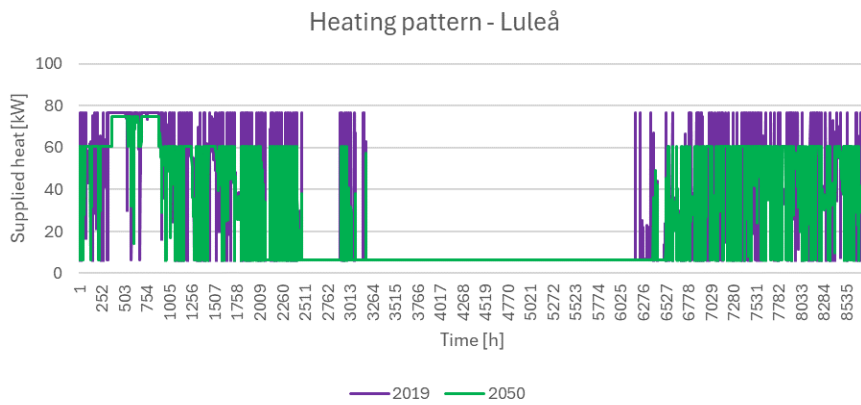


Figure 4.41: Comparison of 2019 and 2050 heating pattern, in BRF 1988

The power share of the running cost (which includes the DH power fixed, DH power variable and HP grid) increases in the 2050 scenario, which was the aim when constructing the price models.

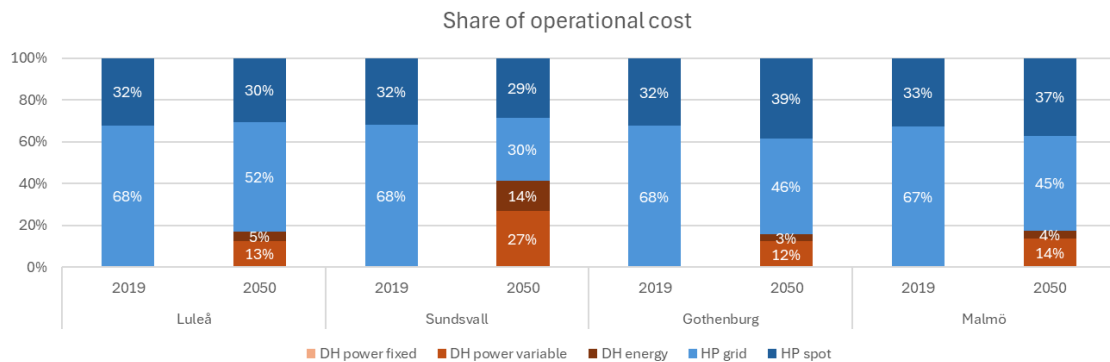


Figure 4.42: The share of the operational cost of DH and HP of BRF 1988 for 2019 and 2050

A comparison between the fixed, yearly costs and variable costs between 2019 and 2050 can be seen in Figure 4.43. The fixed DH cost includes the annual investment cost, annual maintenance costs and the DH power costs. The variable part includes the DH energy costs and energy tax. For the HP are the fixed costs the annual investment and maintenance costs while the variable costs are the grid and spot electricity price as well as the tax.

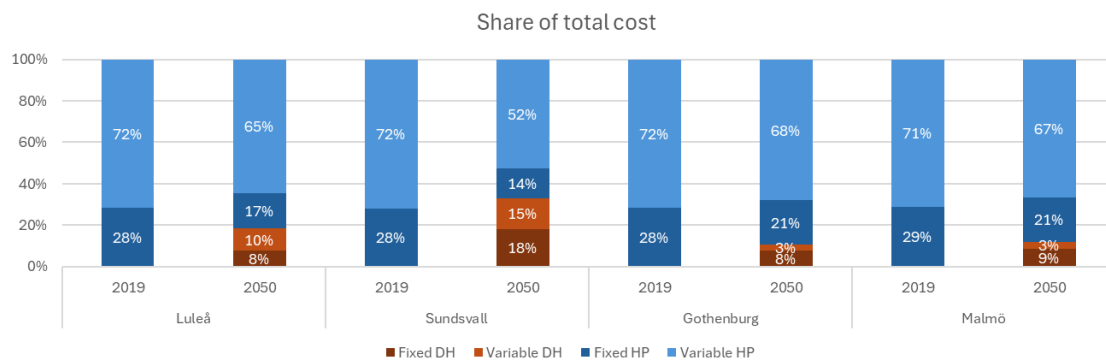


Figure 4.43: The share of the total cost between fixed and variable costs between HP and DH of BRF 1988

4.3.2 BRF 2018

The change of installed capacity of DH and HP between 2019 and 2050 can be seen in Figure 4.44. The results are similar to the results in BRF 1988. In Luleå and Sundsvall, the model maximizes the 34-68 kW HP capacity range, and in Malmö the 0-34 kW HP capacity range. The explanation behind the Gothenburg results is due to the constant hot water demand of 15kW/h.

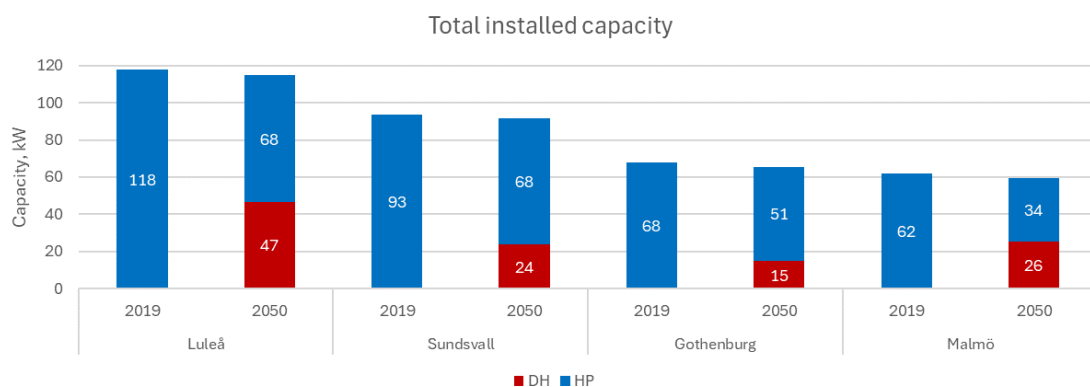


Figure 4.44: The share of installed capacity of DH and HP of BRF 2018 for 2019 and 2050

The load duration curve of 2019 and 2050 can be seen in Figure 4.45. When comparing the full load hours between the years, 2019 has 3606 FLH and 2050 has 3614 FLH.

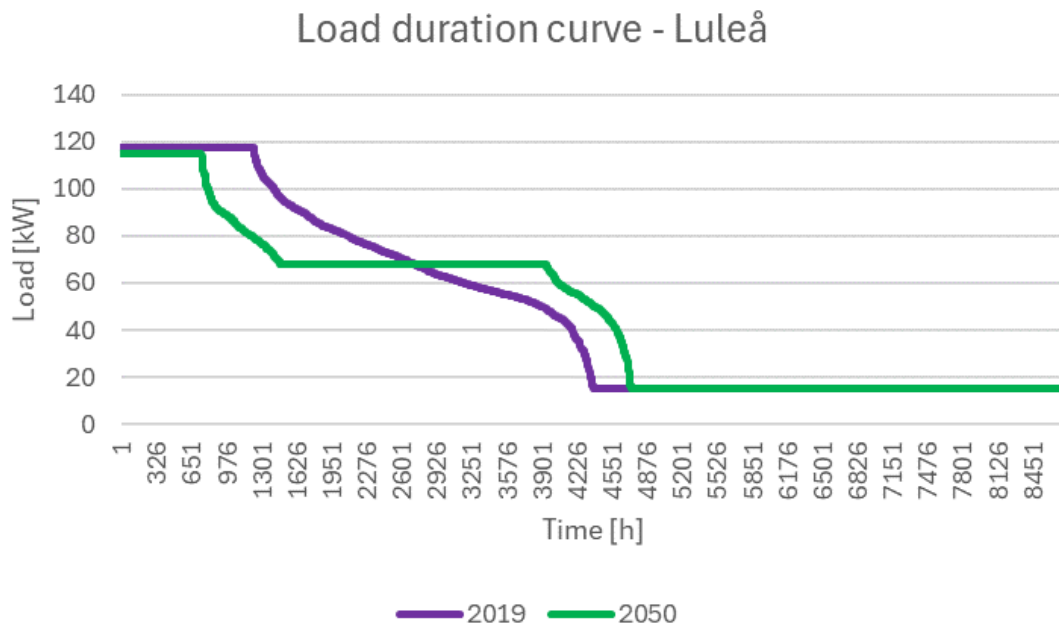


Figure 4.45: Comparison of 2019 and 2050 load duration curves, in BRF 1988

The heating pattern of 2019 and 2050 can be seen in Figure 4.46. Similar trends as in BRF 1988, in 2050 the capacity of the HP (68 kW) is frequently being used, and DH helps during cold outdoor hours (i.e. when more heating is needed).

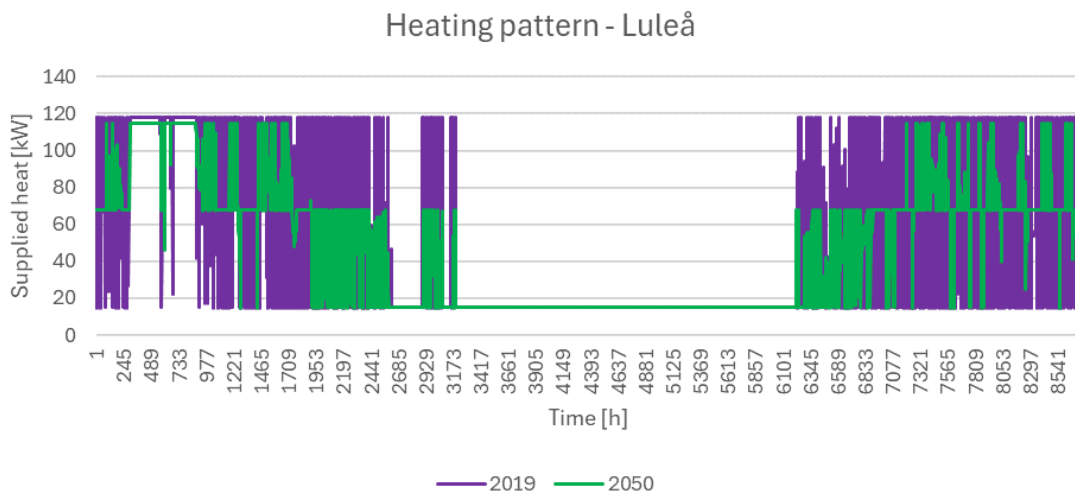


Figure 4.46: Comparison of 2019 and 2050 heating patterns, in BRF 2018

The distribution of the running costs are shown in Figure 4.47. The share of cost of power for DH and HP, that were dependent on the largest outtake, increases in the 2050 scenario (including the DH power fixed, DH power variable and HP grid), especially when installing a larger share of DH.

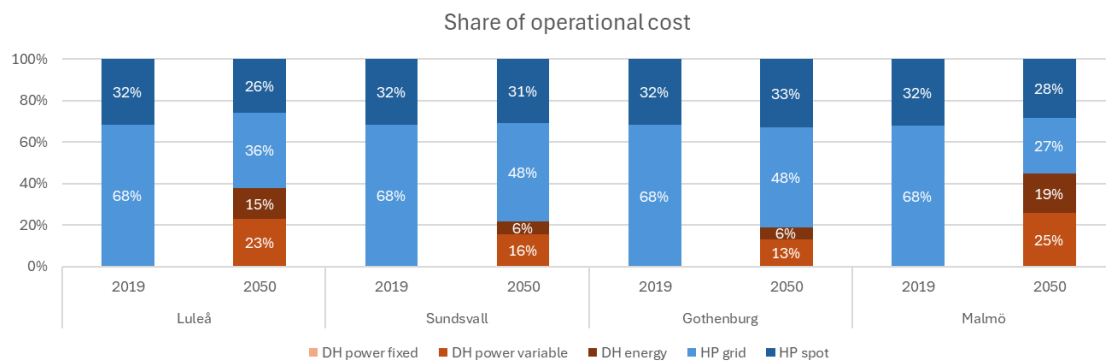


Figure 4.47: The share of the operational cost of DH and HP of BRF 2018 for 2019 and 2050

The share of the total cost can be seen in Figure 4.48. The variable part of the HP (spot and grid electricity costs, tax) and DH (DH energy costs and tax) cover larger shares than the fixed parts of HP (annual investment and maintenance costs) and DH (DH power, annual investment and maintenance costs).

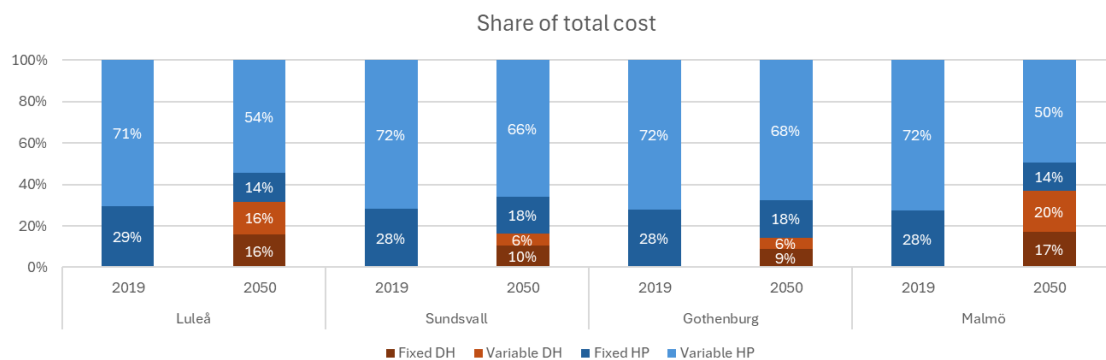


Figure 4.48: The share of the total cost between fixed and variable costs between HP and DH of BRF 2018

4.4 Summary of results

Geographical location change

This study wanted to see if there can be obtained trends in the installation of different heating technologies for different locations in Sweden. Luleå, Sundsvall, Gothenburg, and Malmö were chosen to represent the four electricity zones in Sweden, but also because of their contrary outdoor conditions.

The results showed that cities in the northern regions of Sweden have less solar and temperature heat gains compared to the southern regions. While cities in the south benefit from “free” energy in the form of heat from the outdoor conditions, must those in the north rely more heavily on purchased energy sources to meet their heating demand. The heat demands are closely connected to the installed heat

capacity, and it can be seen that the same house in different parts of Sweden had a varying installed capacity to cover the heat demand. The heating seasons also vary with the geographical location with a longer heating season in the north (Luleå and Sundsvall) and a shorter heating season in the south of Sweden (Gothenburg and Malmö), which can be explained by colder outdoor temperatures (which drives the transmission losses through the construction parts) and smaller amounts of heat gained by the sun. The HP seems to be the most cost-effective heating technology regardless of geographical location in Sweden.

The influence of the geographical location and seeing that similar trends occur for all four studied cities is partly because of the independence between city and heating respectively electricity price. Apart from the electricity spot price, which was according to the electricity zone the analyzed city is located in, the DH energy and power price, as well as the grid tariff on the electricity, were based on average or extreme values. This was the approach for this study to decouple from the local price setting. In reality, these assumptions can not be made, leading to problems but also potentials. How the local DH suppliers create their prices is highly individual and dependent on the local prerequisites. The aim of DH remains to use fuels or heat that would not have been used or wasted to supply to customers. If the industries or resources locally are sufficient leading to low costs for the DH companies and therefore low prices for customers, the cheapest heating possibility might remain DH, especially if grid tariffs in that region are high. On the other hand, with insufficient waste heat and fuels, the DH suppliers will have higher costs and the customers higher prices. In that scenario, the implementation of a HP might be the more efficient option. Therefore, is it difficult to apply trends that count for all buildings and regions in Sweden, as it at last is a very individual price and cost setting.

Indoor temperature range

The trends that were observed when increasing the indoor temperature range were decreased heating demand, decreasing total annual cost, and decreasing total installed capacity. The decreased heat demand is because the demand decreases when it's accepted to have a lower indoor temperature due to lowering the transmission losses through the building envelope (which is driven by the temperature difference between indoor and outdoor), but it also increases the possibility to use the "free" heat gained by the sun, since the envelope could store the heat. A lower installed capacity is due to a lower heat demand, especially during cold outdoor hours when the transmission losses are larger, the installed technology only needs to keep the indoor temperature at 19 °C for a large indoor temperature range than at 21 °C.

The results show that HPs seem to be the most cost-effective heat technology, especially when increasing the indoor temperature range. This study was limited to the two buildings examined and their respective heat demands in different locations. The installation of DH for BRF 2018 in Luleå and Sundsvall gets more cost competitive. This can be described by the heating pattern. Both cities have few hours (with in the non-flex temperature range) where a larger installed capacity is needed.

Due to a higher investment cost of the HP, it's more cost-competitive to install DH capacity to fulfill the demand during those hours than to have a larger HP capacity (see Figure 4.31). However, future studies could show better trends regarding the correlation between total heat demand, temperature range, and the installation of DH.

District heating price change

When changing the DH power price, it can be seen in both buildings and all the cities, that the total installed capacity remains constant, probably due to its already cost-optimized size according to the heat demand. A cheaper DH power cost results in a larger share of DH, which indicates that DH can be cost competitive with a lower power price compared with the HP.

The decrease of the DH energy price doesn't seem to affect the results on BRF 1988, but slightly affects BRF 2018, which could be due to a higher overall heat demand but also a higher constant heat demand (the hot water demand). With small changes in share of installed capacity giving small changes in total annual cost.

Electricity price change

The electricity grid price is an additional cost next to the spot price for the customer, so the grid tariff could be seen as an additional running cost, which depends on the usage. Similar results as when changing the DH energy price were obtained which could be due to the same category of costs (variable running costs). Since the major part of installed capacity is HP, the total annual cost is highly affected by the grid price adjustments, especially on BRF 2018 which has a larger heating demand to fulfill. Electricity grid tariffs' magnitude of price plays the largest role when assessing the total annual cost.

Heat pump lifetime change

When decreasing the HP lifetime, the results end up with increasing the share of DH of the total installed capacity. In most of the cities for both buildings it is cost efficient to install DH to cover the hot water demand. It's also important to point out that the model at least needs to cover the hot water demand when installing a technology, to make the results reasonable in the reality. This means that a lower share of DH could be more economically favorable, but the model is constrained to either 0 or above the hot water demand. The last thing noticed about the change of the HP lifetime, is that it has a greater impact on BRF 2018, in the northern cities (Luleå and Sundsvall), due to the larger total installed capacity.

5

Discussion

Comparison of buildings

A reason for conducting this study was to understand how building properties impact results. Choosing two different buildings of different eras was done to see the potential of flexible heating not only for buildings built now or in the future, but also if with the help of a retrofit solution older buildings could profit from it. As mentioned in previous paragraphs, a lot of the trends have been seen as similar in both of the buildings. The large differences between them are the heating demand, the hot water demand, and the thermal inertia. Regarding the thermal inertia and the building properties such as the thermal resistance in the different construction parts, it has been seen that BRF 1988 has a larger heating demand per heated area, which is assumed to be due to the larger losses in the construction parts and the more limited ability to keep the heat (coupled with the thermal inertia). The other way around, it takes more heat to heat up BRF 2018 due to the thermal inertia, but once the heat is stored in the building, BRF 2018 stores it for a longer time. This can be shown in the indoor temperature development of the two buildings (see Figure 4.9 and Figure 4.27) as the fluctuations in BRF 1988 are larger than for BRF 2018. Having the possibility to store heat for longer enables us to endure during high electricity prices. During low prices can the building then reheat to a comfortable indoor temperature. When using DH, a constant DH price that only differs monthly offers no possibility to take use of low prices. This is shown in Figure 4.7 and Figure 4.25, where BRF 2018 needs a longer time to heat up the building, but on the other hand also remains longer without heating, which is due to the greater thermal inertia (compared with BRF 1988). But it's also seen that when BRF 2018 critically needs heat to maintain the indoor temperature, it takes longer periods of heating compared with BRF 1988, which is also due to its thermal inertia.

Future studies should address the cost reduction of a larger indoor temperature range and flexible heating more. The differences of annual costs between differing temperature ranges were a combination of a larger allowed temperature span but mainly due to the lower temperature limit. The indoor temperature ranges could have had the same lower temperature limit but higher allowed upper limits to study the impact of the flexible heating made possible by the varying electricity spot prices more.

Uncertainties: Many assumptions of the buildings' behaviors

Basis of this study was the data provided by Riksbyggen that contained the drawings of the examined buildings BRF 1988 and BRF 2018 as well as their respective heat demand, indoor and outdoor temperature. With the help of these, a ther-

thermodynamic model was set up to create an hourly indoor temperature model. The focus of this study was to examine the cost optimizing solution for the buildings. However, it needs to be said that assumptions needed to be made that started with the modelling of the two buildings. As the focus was not on designing a mathematical building model that describes the parameters and behaviour of actual building to the exact values, the assessed properties and characteristics may differ from the actual. The determined heat demands, indoor temperatures and installed capacities are therefore not to be taken as real values but to show trends. With more data on the building properties and a larger focus on assessing the thermodynamic behavior of the buildings, values closer to the actual ones could have been the result.

Uncertainties: Is it reasonable to install both heating technologies?

A question asked when conducting this study was to find the most cost-efficient implementation of heating technologies, whether only DH, HP, or a combination. If a combination of both heating technologies is actually reasonable in an actual set up is questionable. After all, would two technologies lead to two separate capital and operational costs. HP's investment and fixed operational cost is greater than the one of DH, leading to the fact that it needs to have many full load hours per year to get back the investment. DH will then only be operated during cold outdoor temperatures during which the HP can't cover the total heat demand, a system that is detrimental to the DH suppliers. Lygnerud et al. [53] have conducted a study simulating and testing business models combining HPs and DH in buildings to generate cost and emission savings. Their results showed cost (maximum 33%) and emissions (maximum 75%) savings, however, with multiple challenges facing the implementation of widespread HPs for buildings. Swedish DH companies tend to see household HPs as competition to their customers' heat supply and something to avoid. Furthermore, does the low level of maturity in service provision for HPs face a challenge. However, the study by Lygnerud et al. did not consider investment costs for DH and HP installations, which could affect the system costs and benefits. Furthermore, is it a financial burden on the customer that influences the cost savings. It will therefore be interesting to see how the investment and running cost of both DH and HP will develop.

Uncertainties: Indoor temp range realistic?

Another aspect that was shown during this study was that a larger indoor temperature range can lead to lower annual heat supplied (see Figure 4.8 and Figure 4.26) and lower total costs (see Figure 4.10 and Figure 4.28) which is favorable for the residents. If the residents were available or interested to allow a larger indoor temperature range is questionable though. Aqilah et al. [54] summarized different indoor temperature ranges that had been studied and tested. A study by Han et al. [55] showed that 90% of the residents that were part of their study accepted a span of 22-25,9 °C. A study by Gong et al. [56] identified comfortable indoor temperature ranges of 12,2-20,1 °C for winter and 20,9-27,5 °C for summer. Yu et al. [57] presented in their work an acceptable span of 10,2-22,9 °C. Rijal et al. [58] came to the conclusion that a mean indoor temperature of 19,8 °C during winter and 25,6 °C during summer got accepted by the residents. It needs to be said that in these

studies the economical background of the residents was not regarded, which could lead to the low allowed indoor temperatures that may not stem from comfort but from financial reasons. However, whether the residents accept a larger temperature range is highly individual. If aiming to make a reasonable impact on the electricity and energy system to take the load of it, a large percentage of the population needs to enable a larger indoor temperature range.

Prices

A further uncertainty of this study are the prices. The installation costs for HPs and DH systems were provided by the Danish Energy Agency. In reality these costs can vary depending on location, provider and other aspects. Furthermore, the Danish Energy Agency had to rely on assumptions when predicting the prices for 2050. The electricity grid tariff presents another cost uncertainty, as this study was dependent on using the values provided by the Nils Holgersson report. Due to the lack of information for both BRF 1988 and BRF 2018 regarding electricity grid trading contracts were the simplifications necessary.

The assumptions taken were all argued for, but they have lead to a contrasting picture between the model and the actual installations. As described before covers DH the largest part (90%) of heat demand for multi-family dwellings. However, our model indicates that HPs are the more cost efficient heating technology. As described before can the electricity grid tariffs been a reason for that. A further reason could have been that the CAPEX values of both heating technologies obtained by the Danish energy agency were converted to euro per installed capacity rather than per unit (which was 160 kW). The discrepancy between in the reality widely installed DH and our HP solutions could be due to multiple reasons, and the used prices could be one, but these price assumptions needed to be made.

Model design

It also needs to be said that all models and simulations were based on perfect foresight. The weather, electricity, and DH price data of 2019 was implemented leading to the system knowing beforehand at which hours there was a need of heat, when there was availability to cool the buildings and at which prices to do that. In reality this predictability is only partially possible. It is also advisable to install larger capacities of a heating technology to withstand low outdoor temperatures which exceed the optimized capacities of the GAMS model.

System perspective

As this study has shown, it can play a large role whether DH or HP is installed and implemented. A large difference between the two technologies is the lower investment but higher running costs for DH in contrast to the higher investment but lower running cost of the HP. What makes the comparison even more interesting though is the more dynamic price development of both technologies. It has been shown that the DH energy price is dependent on the month, while the electricity prices vary hourly and are a result of the trade platform Nord Pool. The low electricity prices emerge out of the combination that there is a low demand during a

certain hour and/or a high electricity production. Installing an HP, enlarge the indoor temperature range and take use of the low electricity prices while avoiding the high price periods can save costs. However, what would be the consequences if all households in Sweden would shift to those techniques? If all buildings shifted their heat production to low electricity price periods, a new load in the electricity system would appear, leading to an increase of electricity price. It is necessary to say that this does not occur if single households shift their load but a large amount of buildings. In that case the household owners could profit less of using an HP. However, this can be avoided with an aggregator bidding in the electricity demand to the market.

Looking from an electricity system perspective, the large implementation of HPs can also offer opportunities. It is predictable that the total demand of electricity will increase, hence the energy transition. The Swedish grid operator Svenska Kraftnät predicts in their future market analysis an electricity consumption of 209 TWh in their most conservative prediction and 365 TWh for the most optimistic prediction compared to the current 130 TWh [59]. It requires large investments in the electrical infrastructure to secure the functionality of all processes in the future system. But another challenge of the future system is the ability to balance loads. As described before, wind power will add a large share of the future electricity production, but its intermittency can cause problems. Flexible heating can be one option to balance the electricity system, as not heating a building for a few hours often can be an uncomplicated solution to lower the total load on the system in comparison to other processes. Here again though, only a large enough load in terms of many buildings could make a difference.

Not only the development of the electricity system will be interesting to follow in the future, but also the development of the DH system and market. Currently, the Swedish DH system relies heavily on waste and biomass. With the aim to reduce the waste production totally and with competing uses of biomass in the future, as feedstock for the production of chemicals, transportation fuels and plastics, costs ultimately will increase for the DH suppliers that will have to be covered by the customers [6]. A different implementation to the DH system are large-sized HPs. These could likewise to household HPs take use of temporary low-cost electricity and produce heat that is being directly distributed or stored. The competitive conditions between CHP plants and large HPs on the DH market will depend on the price of electricity and the national electricity tax [60]. These uncertainties regarding the Swedish DH system makes it difficult to predict future potentials whether to use an HP or DH for household heating.

2050 future scenario

The overall trend seen from the 2050 future case (section 4.3), when implementing an installed capacity grid-based fee (HP) and an increased DH power fee, was an increase of installed DH. But it's worth mentioning that a large difference between 2019 and 2050 was the "spot DH price". As mentioned in the method, the DH 2050 price was the marginal price of heat from DH, which fluctuates on an hourly basis

rather than a monthly basis (as was the case in 2019). So if installing in DH or HP in 2050, the results of the heating pattern will be flexible regardless.

The heating patterns of 2019 and 2050 seem to differ, this could be described by the increased indoor temperature range in 2050, which decreases the heating demand, and it will therefore be more cost-effective to use the HP all of the time and then use the DH as a peak producer. As mentioned before, has the 2019 DH and 2050 DH different energy prices, whereas the 2050 DH looks similar to the electricity with a "spot price". The HP is a huge investment compared with the DH from a customer's perspective and therefore needs to run at full capacity for many hours of the year, to pay back the investment.

The final point worth mentioning is the uncertainties regarding the installed capacity grid-based fee (HP). Likewise, to the DH power price, which is based on the largest outtake of heat, the capacity grid-based fee was based on the largest outtake of electricity. This price is divided into a fixed and variable part that depends on the size of the outtake and the corresponding range (see Table 3.15). To avoid the larger fixed variable, it is cost-efficient to install the upper limit of a lower capacity range, while covering the remaining capacity with the other heat technology. However, with the assumptions described it resulted in DH being more cost-competitive in the future. With the Swedish DH system heavily relying on biomass and the increasing demand of it leading to higher prices it is questionable how the composition of heating will look like in the future. A study by Åberg et al.[61] concluded that a replacement of all DH by ground source HPs is unrealistic due to the geographical area of the energy wells. Our assumptions regarding larger power shares leading to larger fixed, yearly cost was based on trends described earlier. To form predictions of how buildings will be heated in 2050 is difficult and dependent of political and societal decisions.

Whether is it reasonable to use DH as a peak production unit in reality is highly questionable. After all, represents a plant that is producing heat and/or electricity a large investment that is supposed to have many running hours throughout the year. Peak-producing technologies usually offer low capital costs but high running costs [62]. As our model only covers the customer side, where a HP has a large capital and low operational cost and DH vice versa, these trends can be seen. But from a system's perspective, there are different technologies that cover the peak demand such as electric boilers.

The heating systems and market in 2050 may also face other challenges that have not been looked at during this study. An assumption made was that the building properties would be unchanged between 2019 and 2050, but in reality, the buildings of 2050 have fewer losses due to their higher efficiencies. A warmer climate and the corresponding lower heating demand could also influence the heating pattern of the residents. On the other hand, could higher temperatures also lead to cooling demands.

6

Conclusions

The main conclusions of this master thesis about “The potential of flexible heating for multi-family houses in Sweden” were following:

- Heat pumps are the most favorable choice for implementing flexible heating, primarily due to their lower operational costs. Regardless of the higher CAPEX required for heat pump installations, their efficiency, and cost-effectiveness in the long run make them the preferred option.
- The heat pump appears to be the most favorable choice in all cities examined in the study.
- By allowing wider temperature fluctuations within buildings, residents can benefit from reduced energy consumption, thereby achieving significant cost savings over time (up to 14% annually).
- A combination of district heating and heat pump seems to be favorable under conditions of lower DH power price, decreased DH energy price, increased electricity grid price or a variable DH price (similar to the electricity spot price)
- This study includes several uncertainties such as assumptions about building behaviors, the feasibility of installing a combination of DH and HP and the acceptance of larger indoor temperature ranges. Future research should address these uncertainties to provide more robust insights into optimal heating results.

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