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Demand flexibility potential from heat pumps in multi-family residential buildings

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Abstract

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The Swedish energy power system is in the middle of a paradigm shift where the increased share of intermittent energy sources place higher demand on the ability to regulate and balance the generation and consumption of electricity. Demand flexibility, which means that consumers can adjust their energy consumption, is a promising solution to manage the imbalance in the power system. Electric heat pumps in residential buildings are recognized to have potential to serve as a flexible load.

In this thesis, an aggregated multi-family residential building model is developed to generate heat load profiles for a larger number of buildings which facilitate an assessment of the heat pump flexibility. The flexibility assessment is performed for a local distribution grid area with 174 buildings and an electricity price region in Sweden with 10 146 buildings with heat pumps. The flexibility assessment analyses the heat pump load deviation between a base load case and a case where the heat pumps receive an off-signal. The assessment takes into consideration seven flexibility parameters and is conducted for ambient temperatures between -20°C and 15°C. The thermal inertia of multi-family residential buildings facilitates a load shift with a duration of 4.4 to 9.8 hours depending on the ambient temperature. The maximal average power reduction for one hour of 10 MW in a distribution grid and 169 MW in an electricity price region illustrates the potential of using heat pumps as a demand flexibility solution in the electricity grid.

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Populärvetenskaplig sammanfattning

Andelen förnybara energikällor har ökad stadigt i Europa de senaste åren. Europeiska kommissionens direktiv om att 20% av energibehovet år 2020 ska vara producerat av förnybara energikällor och Sveriges regerings målsättning om ett hållbart och resurseffektivt energisystem med noll nettoutsläpp av växthusgaser till 2050 pekar på att andelen förnybara energikällor kommer att fortsätta öka. Ökningen av förnybara energikällor har inneburit en ökning av väderberoende energikällor såsom solenergi och vindkraft vilket betyder att det har blivit svårare att styra och predikera energiproduktionen. Detta har medfört att det har blivit svårare att upprätthålla balansen mellan produktion och konsumtion på elnätet och behovet av flexibilitet har ökat. Flexibilitet i energisystemet syftar till förmågan att anpassa produktionen eller konsumtionen av el från elnätet. Flexibilitetsanpassningar som sker på konsumentsidan av elsystemet kallas förbrukningsflexibilitet eller *demand response.* Värmepumpar i bostäder har identifierats som en möjlig förbrukningsflexibel last då det är möjligt att stänga av eller på värmepumpar under en viss tid utan att inomhustemperaturen förändras märkbart tack vare byggnadernas isolering. Bostads- och servicesektor står för cirka 40% av Sveriges energibehov och 51% av den energin används till uppvärmning. Detta innebär att det finns en stor potentiell förbrukningsflexibilitet i att stänga av ett antal värmepumpar under tidsperioder när elnäten är under hög belastning. Syftet med detta examensarbete är att utvärdera potentialen för förbrukningsflexibilitet som uppkommer av att stänga av ett stort antal värmepumpar i flerbostadshus samtidigt. För att uppnå detta, har en modell i programmeringsspråket Matlab utvecklats och använts för att beräkna förbrukningsflexibiliteten. Simuleringar för att generera lastprofiler för ett aggregerat nummer av värmepumpar i ett nätområde med 174 flerbostadshus med värmepumpar och ett elområde (14 län ingår i elområdet) med 10 146 flerbostadshus med värmepumpar har genomförts. Arbetet har utförts i samarbete med Vattenfall AB.

I detta examensarbete har värmepumpens förbrukningsflexibilitet betraktats som en lastförändring mellan hur värmepumpar drivs i vanliga fall och när de har mottagit en off-signal och stängts av vid en viss tidpunkt i simuleringen. Analysen av förbrukningsflexibiliteten från värmepumpar är en komplex process där sju olika parametrar tas i beaktning. De mest framträdande resultaten visar att 174 flerbostadshus med värmepumpar i ett nätområde kan frigöra 10MW under en timme och 10 146 flerbostadshus med värmepumpar i ett elområde kan frigöra 169 MW under en timme. Simuleringarna visar även att det finns en risk för att det kan skapas större effekttoppar efter att värmepumparna har mottagit en off-signal och varit avstängda. Det är därmed viktigt att ha detta i åtanke vid användandet av värmepumpar som en förbrukningsflexibel last och vidare studier skulle kunna undersöka möjligheten att minimera effekttopparna som orsakats av en synkronisering av värmepumparna vid en off-signal.

Acknowledgement and foreword

This master thesis is part of a degree Master's Programme in Sociotechnical System Engineering at Uppsala University. The thesis has been conducted at the Reseach and Development department and part of the Data Analytics and ICT Solutions team at Vattenfall AB. I would like to thank all employees at Vattenfall that I have been in contact with and especially my mentors, Anders Lindgren, Nader Padban and Mats Hagelberg for their support and feedback throughout the project. I would also like to thank my subject reader Magnus Åberg at Uppsala University for his comments and suggestions.

Claes Sandels, from Research Institute of Sweden (RISE) have been an extra resource throughout the project, thank you for your advise and help with model developments, possibilities and restrictions. The thesis has been conducted in close collaboration with Rebecca Grill, an other master thesis student at Vattenfall AB. The purpose with Grills's thesis was to investigate the market oppertunities for heat pump flexibility for a balance responsibility party and a distribution grid operator.

Sabina Oehme

Uppsala, May 2018

List of abbreviations

ASHP	Air Source Heat Pump
BRP	Balance Responsibility Party
DHW	Domestic Hot Water
DR	Demand Response
DSM	Demand Side Management
Ei	Energimarknadsinspektionen (Swedish Energy Markets Inspectorate)
GSHP	Ground Source Heat Pump
HP	Heat pump
HVAC	Heating, Ventilation and Air Conditioning
MFRB	Multi-Family Residential Building
SvK	Svenska Kraftnät

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1. Introduction

The European union renewable energy directive states that by 2020 should 20% of the energy demand be fulfilled by renewable energy sources. The share of renewable energy has increased steadily in Europe and Sweden the last couple of years and is estimated to continue to do so because of the Swedish parliament vision of a sustainable and resource efficient energy supply with no greenhouse gases emissions (European commission, 2018). The increase of renewable energy has also meant an increase of intermittent energy sources, such as solar and wind energy, in the electricity production which puts a higher pressure on the ability to be flexible in the generation and demand of electricity. At the same time as the share of weather depended energy sources increase in the electricity production an increase in electricity driven vehicles are to be expected. The Swedish government vision of a sustainable energy supply includes a vehicle fleet that is independent of fossil fuels by 2030 (European commission, 2018). An electrification of the vehicle fleet will increase the demand for power in urban regions that might already experience problems with grid congestions and grid capacity.

One promising solutions for the balancing of consumption and production is demand flexibility. Demand flexibility in a power system refers to the capacity to adjust energy consumption in a system (Fisher et al., 2017). Demand flexibility can therefore facilitate an increased implementation of renewable energy sources as it can adapt the consumption of electricity based on the production from the intermittent energy sources. The demand flexibility could be utilized through a Demand Response (DR) solution that means that consumers can shift or reduce their electricity usage during peak periods in response to external signals e.g. electricity price rates. A demand response solution can therefore be used to balance the supply and demand of electricity without increasing the power.

The household and the service sector stands for approximate 40% of the Swedish energy demand and 53% of the energy is used for heating. The large energy demand for heating consequently leads to a potential for demand response solutions. Heat Pumps (HP) have been recognized to have potential to serve as a demand response solution in the electricity grid. The thermal inertia of the building envelope can be utilized in a demand response solution together with heat pumps without effecting the resident indoor temperature comfort as the indoor temperature will decrease slowly after the HPs are turned off. Several studies (Fisher et al., 2017; Baeten et al., 2017; Hong et al., 2012) have focused on the HP flexibility potential in detached houses where 51% of the heat demand is covered by electricity (Energimyndigheten, the Swedish Energy Agency, 2017a). This thesis aims to investigate the potential to utilize thermal inertia together with heat pumps in Multi-Family Residential Buildings (MFRB). Approximate 3% of the heat demand in MFRB are covered by electricity which is lower than in detached houses but on an aggregated level, the number of MFRB in Sweden and the capacity of the HPs makes it an interesting DR solution to investigate.

1.1 Aim and research question

The aim of this thesis is to analyze the aggregated potential of using heat pumps in MFRBs as a demand response solution in the electric grid. A model is developed in Matlab to simulate a load profile of heat pumps in MFRBs and to assess the flexibility of HPs in a large building stock. Sandels's (2018) simulation model, that generates electricity consumption profiles for Swedish residents living in multi-dwelling houses with electric heating systems, will serve as a base when developing the aggregated MFRB model that generates at aggregated HP load profile. The aggregated potential of flexibility of heat pumps, arising from the thermal inertia of the building envelope, will be calculated for a distribution grid area and an electricity price region area.

The following research question will be answered:

- What can end users provide in terms of demand flexibility from heat pumps utilizing the thermal inertia of multi-family residential buildings?

2. Background

2.1 Collaborations and context of the thesis

The thesis has been conducted in close collaboration with Rebecca Grill, an other master thesis student at Vattenfalll AB, Research and development department. The purpose with Grills's thesis "Market potential for using demand response from heat pumps in multi-family buiildings" is to investigate the market oppertunities of HP flexibility for a BRP and a distribution grid operator and have recieved of the results from this thesis to do so. The collaboration with Grill has facilitated an continuesly dialog between the authors where Grill's analysis of the demand from the BRP and grid operators have been translated to flexibility parameters in this thesis. Both thesis is part of a project, *Grid flexible heat pumps*, financed by Energyimyndigheten and a collaboration between NODA, NIBE, Research Institute of Sweden and Vattenfall AB. A result from an earlier stage of the project is Sandels's multi-dwelling building load profile model and which layed the foundation for the development of the aggregated MFRB model in this thesis.

2.2 Heat pumps

In 2016, 32 400 HPs were in operation in MFRB in Sweden, 49% of these were ground source heat pumps (GSHP) and 51% were air source heat pumps (ASHP). The most common, with 11%, of the heating system concept in Sweden's MFRB stock is district heating in combination with a ASHP, usually an air-water or an exhaustion air HP. This heating concept set up is defined here as a bivalent system, other heating concepts are, monovalent and mono-energetic concept.

- Monovalent concept: One type of heating technology and one type of energy carrier. For example, a single HP
- Mono-energetic concept: Combined heating technologies but only one energy carrier. For example, HP and direct electric heating.
- Bivalent concept: Combined heating technologies and more than one energy carrier. For example, HP and district heating (Sandels, 2018).

A HP converts stored energy in the ground or air to space heating and domestic hot water (DHW) use in buildings. A brine fluid, for example glucose, circulates in a collector circuit and absorbs heat from the external medium (ground/air) at a low temperature. The temperature of refrigerant fluid, usually carbon dioxide, is then increased in the evaporator. The core of the heat pump, the compressor, increase the pressure on the refrigerant fluid and as the pressure increase so does the temperature. The next step in the HP is the heat exchanger, where heat is transferred from the now hot refrigerate fluid to the distribution system of the HP (under floor, ventilation or radiators) (Thermia, 2018).

2.3 Demand side management

Demand side management (DSM) involves all electricity management measurements taken on the demand side of the energy system as opposite to supply side management that refers to management of the production of electricity (Aduda, et al., 2016). DSM can be divided into the following sub-categories, energy efficient solutions and demand response solutions (Behrangrad, 2015; Kreuder & Spataru, 2015). Energy efficient solutions refers to products with a reduced the energy demand in comparison to older versions of the same product. Demand response (DR) refers to end consumers change in behavior pattern when it comes to energy consumption in response to an external signal. That external signal can be electricity price for example, reducing the consumption when the electricity price is high or increasing it when the price is low. A DR solution could also mean reducing the consumption when the electricity grid is experiencing high loads by using the load on the electricity grid as an external signal (Ei, 2014).

The three most common use of DR is: (1) Peak clipping/peak shaving, (2) Load shifting and (3) Valley filling (Zhaoguang et al. 2013; Gellings, 2017). Peak clipping means reducing one's electricity demand during peak load. Load shifting refers to the act of shifting load from peak hours to hours with a lower total power demand. Valley filling is the practice of creating a more even demand load by increasing the load during off peak hours (Gellings, 1985). The focus of this thesis was load shifting and more specifically a certain control strategy within the discipline of load shifting called discrete demand side control. Discrete demand side control strategies use intelligent algorithms to change consumers' electricity demand pattern with constraints to keep certain parameters within upper and lower limit of acceptability, e.g. indoor temperature comfort. Discrete demand side control makes it possible to implement automated load control systems and in the case of controlling a heating load in a building, the constraints of the algorithm is the indoor temperature comfort (Hong et al. 2012).

2.4 Heat pumps as a flexible load

Demand side flexibility falls under the theoretical framework of DR as the Swedish Energy Market Inspectorate (Ei) defines demand side flexibility as the following:

> *"Demand side flexibility is a voluntary change in the demand for electricity from the grid during shorter or longer periods caused by some type of incentive."* (Ei, 2017).

Many electricity consumers can provide flexibility by reducing or increasing their demand. Larger industries, energy storages and centralized power plants can trade flexibility while smaller loads, such as heat pumps are not participating in the trade due to lack of experience or to low electricity demands (Ei, 2017). Aggregators, an intermediary market player, would need to trade the flexibility for a number of smaller customers with heat pumps, often referred to as a pool of heat pumps, in order to utilize the HP flexibility (Eurelectric, 2014).

Several studies (Sandels, 2016; Fisher et al., 2017; Baeten et al., 2017; Hong et al., 2012) recognize the potential of using heat pumps in buildings as a flexible load. The electric load demand of the HP can be decreased during periods of large electricity demand from the grid without sacrificing the indoor temperature comfort of it residents by utilizing the buildings thermal inertia. The building envelope will release its stored energy when the HP are turned off ensuring that the indoor temperature is kept within a lower and upper limit given a well-controlled and monitored DR system (Baetan et al., 2017). Flexibility can mean different things depending on the context and when it comes to HP flexibility it con not be defined as a single parameter but is a combination of different parameters that together contributes to a holistic understanding of the demand flexibility from HPs.

Table 1 offers an overview of parameters used in different studies to describe the flexibility from HP. Depending on the actor that wants to use the flexibility from HPs will different parameters be the most important.

Table 1. Flexibility parameters

Study	Flexibility parameters
SvK (2017)	Flexible power, duration of load shift, respond time
Wolf (2016)	Flexible power, Duration of load shift, Regeneration time, Flexible energy
Eurelectric (2014)	Power, Duration, Rate of change, Respond time, Location
Ecofys (2014)	Reaction time, Charging/discharge capacity, Full cycle efficiency, Maximum period of shifting, Storage content

2.5 Market actors' interests for demand flexibility

Two possible actors that could utilize the flexibility from HP are a Balance Responsibility Party (BRP) and distribution grid operators.

A BRP is a company that has the responsibility for the electricity balance for generation and consumption in a certain area and its customers. A BRP trades electricity on different markets in order to achieve a balance in their consumption and production. These markets are, day-ahead market, intra-day market, balance market and power reserve. A BRP could use demand flexibility to reduce imbalances in the power system by trading the flexibility on the above-mentioned electricity markets (Interview BRP, 2018).

Local distribution grid operators are responsible for delivering electricity to smaller industries and private consumers. Grid operators could benefit from demand flexibility by peak power reductions in the electricity grid, reduction and to avoid expensive constructions and expansions of transmissions lines and distribution networks (Logenthiran et al., 2014).

3. Multi-family residential electricity load model

In this section, Sandels (2016) multi-dwelling building load simulation is described. The model consists of three modules; the end users' behavior module, the appliance module and DHW load module that is dependent on the behavior of the end users and the Heating, Ventilation and Air Conditioning (HVAC) module. The HVAC module is dependent on the ambient temperature, solar radiation, the buildings' thermodynamic properties, the space heating systems design and output from the other modules.

The model is designed to be as simple as possible without sacrificing the ability to adequately capture the real electric consumption in MFRBs (Sandels, 2016). The standardized and simplified attributes of Sandels models makes it a suitable model for simulating a large-scale scenario where it is not necessary capture a specific group of buildings properties. The use of behavior models to simulate the activities of the residents in the building distinguish this model from other models. Sandels' model also tracks indoor temperature over time which makes it possible to implement and simulate various DR schemes. These features of Sandels's model are the reasons to use this model to develop the aggregated MFRB model from.

3.1 Behavior module

A non-homogenous Markov chain methodology is used to capture and simulate the behavior of the individual resident in the multi-dwelling building. The Markov chain has 11 states related to DHW and electric appliance usages. The states are denoted as the following; 1) away, 2) sleeping, 3) cooking, 4) dish washing, 5) washing, 6) TV, 7) computer, 8) audio, 9) bathing, 10) showering, 11) other. A person moves from one state *i* to another *j,* with the transitions probability $p_{ij}(t)$ between the given time step t-1 and t. The transition probabilities will change during the course of the day since some activities are more likely during certain times of the day e.g., sleeping during the night and cooking between 17.00 and 20.00 (Sandels, 2016).

3.2 Appliance and domestic hot water module

The appliance module generates electricity and DHW profiles from the activity profiles created in the behavior module. Three basic conversion formulas are used for the conversion from activity profiles to electricity and DHW profiles; 1) constant power during the whole activity with the possibility of a stand-by option with a lower power, 2) a load cycle that starts with the activity but end either when the activity ends or when the load cycle ends e.g., filling up a bath, 3) a load cycle that starts when the activity ends and ends when a certain time has passed e.g., start dishwasher after the activity "fill the dishwasher" has ended. Exception to these simplified conversion formulas is the indoor lightning that is dependent on daylight and the total occupancy of the apartment.

The DHW usage is converted to heat use (Q_{dhw}) through equation (1)

$$Q_{dhw}(t) = V^{a}_{flow}(t) * C_{p,water}\left(T_{0utlet} - T_{inlet}\right) \quad [W] \tag{1}$$

Where $C_{p,flow}$ is the specific heat capacity of the water. T_{outlet} and T_{inlet} are the outlet and inlet water temperature. V^{a}_{flow} is the hot water flow that serves a specific individuals DHW activity (Sandels, 2016).

3.3 Heating, ventilation and air conditioner module

Three types of dynamics are included in the heating, ventilation and air conditioner (HVAC) module; 1) the heating demand of the building, 2) the characteristics of the HVAC system and 3) the different HVAC control strategies. The module also accounts for the usage of the heating system to sustain an indoor comfort and the thermodynamic processes of the building (Sandels, 2016).

3.3.1 The heating demand of a building

A residential buildings heat demand is to a large extent correlated to the indoor temperature (T) and its deviation from the reference indoor temperature (T_{ref}). The heating imbalance ($Q_{imbalance}$) affect the indoor temperature and consequently also the heating demand. The heating imbalance is affected by three disturbances, heat loss (Q_{loss}), solar radiation (Q_{sun}) and internal heat gains (Q_{int}).

$$Q_{imbalance} = Q_{int}(t) + Q_{sun}(t) - Q_{loss}(t) \quad [W] \tag{2}$$

Where Q_{int} is the heat gain from occupants and appliance and is derived from the stochastic appliance and DHW profiles determined in the appliance and DHW module. Q_{sun} is the heat gained from solar radiation is calculated through a simplified model dependent on total window area and a reduction factor due to shading. Q_{loss} is caused by the ambient leakage that is transferred between the indoor and the outdoor climate.

$$Q_{loss} = \Lambda*(T(t) - T_{out}(t)) \quad [W] \tag{3}$$

Λ is the total heat losses due to ventilation and the properties of the building's envelope and is given by:

$$\Lambda = \sum Uj*Aj + V_b* \bar{N}_{vent}*C_p*(1-\alpha_{rc}), \qquad [\tfrac{W}{°C}] \tag{4}$$

U_j is the transmission coefficient of each building component, j, and A_j is the total area of said component. V_b is the volume of the whole building and $\bar{N}_{vent}$ is the air exchange rate. C_p is the specific heat capacity of air and α_{rc} is the heat recycle coefficient (Sandels, 2018).

3.3.2 The characteristic of the HVAC system

The HVAC system serves the DHW demand and maintain the predefined indoor reference temperature (T_{ref}). Three attributes are considered here when designing the HVAC system, the heat supply system concept (monovalent, mono-energetic and bivalents systems), the Coefficient of Performance (COP) and the heating system capacity. As for the COP value, the source temperature is a determining factor. For an air source HP, the COP will decrease with the outdoor temperatures and will reach zero when the temperature is cold enough. A ground or lake source HP has a more stable COP since the sources temperature varies less than the outdoor temperature. A ground or lake source HP often needs a compliment heat supply for peak demand during low outdoor temperature. When determining the dimensions of the heating capacity the COP, the thermal inertia of the building and the lowest registered average temperature in the region in the last 10 years is considered (Sandels, 2016).

3.3.3 HVAC control strategies

Sandels model employees a reactive control strategy based on either outdoor temperature or indoor temperature. The controller reacting on the indoor temperature as data input measures the temperature in the indoor climate and compares to the set reference temperature. When the measured temperature exceeds the reference temperature plus a set temperature interval the controller will decrease or increase the supply temperature to influence the indoor temperature. The control strategy that utilize the outdoor temperature as input data works on the same principle as the indoor temperature control strategy but use the outdoor temperature to determine which operation power consumption of the HP. Both control strategies account for internal heat gains and the buildings thermodynamic properties.

4. Methodology

Before the aggregated MFRB model could be develop the author needed to get familiar with Sandels's model to gain a understanding of how the aggegated model could be structured.

A literture revies was conducted to get a better understanding of how HP systems work, common building heating system set ups, and how flexibility can be defined and used for different purposes.

Figure 1 provides an overview of the steps necessary to assess the flexibility from heat pumps and includes the development of the aggregated MFRB model.

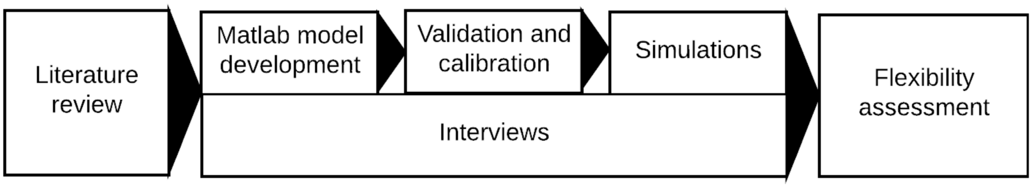

Figure 1. Methodology overview

The information and knowledge gained from the interviews was used to make decisions about the aggregated MFRB model development and gain a deeper understanding about demand response, flexibility, HPs and to understand the broader context in which they are active. See appendix A for a compilation of interviews conducted. The interviews held was semi-structured to give the interviewee the opportunity to illuminate the factors or subjects they find interesting. It also leaves room for the interviewer to ask follow-up questions that was not pre-written (Kvale & Brinkmann, 2014).

Figure 2. shows a more spesific overview of how the HP loads were simulated and the flexibility calculated. The Aggregated MFRB model was developed from Sandels's multi-family residential electricity load model and then used to simulate base line HP load profile. A DR control application was implented in the aggregated model to generate HP load profile wherean external signal turned off the HP at a specific time point in the simulations. The base line case and the DR control case was then compared to each other in order to assess the flexibility potential from HPs.

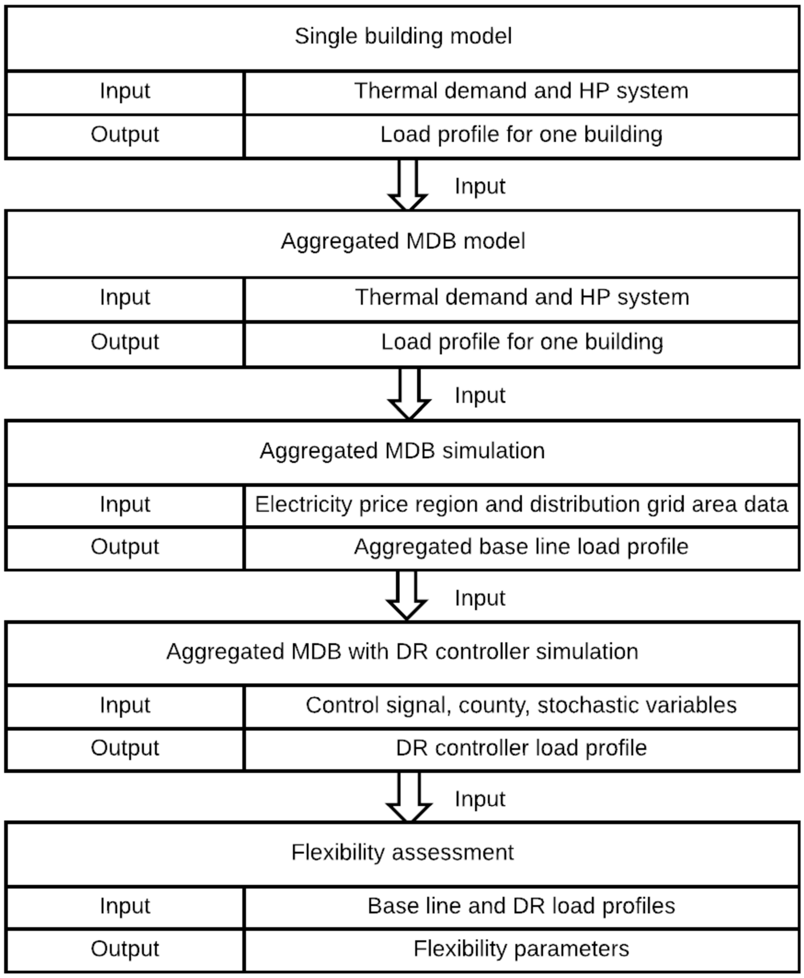

Figure 2. Flexibility assessment overview

Data extracted and used in the flexibility assessment and as input in the aggregated MFRB model is presented with sources below:

- Ambient temperature and solar radiation (Swedish Meteorological institute)
- The building area and number of apartment in the Swedish MFRB stock with HP (Statistics Sweden, National Board of Housing, Building and Planning, hereafter referred to as Boverket)
- Energy solutions in the MFRB building stock in SE3 (Boverket)
- Heat transmissions coefficients (U-values) (Boverket)
- Size of MFRB with heat pumps (Boverket)
- COP values (NIBE)

4.1 Flexibility assessment

The flexibility depends on the electricity load deviation between a base line case without a control signal and a second case with an DR control off-signal. Direct electricity heating is included in the flexibility assessment since consume the same energy carrier as HP while the district heating load is excluded from the flexibility assessment due to the difference in energy carrier. See figure 3 and equations 5-9 for a definition of the flexibility parameters, used to gain a holistic assessment of the flexibility in this thesis. The collaboration with Grill meant that it was possible to define the flexibility parameters with the need from a BRP and grid operators in mind. For the BRP and grid operators it is important to know how often the flexibility resource could be used, the amount of energy that is flexible on an hourly basis and the duration of the load shifts.

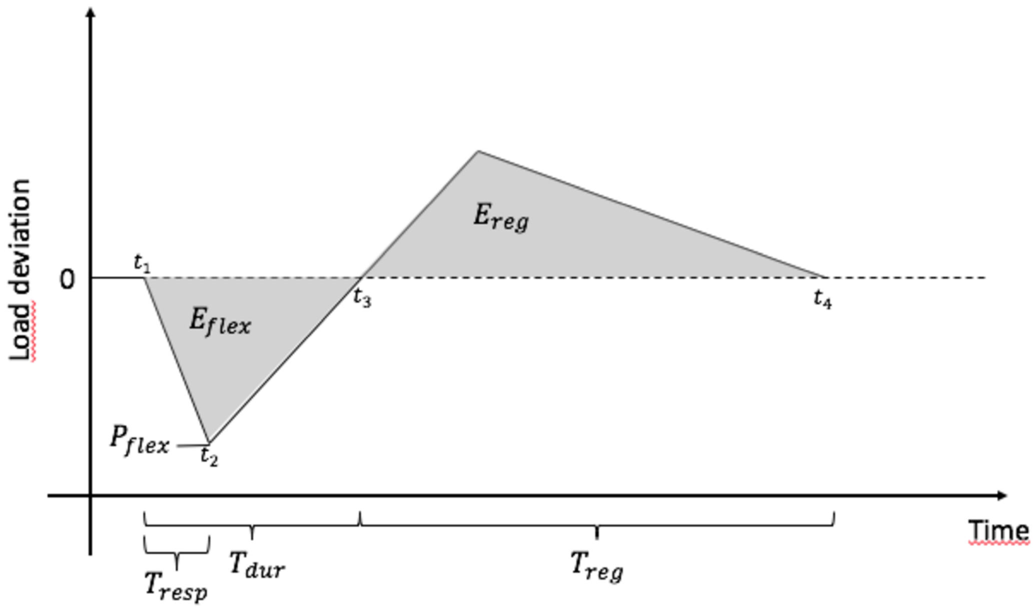

Figure 3. Example figure of flexibility parameters

The *respond time* (T_{resp}) of the system refers to the time it takes from that the off signal has been sent until the maximum flexible power have been reached. The time delay in updating the HP information and the start-up time of the HP compressor determines the respond time.

$$T_{resp} = t_2 - t_1 \tag{5}$$

The indoor temperature and the buildings heat transmission coefficient determines how long the HP can be turned off before the lower limit of the indoor temperature is reached and the HPs are turned on again consequently determining the *duration of the load shift* (T_{dur}).

$$T_{dur} = t_3 - t_1 \tag{6}$$

Flexibly energy (E_{flex}) refers to the total amount of energy that is released by turning of the HP and depend on the electricity power consumption from the HP when the DR control signal was activated and the duration of the load shift. Equation 7 explains how the flexible energy is calculated. The simulation is on a minute basic hence the multiplication with the factor 1/60 to get the power in W [J/s].

$$E_{flex} = \sum_{i=t1}^{t3} P_i * (1/60) \tag{7}$$

Flexible power (P_{flex}) is the highest hourly mean value of the power reduction that arise from turning of the HP. It is possible to calculate P_{flex} for different time intervals down to a minute level which is the time unit used in the simulations. An hourly mean value is used in this thesis to make the result applicable for Grills thesis work since the BPR plans and trade electricity consumption and production on an hourly basis.

The *regeneration time* (T_{reg}) is interesting to investigate since it means a difference in load, due to the off signal, from the base line case. A deviation from the base line case could mean negative or positive effects for the BRP or distribution grid operators. It is the synchronization of the HP by turning them off at the same time give rise to an increased demand for electricity from the HP during a certain time period, in this thesis referred to as the regeneration time.

$$T_{reg} = t_4 - t_3 \tag{8}$$

The amount of energy consumed by the HP during the regeneration time is defined as the *regeneration energy* (E_{reg}).

$$E_{reg} = \sum_{i=t3}^{t4} P_i * (1/60) \tag{9}$$

The *repeatability* (T_{rep}) of the flexibility resource refers to the time it takes after a control signal has been active until the same flexible energy available again. For the same flexible energy to be available again two requirements must have been met. First the aggregated HP power must have reached the same value as when the first control signal was activated which happen at time point t_3, secondly, must the indoor temperature recover. Figure 4 illustrates how the indoor temperature is presumed to be recovered when 50% of the MFRB's indoor temperature is above 21ºC. The control off-signal is activated at t_5 and the indoor temperature assumed recovered at t_6.

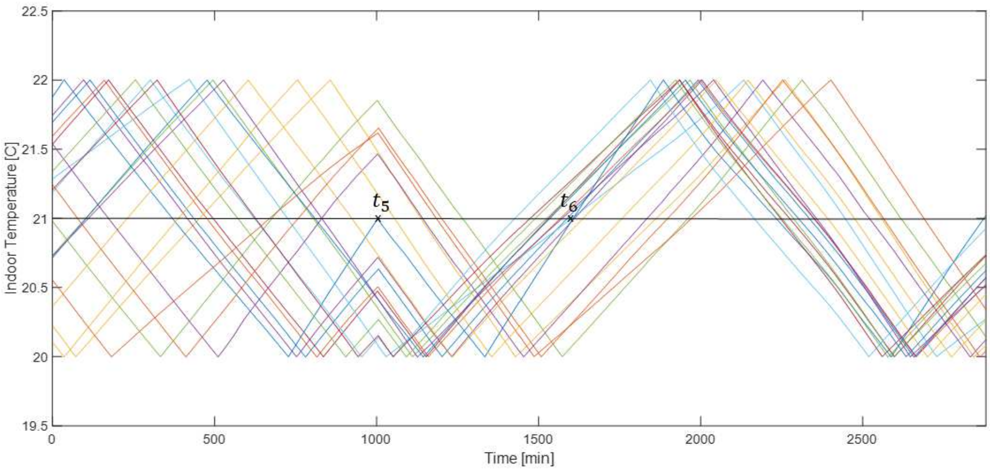

Figure 4. Example of the indoor temperature curve for 20 MFRBs at 0ºC

$$Rep = \begin{cases} t_3 - t_1 & \text{if } t_3 > t_6 \\ t_6 - t_5 & \text{if } t_6 > t_3 \end{cases} \tag{10}$$

Equation 10 describes how the repeatability depends on either the indoor temperature recovery time or the duration of the load shift depending on which has the longer time interval.

5. Aggregated multi-family residential building model

Several studies (Fischer, 2017; Madani, 2017; Wolf, 2016; Hong et al, 2012) discuss and examines what factors that are most distinctive in a HP system and the most influential when it comes to determining the demand flexibility. Figure 5 illustrates the factors that needs to be considered in determining the dimensioning of HPs and to assess the flexibility. The first level factors that are marked in bold italic text represent the factors that are taken into consideration in the aggregated model presented here. The first level factors are divided into second and third level factors. In the end, the dimension and performance of a HP system is dependent on the third level factors, thermal demand and HP system characteristics. The decision of which factors to include in the model was foremost based on inclusion/exclusion in Sandels's model. The factors were also discussed with personnel at Vattenfall AB to determine their relevance in this thesis.

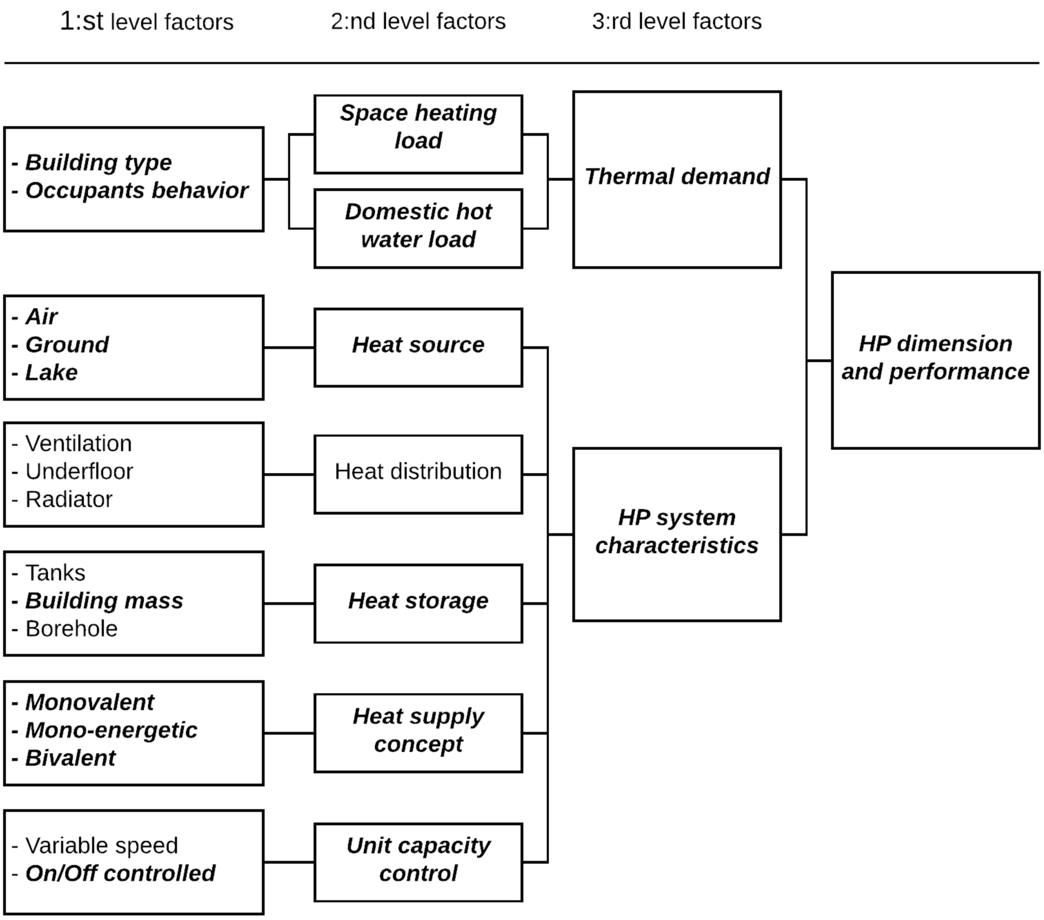

Figure 5. First, second and third level factors that determine the dimension (installed power demand) and performance of a HP system. Factors in bold and cursive text are considered in this thesis.

Various parameters in Sandels's model depends on the geographic location of the MFRB, the energy system set up and control strategy. The parameters in Table 3, are varied depending on geographic location, experts' recommendations and type of energy system concept.

Assumptions and simplification were made to keep the simplicity of the model and to maintaining the purpose of the model, which is to build a large-scale simulation model of part the Swedish MFRB stock with HPs.

Table 3. Input parameters for one building

Type of parameter	Parameter	Value	Dependency
Building	Number of apartments	Numeric	County
Building	Total building area	m^2	County
Building	Building age	old/medium/ new	County
HVAC	Coefficient of Performance (COP)	Numeric	HP energy source
HVAC	Dimension for winter temperature (Tdvut)	Celsius	County
HVAC	Energy system concept	Bivalent/mono-energetic	County
HVAC	HP energy source	Ground/air	County
Controller	Type of controller	Indoor	Experts recommendation
Controller	Probability of HP is on (ProbonStart)	Numeric	Season

The distribution for the parameters are determined based on data for the Swedish MFRB stock and heat pumps from Boverket database "GRIPEN", weather data from SMHI and discussion with HP experts at Vattenfall AB. The parameter "Building age" has three possible values (old/medium/new) that are assigned different thermodynamic properties (U-values).

5.1 Building parameters

To evaluate the potential for utilizing the HP flexibility in a local distribution area and an electricity price region data was collected from Boverket about the MFRB stock. Boverket gather statistics to describe, understand, and forecast the building stock. The energy system solutions in the building stock are part of the data Boverket has gather and compiled in a report throughout the years. See table 4 for data for the MFRB stock obtained from Boverket. For the counties that are partly included in SE3 an estimation of the percentage of MFRBs that should be included in the simulations was based on maps over the counties and the price region.

Table 4. Number of HP in MFRB in SE3 sorted in decreasing order.

County	Inclusion in SE3	Number of MFRB with HP	Percent of total
Stockholm	Yes	3869	34.1
Västra Götaland	Partly: 90 %	2837	25.0
Jönköping	Partly: 90 %	809	7.1
Värmland	Yes	702	6.2
Östergötland	Yes	559	4.9
Södermanland	Yes	460	4.1
Örebro	Yes	456	4.0
Uppsala	Yes	454	4.0
Dalarna	Partly: 90 %	424	3.7
Kalmar	Partly: 33%	160	1.4
Västmanland	Yes	135	1.2
Gävleborg	Partly: 33%	100	0.9
Gotland	Yes	83	0.7
Total		11335	100

The first 8 counties listed in table 4 covers 92.1% (10 146 MFRBs) of the HP resource found in SE3 and 59.9% of the resource is found in Stockholm and Västra Götaland Counties where Sweden's largest cities, Stockholm and Gothenburg are located. Dalarna, Kalmar, Västmanland, Gävleborg and Gotland counties were excluded from the simulations for efficiency reasons and time restrictions of the thesis. Together these counties stand for 7.9% of the HP resource which was found to be a low enough percentage to not have a significant impact on the results.

Depending on the year of construction a MFRB will have different thermal dynamic properties. Newer buildings have improved insulation which means that the thermal transmittance i.e. U-value is lower than for older buildings. Boverkets planning and building policy dictates the required U-value which has in total decreased constantly since 1945 which is the oldest policy available (Boverket, 2018a). Different building archetypes based on year of construction were defined in the aggregated MFRB model with corresponding U-values. See table 5 for the building archetypes implemented in the model.

Table 5. Buildings archetypes

Building archetype	Building year	U value floor	U-value roof	U-value wall	U-value door	U-value window
Old	-1970	0.35	0.50	0.90	1.50	2.50
Medium	1971-2000	0.18	0.18	0.28	1.00	2.00
New	2001-	0.13	0.13	0.18	1.30	1.30

The building archetypes were decided upon after investigation of the change in U-values from 1945 to 2017. Significant change of U-value was found between the years 1970-1971 and 2000-2001 hence the resulting three building archetypes (Boverket, 2018a). Three archetypes were considered to be enough to capture the dynamics of the aggregated MFRB stock since the major trend in U-values and the purpose of the model is to create a generic simplified version of reality.

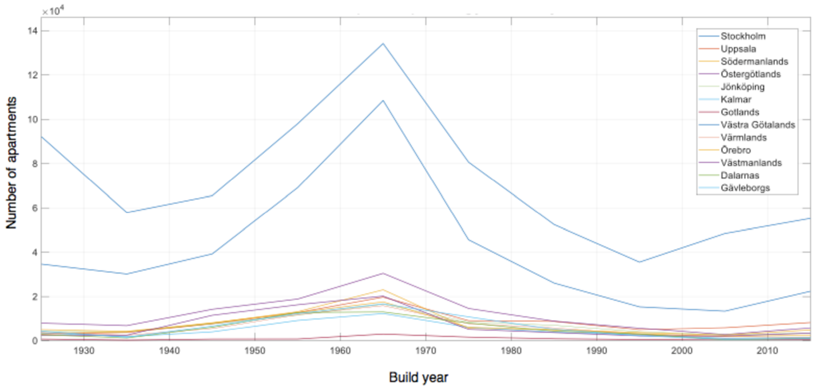

Figure 6. Number of apartments per year of construction interval. (Statistic Sweden, 2018)

Figure 6. shows the distribution of building year for apartments in the counties included in SE3. The datasets were used to generate a generic distribution for SE3 the building year of an MFRB. It is assumed that the building year distribution for MFRB in SE3 is the same as the distribution for apartments and is approximated to be a normal distribution with the mean value of 1965 and standard deviation of 25. The parameter building age in the model is selected stochastically from the building year distribution see equation 11 for the normal distribution for the building age.

$$Building\_age \backsim \mathrm{N}(\mu, \sigma^2),\ \mu = 1965,\ \sigma^2 = 25 \quad (11)$$

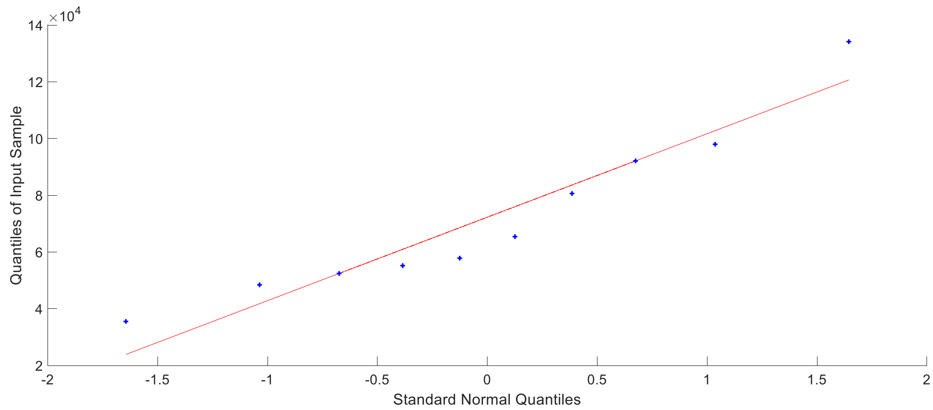

Figure 7. Quantile-quantile plot of Stockholm construction year versus standard normal

The quantile-quantile plot generates an approximately straight line, suggesting that the construction year follow a normal distribution. Since Stockholm has the largest share of HP in SE3 the data from Stockholm was used in the quantile-quantile plot. Stockholm data was also plotted against the other counties in quantile-quantile plots to determine that they had the same distribution.

5.2 Heating, Ventilation and Air-conditioning system parameters

Two energy system concepts were included in the aggregated HP model, mono-energetic and bivalent energy heating systems. These two solutions are the most common in MFRB and therefore interesting system solutions to simulate. A COP value that decrease with the ambient temperature captures the dynamics of a mono-energetic system where the direct electric heating in the HP will produce a larger share of heat with the decrease of ambient temperature. Direct electric heating has a lower power to heat efficiency than a HP which means that the entire systems efficiency decreases with falling ambient temperature. Table 6 shows the lower and upper bounds of the random number generation that produced each building HPs COP value. The boundaries are based on values received from NIBE for Air Source Heat Pumps (ASHP) and Ground Source Heat Pumps (GSHP).

Table 6. COP values depending on ambient temperature

Ambient temperature [°C]	-20	-15	-10	-5	0	5	10	15	20
COP lower	1.5	1.9	2.5	2.7	3.6	3.8	4.0	4.5	3.6
COP upper	2.0	3	3	3.5	3.8	3.9	4.5	5.0	4.0

In the case of a bivalent energy solution the base load is covered by the HP and it is assumed that district heating is used to supply the peak load, a common energy system set up in MFRB in Sweden (HP expert 1, 2018). For bivalent systems, the COP set to 3.8 which represent a seasonal coefficient of performance (SCOP) (Interview NIBE, 2018). SCOP can be described as a HPs average COP value for one year. It was assumed that the domestic hot water (DHW) demand always was covered by district heating and therefore excluded from the flexibility. Direct electric heating is included in the flexibility since it has the same energy carrier (electricity) as HPs.

In the bivalent energy systems is the relationship between the heat provided by the HP and the DH system depending on the energy source of the HP. The GSHPs in SE3 covers an average of 86% and ASHPs covers an average of 48% of the yearly heat demand for one building in combination with district heating (Boverket, 2018b). This means that the GSHP are dimensioned for a lower ambient temperature than ASHP and therefore can cover more of the demand. Wolf (2016) refers three different studies where the lowest ambient temperature that the GSHP could provide heat for by itself was set to in-between -5 and -7 degrees. The temperature the GSHP could provide the entire heating demand (dimCoeff) for was set to -5°C for GSHP in the aggregated MFRB model which was confirmed by HP experts at Vattenfall to be a feasible coverage temperature. The corresponding temperature for ASHP in the bivalent systems was 7°C, which was the coverage temperature used in Sandels (2016) model. The relationship between GSHP and ASHP in the simulations are 1:1 since there is 49 % GSHP and 51% ASHP, GSHP includes lake, grounds and sea HP and ASHP include air to air, air to water and exhaust air HPs (Energimyndigheten, 2016).

Each MFRB is assigned a start indoor temperature that was selected randomly between 20 and 22 degrees. The ProbOnStart parameter is also used at the start of each simulation to randomize the HP are initially on, or off. Thereafter the heat demand determines which HP are either on or off. Fisher et al (2017b) have compiled data of share of active heat pumps in a pool of 100 HP for one year. The share of active heat pumps depends on the ambient temperature and range from 95% active pumps to 5% active heat pumps. The relationship between the mean ambient temperature ($\bar{T}$) and share of active HP in the system is described in the aggregated HP model as a linear equation. The constants in the linear equation was based on Fisher et al data.

$$ProbOnStart = (-4.2 * \bar{T} + 58) * 0{,}01 \qquad (12)$$

ProbOnStart will stay at a value of 0.95 and 0.05 when the ambient temperature is below -9 ºC or above 13 ºC respectively. See figure 8 for an illustration of the linear equation that describes the share of active heat pumps.

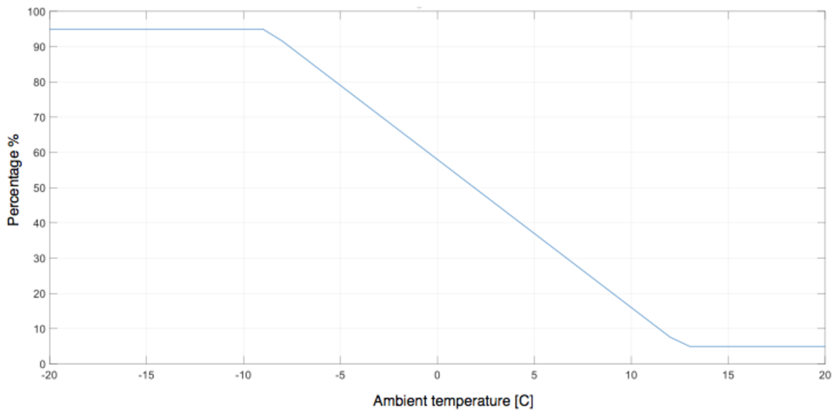

Figure 8. Share of active heat pumps depending on the ambient temperature based on data from Wolf (2016)

One parameter that affects the dimensioning of a HP system is the winter dimensioning temperature (Tdvut). The Swedish metrology institute (SMHI) has gathered historic data of winter temperatures from 1981 to 2010 for several measuring points in each county in Sweden that is used to determine which ambient temperature the heat system should be dimensi9oned for (Boverket, 2018c). The Tdvut also determines the maximal power capacity of the HP. A random Tdvut is selected from SMHI data from the relevant county and assigned to each building in the aggregated HP model.

Table 7. SE3 winter dimensioning temperature data (Boverket, 2018c).

County	Tdvut average [ºC]
Stockholm	-11.8
Västra Götaland	-11.7
Jönköping	-11.4
Värmland	-18.1
Östergötland	-11.4
Södermanland	-10.7
Örebro	-13.4
Uppsala	-14.1

Equation 13-16 describes the dimensioning of the HP systems and the supplement peak load, assumed to be DH in this thesis. The dimensioning of the heating system depends on the parameters described in this section; the total transmission coefficient of the building (Λ), the reference temperature set to 21ºC (Tref), the winter dimension temperature (Tdvut), the HP COP and the temperature determining the temperature the HP can cover the heating demand by itself the for BIV and MONO systems (dimCoeff).

MONO system solutions:

$$P_{HP} = \wedge * (T_{ref} - T_{dvut})/COP \quad (13)$$

$$P_{peak} = 0 \quad (14)$$

BIV system solutions:

$$P_{HP} = \wedge * (T_{ref} - dimCoef)/COP \quad (15)$$

$$P_{peak} = \wedge * \frac{T_{ref} - T_{dvut}}{COP} - P_{HP} \quad (16)$$

5.3 Controller module

An indoor controller is used to ensure that indoor temperature is kept temperature within an interval so that the residents would not notice a change in the indoor climate. The allowed temperature deviation from the reference temperature of 21ºC is set to ±1°C after discussion with personnel at Ngenic and a literature review of similar studies (Interview Ngenic, 2018; Hong et al, 2012). The indoor temperature is updated every minute in the simulation and the HP was turned off when the higher limit of 22°C was exceeded and turned on when the indoor temperature dropped below 20°C. Depending on the ambient temperature in the simulation was three different heating options was used.

- Ambient temperature > 7ºC: HP can provide enough energy to cover the buildings need
- Ambient temperature < 7ºC: HP running maximal power to supply heat, secondary energy source in a bivalent system provides heat to cover the peak load.
- Ambient temperature < Tdvut: the HP and the secondary energy source are running on maximal power to cover the heating demand.

As mentioned in section 5.2, the COP decreases with the ambient temperature in order to capture the dynamics of a mono-energetic system where a HP is complemented with direct electric heating at high demands periods, resulting in a decreased total COP value of the system.

5.4 Model validation and calibration

Sandels's model for simulating the heating demand for one multi-dwelling has been validated and evaluated against data from an existing building. The model is therefore, in this thesis, assumed to be able to capture and represent buildings' thermodynamic properties, the energy system's features and the behavior of the buildings' residents.

The aggregated MFRB model was validated against a simulated heating load profile based on historic measured data from district heating system in an urban area in Sweden owned by Vattenfall AB. Vattenfall AB's district heating system provides heat to detached houses, MFRB and other facilities. Vattenfall use this model to estimate future heating demand profiles when the building stock is changing and expanding. Since Vattenfall AB for the last three years, have used this model and found it to be able to capture the dynamics of a district heating load profile the model is redeemed to be suitable for validating of the aggregated MFRB model presented here. Data of the HP resource and the building stock from the same area in Sweden was used in the aggregated MFRB model when conducting the validation. The simulated load profile generated from the aggregated MFRB model was recalculated from electricity load profiles to heating load profiles by multiplying the HP load profiles with its corresponding COP value.

In the model provided by Vattenfall AB it is possible to define the total building area in m^2 and an average heating demand in kWh per m^2. A heating load profile is generated where the percentage of the yearly heating demand (kWh/year) is defined for every hour depending on the ambient temperature. It was therefore possible to identify 48 hours, which is the simulation time, with the same average ambient temperature as was used in the aggregated MFRB simulations. This made a comparison between the total heating demand for the period of 48 hours possible. The same dataset of buildings was used in both simulations and the total building area was retrieved from Boverkets database. The average heating demand per square meter for a building heated by district heating is defined as $140kWh/m^2$ in Energimyndighetens report "Energy statistics for multi-family residential buildings in 2016" (Energimydigheten, 2016).

The results from the validation is shown in figure 9. A dataset of 200 MFRB was used for the simulations. The lower line, "Vattenfall's model" is the load profile generated by Vattenfall's model and the upper line, "MFRB model" is the load profile generated by the aggregated MFRB model.

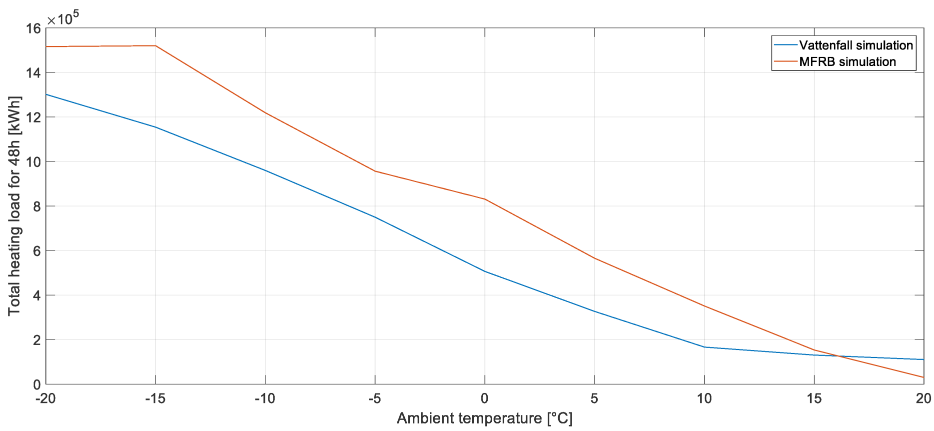

Figure 9. Validation of aggregated MFRB model

The curve for the simulated heating demand is constant for temperatures below -15ºC. This is because the heating system in the simulation is dimensioned for an ambient temperature based on winter dimensioning data from SMHI (2018). The heating system is operating on maximal power at -15 ºC and will not increase with the falling ambient temperature. The load profile from the aggregated MFRB model in figure x is 10-50% higher than the load profile from Vattenfall's model except for ambient temperatures higher than 15 ºC. With an ambient temperature, higher than 15ºC the heating demand consist mostly of the DHW demand. The aggregated model seems to underestimate the DWH demand, hence the resulting lower curve in comparison with Vattenfall's model simulation. Since the DHW demand is assumed to be supplied by the district heating system and excluded from the flexibility assessment it is concluded that it will not affect the result of the flexibility significantly

A calibration of the model was performed to increase the accuracy of the heating demand. To calibrate the model the buildings thermodynamic properties (u-values) was adjusted with the purpose to decrease the heating demand for the buildings in the aggregated MFRB simulations. For "old" buildings were the aggregated u-value multiplied with a factor of 0.85 and for the building type "medium" was multiplied with a factor of 0.95. The factors were decided upon after iteratively trying different values before finding the optimal value. The thermal inertia of these building types was therefore increased and the heating demand decreased. The need for this calibration can be explained by renovations made in old and medium buildings that increase the thermal inertia. It was also found that Tdvut was too high as the indoor temperature decreased even though the HP and district heating system were operating on maximum power at ambient temperatures lower than -10ºC. To increase the accordance of the model was winter dimensioning temperature decreased with 2°C for all buildings. A larger modification of Tdvut with for example 5°C would ensure that the HP and supplementing energy system would always be able to cover the heating demand but would have deviated more from the data retrieved from SMHI that is assumed to be reliable. Figure 10 shows the validation of the model after the calibration.

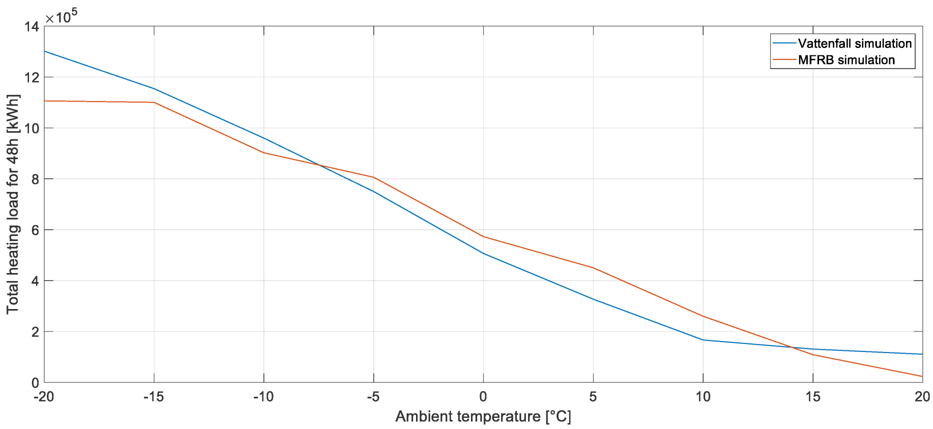

Figure 10. Calibrated validation of aggregated MFRB model

After the calibration, a maximum difference of 20% is found between the load profiles from the Vattenfall model and aggregated MFRB model. This is redeemed to be an acceptable difference for the calculation of the flexibility parameters explained in section 4.1 *Flexibility assessment*.

5.5 Demand response controller

A DR controller was designed and implemented in the indoor temperature controller in order to make it possible to turn off the HPs given an external "HP Off" signal. To assess and evaluate the flexibility from HP utilizing building thermal inertia a simplified signal, that could be easily varied, was used. The DR control off-signal was set to activate at a certain time point in the simulation and then the HPs turned on as the indoor temperature reaches the lower limit of 20°C. Furthermore, the DR controller registers the HP start-up compressor cycle and the update information time for the HP. The off signal allows the HP to finish the first compressor cycle before turning off since turning off a HP in the middle of a start-up cycle can decrease the HP's lifecycle. A HP first compressor cycle after an off mode, is usually between 5-15 minutes and a compressor cycle of 10 min was used in this model (Interview Sustainable Innovation, 2018; Interview Ngenic, 2018). A time delay between 1-5 minutes was also implemented in the aggregated MFRB model to illustrate that a HP usually received new information every fifth minute with an update of how much power is needed to cover the heating demand (Interview Ngenic, 2018; Interview NIBE, 2018). The time (ContrTime [min]) for the control signal to activate was decided upon after analyzing the base line simulation. A discussion with Grill was also conducted in order to identify interesting cases for the further analysis of the market opportunities of HP flexibility in her master thesis.

5.6 Simulations

The flexibility provided by electrical use in heat pumps is, as mention before and illustrated in figure 2, mainly dependent on the thermal demand from the space heating and the characteristics of the HP system solution. The thermal demand varies depending on the ambient temperature and has a strong seasonal correlation. The HP system rarely operates in low demand periods, e.g. the summer when there is a high ambient temperature, which means that the flexibility potential for turning off the HPs is low. Consequently, there is a larger interest in investigating the potential flexibility resources connected to HP during high demand periods, e.g. low ambient temperature periods (Bhattarai et al. 2014). The simulations were performed from -20 ºC up to 15 ºC with a temperature increase of 5 ºC. The ambient temperature input data was retrieved from SMHI and allowed to deviate ±1.5 ºC from the simulated ambient temperature. For the flexibility assessment at 0ºC the temperature can vary between -1.5 to 1.5 ºC for example.

The simulation time was 48 hours (2880 min) as it was important to see the control signals effect on the load profile and it was concluded that 48 hours was a long enough time to see the effect on the load profile after a DR control signal had been activated. For each ambient temperature level, the control signal was activated at three different time steps, 300, 600 and 1000 minutes to capture the variation in number of active HPs and indoor temperature. A mean value of the flexibility parameters was then calculated for each ambient temperature simulation.

The simulations were performed and based on data for the building stock from one electricity price region, SE3, and one distribution grid area in an urban region of Sweden. The reason for performing the simulations on a price region and a distribution area is the ability to analyze the flexibility results impact on the BRP's and distribution grid operators' interests. For more information on how these actors could utilize the flexibility see the master thesis "Market potential for using demand response from heat pumps in multi-family buildings" (Grill, 2018).

5.6.1 Distribution grid area

Data from a specific distribution grid area in an urban region in Sweden was used to assess the potential to use the flexibility resource from HP from a grid operators purpose. The assessment of the flexibility resource could be performed for any distribution grid area given data of the building stock from Boverket. In this case the distribution grid area boarders coincided well with the area of the municipalities and it was therefore possible to use the entire HP resource in the area.

The distribution grid investigated in this thesis is located in a larger urban region where the electricity demand has increased faster than expected according to SvK (SvK, 2018a). It is therefore likely that this distribution grid might experience problems with high power demands and that the electricity infrastructure cannot supply more power which makes it an interesting case to investigate.

See table 8 for a summary of input data for the DG area extracted from Boverkets database GRIPEN.

Table 8. Distribution grid area input parameters

Input	Value
Number of MFRB with HPs	174
Average area/building	3000 m^2
Average number of apartments/building	29
Number of BIV systems	59
Number of MONO systems	115

5.6.2 Electricity price region

The purpose of assessing the aggregated HP flexibility in an electricity price region is to facilitate an analysis if the flexibility could be used by a BRP and add value to their business. When deciding which price region to simulate, the number of MFRBs with heat pumps and electricity demand was considered. The multi-dwelling building stock has its largest share in SE3 and the electricity demand exceeds the electricity production (Energimyndigheten, 2017).

The large amount of MFRB with HPs of 10146 in SE3 (see table 4) meant that in order to make the simulation more efficient the number of calculations that was needed to be performed to simulate the residents' behavior was reduced. The model employs a non-homogenous Markov chain methodology to simulate the resident behavior which means that transitions probabilities to move from one state to another was calculated every minute for each resident By saving the variables for internal gains, power of household appliance, power to supply the domestic hot water use and number of members per apartment after one simulation in each county and load as input in the remaining simulation in said area were the time for each simulation reduced. The action could be summarized as if the behavior of the resident is the same in all simulations for the same county.

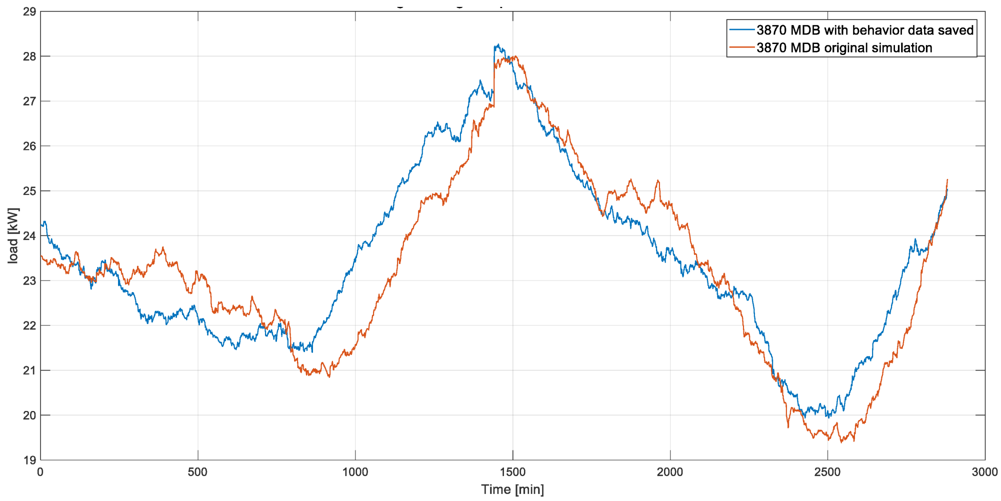

Figure 12. Average heating load profile for simulation with 3870 MFRB where one of the simulation use the same behavior parameters as the first one produced.

Figure 12 shows that the action taken to make the model more efficient did not disturbed the result significantly as the deviation from the original average load profile from the simulation with the entire resource of 3870 MFRBs is small.

See table 9 for a compilation of input parameters for SE3.

Table 9. Compilation of input parameters in SE3

County	Average building area [m^2]	Average number of apartments	Mono-energetic sources	Bivalent sources
Stockholm	2042	22	1469	2400
Västra Götaland	975	11	784	2054
Jönköping	898	10	153	656
Värmland	1104	14	222	480
Östergötland	845	9	103	455
Södermanland	1055	12	148	312
Örebro	838	9	84	372
Uppsala	1402	15	113	341
Average/total	1145	13	3076	7070

6. Results of simulations

6.1 Distribution grid area

A generic assessment of all flexibility parameters was performed so that the results could be applied to different cases. 174 MFRB is located in this area but it is possible to either scale up or down the load profiles to assess the flexibility in other areas. An adaption and evaluation of different DR control strategies was also performed to see what would best fit the specific need in this distribution grid area. The generic flexibility assessment result will be presented first and then the results from simulations where the three different DR control strategies were used.

Table 10 presents a summary of the results from the flexibility assessment for the distribution grid. The demand flexibility assessment is a complex analysis of 7 parameters and depending on the purpose to use the flexibility will different parameters be the most influential one and others will set the constraints of the flexibility potential.

Table 10. Summary of results for the distribution grid area

Ambient temperature	-20	-15	-10	-5	0	5	10	15
T_{resp} [min]	6	6	6	6	6	6	6	6
T_{dur} [hrs]	4.8	5.7	5.9	5.8	6.2	6.2	6.2	7.4
E_{flex} [MWh]	24	33	32	18	11	8	7	3
T_{reg} [hrs]	12.5	5.9	28.6	17.3	11.8	11.9	16.7	31.4
P_{flex} [MW]	10	9	8	5	3	2	2	1
E_{reg} [MWh]	1	3	29	30	21	16	12	2
T_{rep} [hrs]	30.0	25.0	20.0	15.0	10.0	9.0	7.0	7.3

Figure 13 present the results from the flexible energy (E_{flex}) calculations. The figure shows the average flexible energy in MWh.

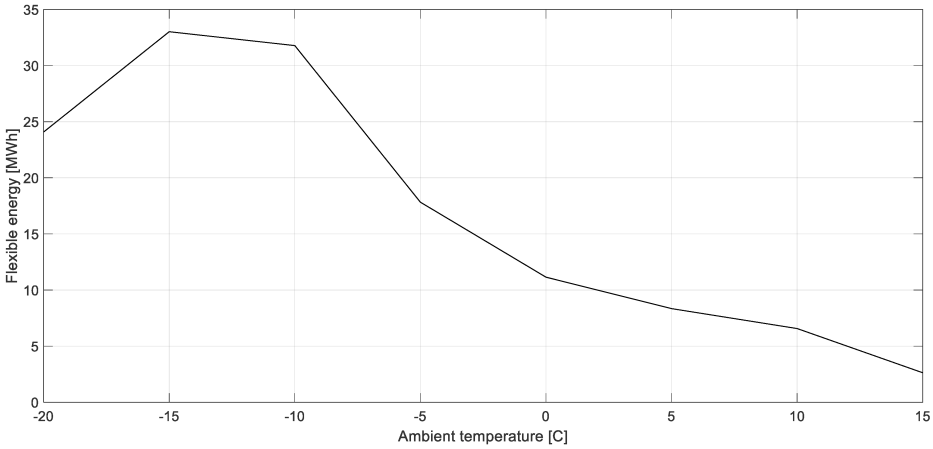

Figure 13. Flexible energy dependent on the ambient temperature

The highest available flexible energy can be found at ambient temperature -15ºC. The reason for the decrease in flexible energy between -15 ºC and -20ºC is the decrease in duration at the same time as P_{flex} have not increased enough to make up for the decrease in duration. Table 10 shows how the duration of the load shift decrease with the ambient temperature due to the fact that the indoor temperature drops faster when it is cold outside. The indoor temperature recovery time increase with a falling ambient temperature and is the most commonly decisive factor when determining the repeatability.

P_{flex} (see table 10) occurs the first hour after the DR control signal has been activated. Thereafter, as the indoor temperature for the MFRB reached the lower limit depending on the indoor temperature when the signal was activated and the transmission coefficient, the HP will turn on again gradually, which means a lower P_{flex} for every hour after the control signal. P_{flex} can be used to calculate the average HP power for the MFRB since 100% of the HPs are active and operating on maximal power. The value for P_{flex} of 10 MW and the number of 174 MFRB, in the distribution grid area results in an average power of 58.41kW per HP installed in the MFRBs.

The regeneration energy and time is of interest since it means a deviation in load between the base line and DR controller case which could have an effect the BRP's or the grid operator's purpose of using the flexibility in the first case. Figure 14 illustrates how the DR controller effect the HP load.

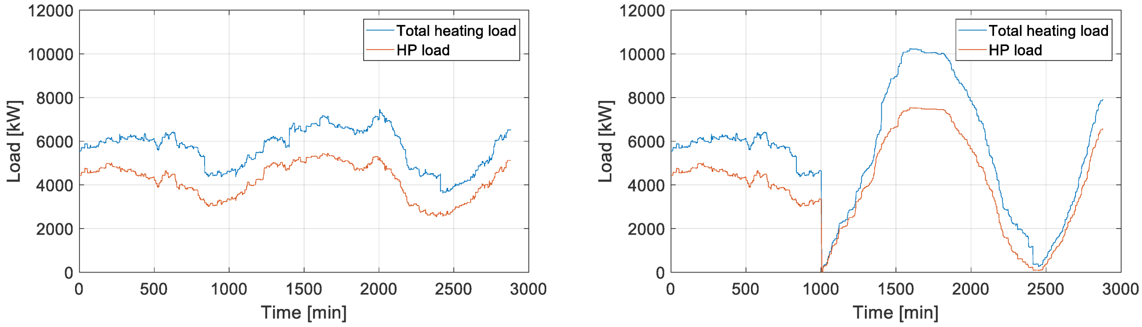

Figure 14. Base line simulation and simulation with DR controller in distribution grid area at ambient temperature 0ºC.

The DR control signal results in a more oscilliating load profile which could mean larger problems for the distribuition grid owner. A more advanced controller which would start the HP gradually after the off signal would possible not experience these large oscilliations (Interview Ngenic, 2018). An indoor controller is used in the aggregated MFRB model which means that when the lower limit for the indoor temperature is reached the HP will start operating on maximal power to increase the temperatur. MFRB's with HP systems usually involves several HP with maximal power between 40-60 kW. Therefore is it possible to start one HP at the time and in that way increase the temperature gradually. This approch would also mean a longer regeneration time. The regeneration energy is caused by a synchronization of the HP due to the control signal that turn off the HP within a time interval of six minutes. See figure 15 of a load deviation curve where the response time can be determined.

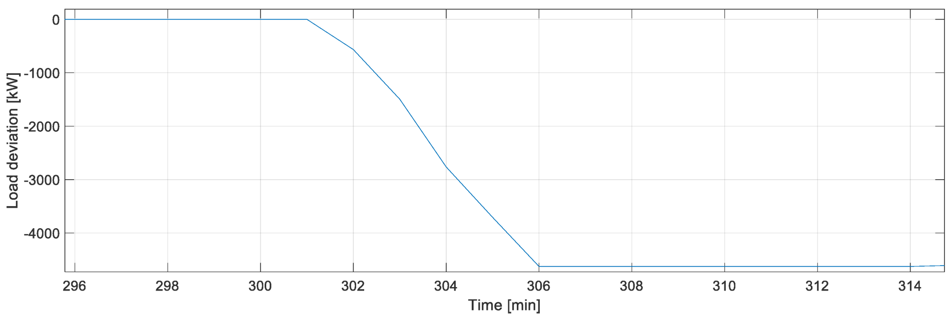

Figure 15. Response time at 0ºC with a control signal at 300 min

Figure 16. illustrates how the HP becomes more syncroniced after a control signal and therfore cause a larger aggregated power peak after the control signal than before.

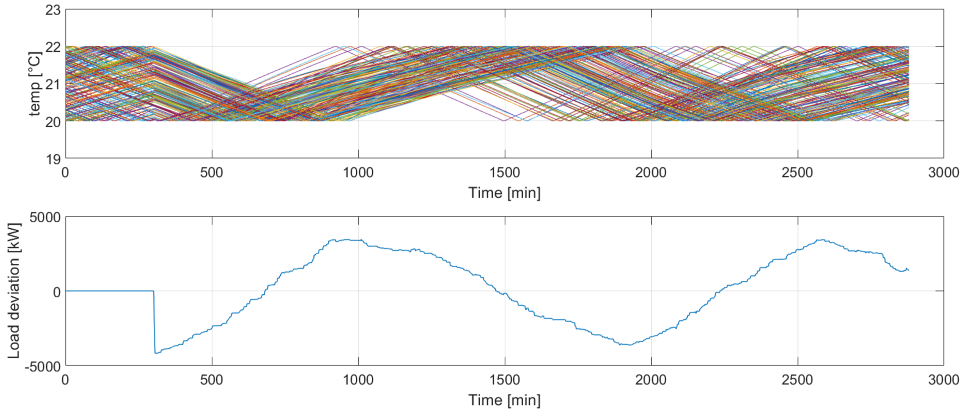

Figure 16. Indoor temperature and the load deviation curve at 0ºC

Before the control signal att minute 300 there is a even distribution of indoor temperatures and approximate 50% of the HPs are on. When the control signal is activated all HP that were active turns off within 6 minutes and the indoor temperature is allowed to decrease to the lower limit. The HPs turns on again when the lower limit is reached and the control signal is deactivated. The synchronization of the HP results in that more than 50% of the HP are in a on-mode after the control signals has been deactivated. When investigating each HP individually the regeneration energy pattern is not observed since the HP have a maximum power and are either On or Off but aggregated the regeneration energy needs to be taken into the flexibility assessment. The flexibility curve for cold ambient temperature (-15ºC and -20ºC) have the same chareteristics as an individual HP. Approximate 95% of the HPs are in an on-mode and operating on maximum power before the control signal has been activated. When the control signals has been deactivated, i.e the lower indoor temperature limit has been reached, the HP turn on and work on maximum power to increase the temperature creating a load deviation curve as presented in figure 17 without any occilations.

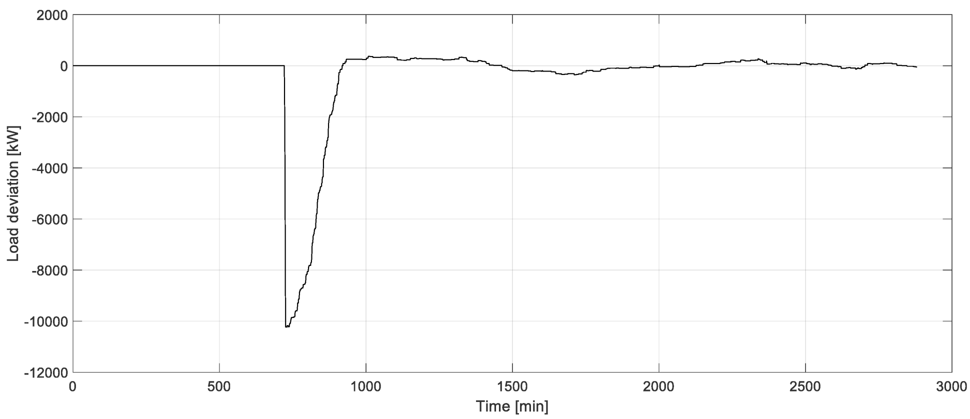

Figure 17. Load deviation curve at -15ºC

Table 10 also compiles the regeneration times and regeneration energy. The regeneration times vary and no clear pattern can be observed. Since the regeneration is defined as the deviation from the base line case the stochastic variables in the model affect the results.

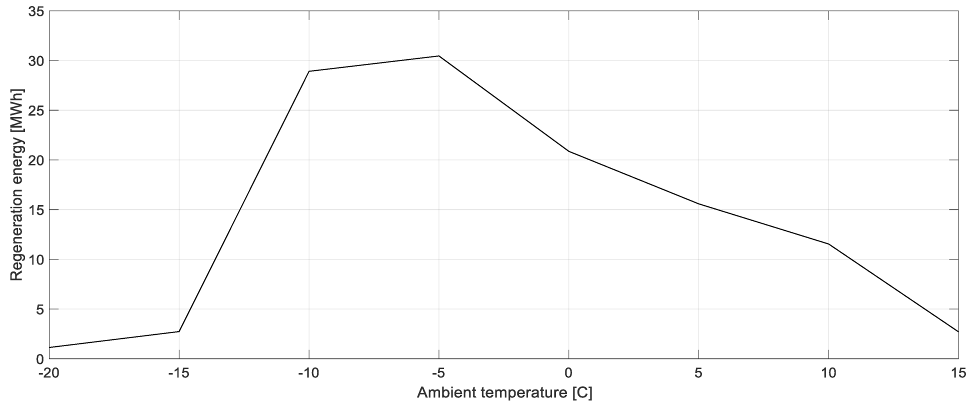

Figure 18. Regeneration energy dependent on ambient temperature

The regeneration energy has it maximum value at -5°C and then steadily decrease with the increase in ambient temperature. The low values of the regeneration energy at low ambient temperatures, -15°C and -20°C, can be explained by figure 17 that shows that the aggregated HP are operating at maximum power before the DR control signal and return to that state after the lower limit has been reached.

The total energy shift that the DR controller causes is demonstrated in figure 19. The zero intersections point for the total energy shift can be found at -9ºC. At ambient temperatures below the intersection point is the flexible energy greater than the regeneration energy and at temperatures above the intersections point the opposite relationship exist.

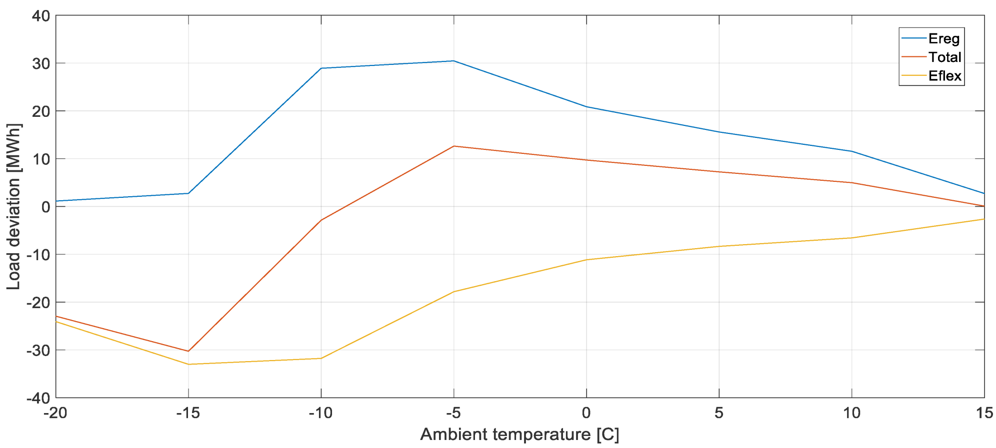

Figure 19. Regeneration energy, total energy and flexible energy

6.1.1 Applied control strategies

After a first assessment of the flexibility and input from Grill, an applied control strategy was design to fit the need from the distribution grid area. It was discovered that during the distribution grid area most critical days, the highest power demand usually occurred at time 12 p.m. and 5 p.m. and at ambient temperatures below zero (Grill, 2018). The five hours between the power peaks mean that the repeatability criteria for the flexibility resource could not be fulfilled and other control strategies need to be considered. The first control strategy that was tested was to activate the DR control signal again at minute 1020 (5 p.m.) after that the control signal had been activated at 720 min (12 p.m.).

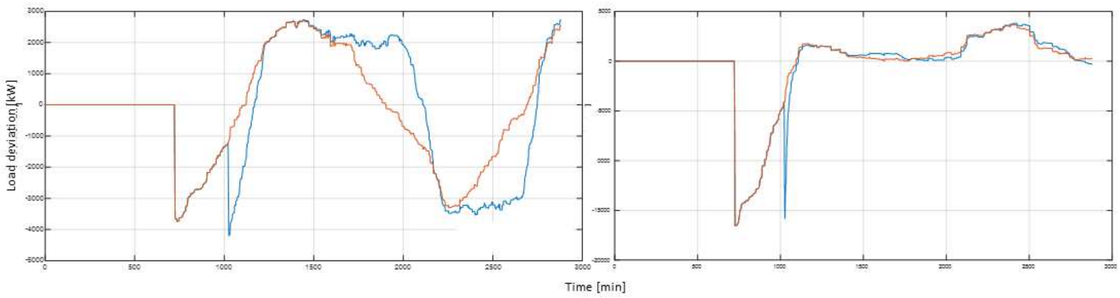

Figure 21. exampel of a controller with two DR off signals at 720 min and 1020 min. Left graph: ambient temperature, -5°C. Right graph: ambient temperature, -15°C

Figure 21 shows how it is possible to use the flexibility resource again before the repeatability time has occurred with the consequence that the flexible energy decreases. This was not an optimal control strategy for the case of this specific ditribution grid area as the power peak at 5 p.m. sometimes was larger than the one at 12 p.m..

The second control strategy investigated was to decrease the duration and repeatability times so that the resource was available again after 5 hours. To achieve this a stochastic element was added to the controller with the purpose to start the heat pumps randomly between time t_1 and t_2 after the control signal was activated. The need for a power consumption reduction (flexible energy) lasted for two hours at both peaks during the critical days meaning that the controller should maximize the energy during these two hours at the same time as the repeatability time should be minimized. By turning on the heat pumps gradually between time points, t_1 and t_2 after the controllers has been activated, the aggregated HP load increase steadily which represent an outdoor controller where the information about the ambient temperature is manipulated so that the HP heat up the building slower and at a lower power than it would have otherwise. The time interval found to maximize the flexibly energy for two hours without causing larger power peaks after the control signal (due to regeneration) was; t_1=90 [min], t_2=210 [min]. A smaller interval resulted in a synchronization of the heat pumps, which lead to a higher regeneration peak than P_{flex}. However, this control strategy was not able to reduce the repeatability to 5 hours and could therefore not be used to cover both power peaks.

The third control strategy tested meant that the MFRBs was divided into subgroups so that a percentage (*x*) of the MFRBs received the off signal at 12 p.m. and (1-*x*) of the MFRBs received the off signal at 5 p.m. It was then possible to optimize the relationship between the subgroups of MFRBs so that both peaks were reduced to the same power. See Grills (2018) work for a more detailed explanation on how the optimal relationship between the number of MFRB in the subgroups was found for each power peak in the distribution grid area.

6.2 Electricity price region

The simulations were performed on a county level and the flexibility was calculated for each county. To obtain the results for SE3 the flexibility results from all counties were considered and either added to the total or used in calculation of mean values. See table 11 for a compilation of the flexibility parameters.

Table 11. Summary of results electricity price region SE3

Ambient temperature	-20	-15	-10	-5	0	5	10	15
T_{resp} [min]	6	6	6	6	6	6	6	6
T_{dur} [hrs]	4.4	5.2	5.5	5.3	5.4	6.0	7.2	9.8
E_{flex} [MWh]	411	502	427	308	233	200	163	61
T_{reg} [hrs]	11.0	9.9	16.1	15.3	11.6	12.5	16.3	8.1
P_{flex} [MW]	169	159	124	93	68	56	36	13
E_{reg} [MWh]	102	115	377	457	413	353	226	44
T_{rep} [hrs]	30	25	20	15	10	9	7	10

Figure 22 shows that E_{flex} for SE3 follow the same pattern as for the distribution grid. The maximum value of E_{flex} is found at ambient temperature -15°C

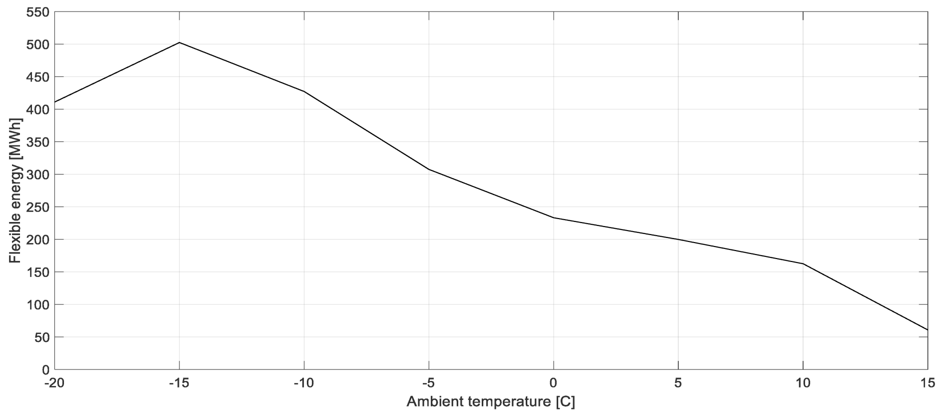

Figure 22. Flexible energy (E_{flex}) depending on ambient temperature

The HP are dimensioned for approximate -15°C which means that there no increase in power between -15°C and -20°C at the same time as the heat transmission losses increase due to the lower ambient temperature resulting in a decrease of T_{dur} (see table 11). The total flexible energy is therefore less at -20°C than at -15°C as can be seen in figure 22.

The duration of the load shift depends on the heat transmission losses and the available HP resource i.e. the number of active HP and their power. The increase in repeatability time between 10°C and 15°C can be explained by the longer duration time of the flexibility energy. At 15°C the indoor temperature decreases slowly resulting in an average Dur of 9.83 hours. The definition of repeatability, see equation 10, then leads to a longer repeatability time than for 10°C. It is quite likely that it would be possible to start approximately 5%, which is the percentage of active HP at 15°C, of the HP's with the corresponding lowest indoor temperature a certain time period after the DR signal has been activated to ensure that the same flexibility resource is available again in 7 hours. The respond time for the HP in SE3 is the same as for the distribution grid area, which had a respond time of 6 min.

10146 MFRB are used in the simulations for SE3, which means that with a P_{flex} of 169 MW, at ambient temperature -20°C, that the average power for an HP is 16.66 kW which is lower than the average power for an HP in the distribution grid.

Figure 23 shows the E_{reg} that in the same way as E_{flex} follow the same pattern as for the distribution grid. For information about T_{reg} see table 11.

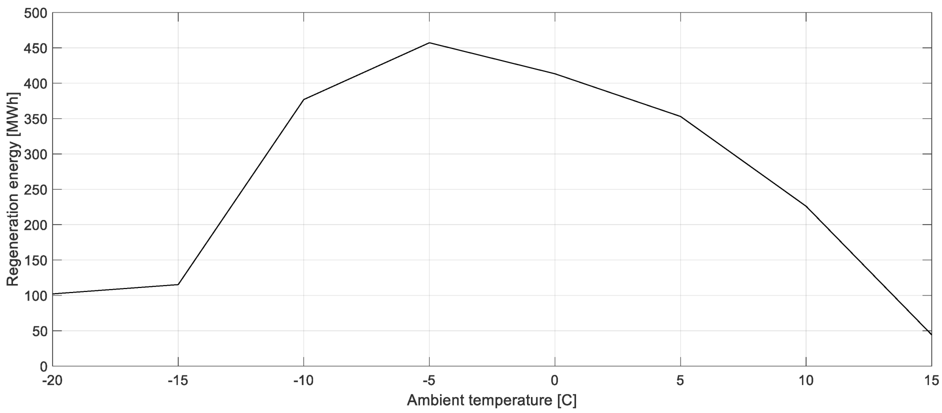

Figure 23. Regeneration energy for SE3 depending on ambient temperature

Figure 24 illustrates how the regeneration varies for the same ambient temperatur but different signal activation minutes. The load curves difference between the different cases where the curve that was activated att 600 min has the longest regeneration time as the flexibility curves comes close to crossing zero at approximates minute 1700 but first do so at approximate minute 2600.

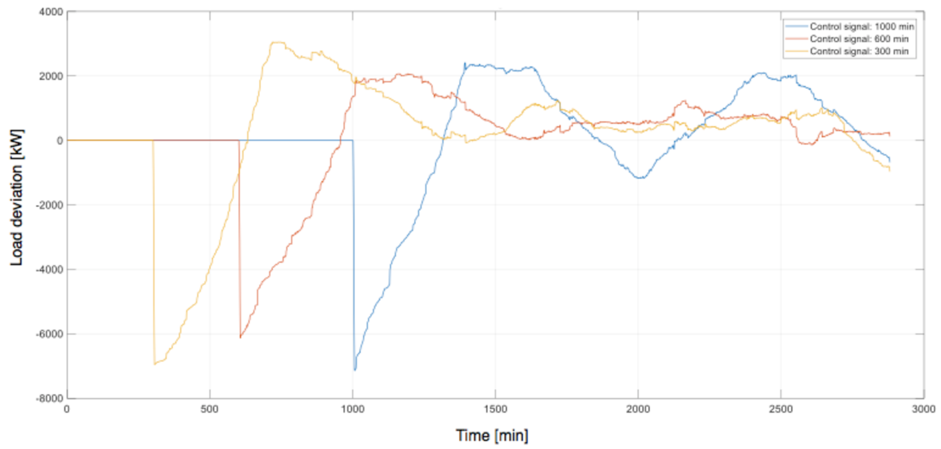

Figure 24. Example of how the regeneration varies depending on the control signals activation minute at ambient temperature -5ºC

The total energy shift that the DR controller cause is demonstrated in figure 25. The zero intersections point for the total energy shift can be found at -8.7ºC.

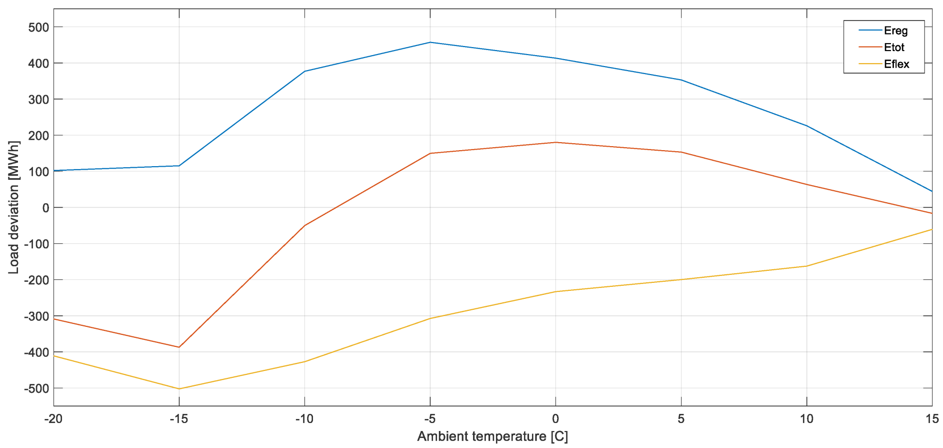

Figure 25. Regeneration energy, total energy, flexible energy dependent on ambient temperature

6.3 Results analysis

The lower average area of the MFRBs in SE3 and the relationship between MONO and BIV system solutions explains the lower average power per HP in SE3 compared with the distribution grid area. See table 12 for a comparison between the input data that explains the difference in average power contribution per HP to the flexibility.

Table 12. Comparison of input data for distribution grid area and electricity price region

Input	Distribution grid area	Electricity price region
Number of MFRB	174	10146
Average area [m^2]	3000	1145
Average number of apartments	29	13
Number of BIV systems	59 (34%)	7070 (70%)
Number of MONO systems	115 (66%)	3076 (30%)

A higher share of BIV systems means the district heating system covers the peak load at low ambient temperatures and the dimensioning of the HP decrease since direct electric heating is not included. The comparison between the distribution grid area and the electricity price region could be used as argument to first and foremost install DR compatible solutions on HP in large MFRBs that have a mono-energetic solution where the direct electricity heating is included in the flexibility assessment.

An interesting finding in the thesis is the size of the regeneration energy and the regeneration time. The purpose with the DR off-signal is to release power during high demand periods in the electricity grid and a large regeneration energy and an oscillating load will do the opposite if it creates an even larger electricity demand after the DR control signal. This will cause problems for the electricity grid if it is still experiencing congestions problems when the regeneration has its peak. For the interest of the grid operator a requirement for using HP in MFRB as a flexible load would be to reduce the regeneration peaks. An advanced, predictive DR control strategy might be to be able to utilize the flexibility from HP without causing oscillations in the HP load and regenerations peaks that is greater than the first peak that triggered the need for the flexibility. A more advanced controller could probably increase the time interval for when the HP turns on after an DR off-signal to prevent a synchronization of the HP and the larger power peak after a control signal. This could be achieved by increasing the indoor temperature in some MFRB before the off signal and/or by turning on some HP before they have reached the lower limit of 20ºC. By reducing the power peaks that would have exceeded the physical limit of the electricity grid could the distribution grid owners potentially postpone or avoid building costs for expansions of the electricity grid infrastructure.

Due to time restrictions of the thesis, three DR control signals were activated per ambient temperature and then used to calculate a mean value. Figure 26 shows an example on how the base line load profile for 3870 HPs in Stockholm county looks like and the responding load profile after an DR control signal had been activated.

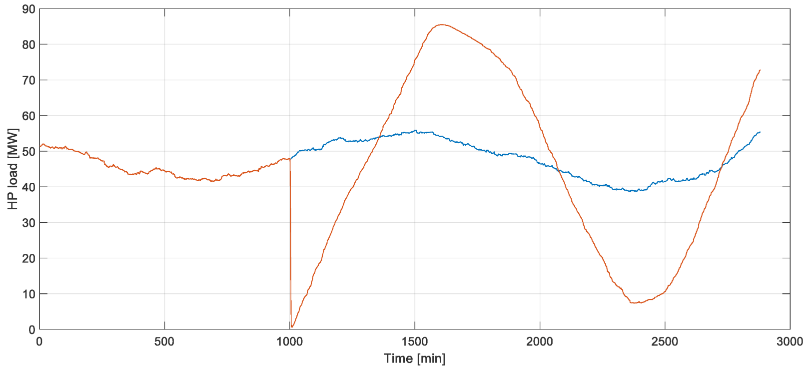

Figure 26. Base line HP load (blue line) and DR controller HP load (red line) for 0°C

Aggregated, the base line HP load appears relative even for the period simulated. This means that the time when the control signal is activated will not have a large impact on the result and that three control signal activations is enough to gain a first opinion about the HP flexibility potential.

The simulations were performed for ambient temperatures between -20ºC and 15ºC. See figure 27 for a demonstration on how the flexibility at ambient temperature 20ºC is close to zero and therefore not further investigated in the thesis.

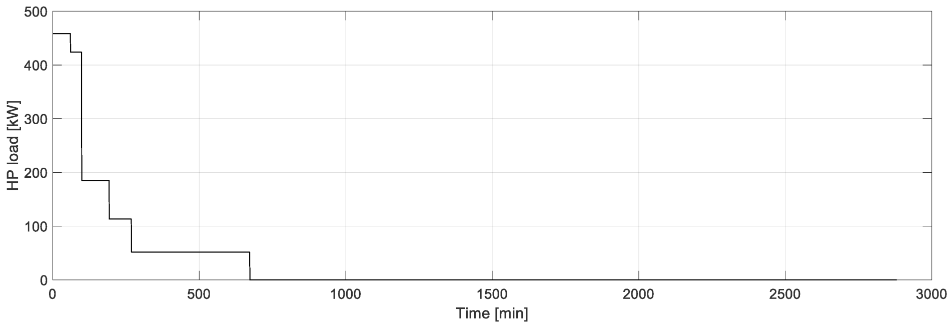

Figure 27. HP load at ambient temperature 20°C in distribution grid area

The probability of an HP being in an on state at 20°C in the beginning of the simulation is 0.05 based on Fisher et al (2018) results. The HP are all turned off after 700 min meaning that no heating is needed from the HP (district heating is needed for the DHW demand).

6.4 Application of the flexibility assessment results

The purpose of this section is to place the results from this master thesis in a context to get an understanding of the potential of demand flexibility from heat pumps in MFRB. The result from the flexibility assessment in this thesis are further analyzed in Grills master thesis "Market potential for using demand response from heat pumps in multi-family buildings" and the following is a summary of the key findings of Grills analysis using the load deviation curves generated in the simulations in this thesis. See Grills thesis for a detailed explanation of the calculations and results.

The two most favorable markets for the BRP to trade the flexibility on is the power reserve market and the balancing market (mFRR). The average income on the power reserve market per season (November to February) is approximate 1 133 000 SEK in administrative compensation and 104 000 SEK per call off. This income is generated by a demand flexibility of 26MW in SE3. The average income potential from the balance market varies between approximate 874 000 SEK and 5 709 000 SEK per season depending on year.

The grid operator in the case study performed in Grills thesis could reduce their highest peak power with an average of 2.92 MW for one year. The peak power reduction generated a cost reduction of 483 000 SEK/year including the reduction of penalty fee and power subscription fee.

7. Discussion

The thesis use data for all MFRB with HP in the simulations for the distribution grid area and electricity price region. It is however not likely that all HP have a built-in information technology system so that the HP can receive and send information, such as an off-signal. Newer HPs, installed in the last couple of years, have this function and could therefore be used as a flexible load reacting on an external signal, for example the need to release power in a distribution grid area under high power demand periods. Interviews with personnel at Vattenfall AB and statistics of the HP development (Energimyndigheten, 2017) implies that the number of HP in MFRB will continue to grow consequently increasing the potential of utilizing the flexibility arising from the thermal inertia of new buildings in combinations with HP that have a built-in information technology solution. The HPs could also be tuned on by an external signal, for example, the BRP could use the HP to increase consumption and decrease their imbalance. But since it might be considerate wasteful to increase consumption instead of decreasing production and the fact that increasing the consumption will always put more pressure on the electricity grid infrastructure only the potential of turning off the HP and utilizing the buildings thermal inertia was investigated in this thesis.

The long regenerations time at low ambient temperatures (30 hrs for -20°C and 25 hrs for -15°C) indicates that the heating system in the simulation is under-dimensioned as it takes a long time to increase the temperature in the MFRB one degree. After a discussion with personnel working with heating system in MFRB at Vattenfall it was discovered that the winter dimension temperature commonly used by them in Stockholm is -18°C which differs from the data extracted from SMHI that had an average winter dimension temperature of -11°C in Stockholm. During the calibration of the model the winter dimension temperature was lowered with two degrees. A larger adjustment of the winter dimension temperature would have probably increased the repeatability of the flexibility by increasing the HP power capacity. A lower winter dimension temperature would therefore positively influence the flexible power parameter, the flexible energy and the repeatability of the flexible energy by increasing them.

The simulation time was 48 hours (2880 min) as it was important to see the control signals effect on the load profile. A longer period would mean a longer simulation time and was decided against due to efficiency reasons and time restrictions of the thesis. A longer simulation period would show how the oscillation of the load deviation curve would decrease with time after DR controller had been activated and it would have been possible to calculate the entire energy difference between the base line HP load and the DR control HP load. A longer simulation time would therefore be suitable for analyzing the effect a DR solution would have on end-consumers' HP demand.

8. Conclusion

An aggregated MFRB model that generates heat load profiles for buildings was developed and validated. A DR controller was implemented in the model to facilitates an assessment of the potential to use HP as a demand response solution.

Conducting a flexibility assessment is a complex process that involves several parameters. Seven flexibility parameters were defined in this thesis to contribute to a holistic assessment of the HP flexibility potential; (1) Respond time, (2) Flexible energy, (3) Duration of load shift, (4) Flexible power, (5) Regeneration time, (6) Regeneration energy and (7) Repeatability. The importance of each flexibility parameter varies with the purpose to use the HP flexibility.

The results show that there are potential to use HPs in MFRB as a flexible load to either be traded by a BRP on different markets or to deliver power during high demand periods in a local distribution grid. The thermal inertia of MFRB facilitates a load shift with a duration of 4.4 to 9.8 hours depending on the ambient temperature. The maximal average power for one hour, that occurs the first hour after the off-signal has been received by the HPs, of 10 MW in a distribution grid with 174 MFRB and 169 MW in an electricity price region with 10146 MFRB illustrates the potential of using HPs in MFRB as a demand response solution. The duration of the load shift and the aggregated power during the load shift determines the flexibility energy that varied between 3MWh and 33MWh in the distribution grid has it maximum value at -15 ºC. In the electricity price region, the flexible energy varied between 61MWh and 502MWh with the maximum value at -15 ºC. The regeneration energy and regeneration time are caused by a synchronization of the HP after the DR control signal and important parameters to consider when assessing the flexibility potential since they represent a load deviation that increase the demand on the electricity grid in comparison to a case where no DR control signal was used. The flexibility potential from HP are higher at low ambient temperatures as the number of active HP increase when the temperature decrease. The maximum value of the flexible energy, the high flexible power and the low value of the regeneration energy makes -15ºC an optimal ambient temperature to use the HP flexibility, if the purpose is to reduce the peak load during a shorter period and without causing a larger peak after the control signal.

The regeneration energy and time place constraints on utilizing the flexibility from HP in MFRB which means that it would be interesting to further investigate DR control strategies that would minimize the regeneration energy and regeneration time. An advanced predication of the electricity demand is also of great importance as it is crucial to use the HP flexibility at the right time to not cause larger peak demands after a DR control signal. It would also be interesting to study different energy storage, such as bore holes and accumulation tanks effect on the demand flexibility. Furthermore, could future work include an analysis on how district heating and HPs in MFRB could be controlled, operated and optimized in the interest of grid operators and end-users.

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Appendix A

Compilation of interviews

Organization	Position	Date and place
Vattenfall AB Research and development	R&D senior engineer	Regular meetings, Solna
Vattenfall AB Research and development	R&D senior engineer	Regular meetings, Solna
Vattenfall AB	Senior sourcing manager: BRP	Regular meetings, Solna
Vattenfall AB Research and development	Program manager R&D	2018-02-20 Solna
Vattenfall AB Research and development	Customer solutions portfolio manager	2018-02-28 Solna
Sustainable Innovation	Project engineer in pilot project of flexible HPs "KlokEl"	2018-03-29 Phone interview, Solna
Ngenic	CEO	2018-04-18 Uppsala
Vattenfall AB Eldistribution	Business developer	2018-04-19, 2018-05-03 Solna
Vattenfall AB Inhouse	HP expert 1	2018-05-10 Phone interview
Vattenfall AB InHouse	HP expert 2	2018-05-24 Solna
NIBE	HP expert 3	Email conversation