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Market potential for using demand response from heat pumps in multi-family buildings

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Abstract

Market potential for using demand response from heat pumps in multi-family buildings

Rebecca Grill

More renewable energy leads to higher energy imbalances in the Swedish electric power system. In the same time, the grid capacity is almost reached in some regions which requires an extension of the current grids or a reduction of the power consumption. Demand response could be a key factor for both stabilizing the energy balances and reducing the grid congestion. The aim with this thesis is to analyze the potential incomes that demand response from heat pumps can generate for the balance responsibility parties and the grid operators and evaluate how it would affect the end-consumers.

The investigated local grid that contains of 174 multi-family buildings with heat pumps could reduce its highest peak power with 2,9 MW. This peak power reduction generated a cost reduction of 483 000 SEK per year or 2800 SEK per building per year in reduced penalty fees and power subscription fees. The mFRR market and the power reserve market were determined to be the most suitable markets for using demand response from heat pumps on for the balance responsibility party in the electricity price region SE3. SE3 consists of 10146 multi-family buildings with heat pumps. The mFRR market generated an average income of 2 699 000 SEK per winter season whereas the power reserve market generated a yearly administrative compensation of 1 133 000 SEK per season and 104 000 SEK per call-off. It is important that end-consumers obtain demand-based tariffs or hourly based tariffs to enable a cost reduction from the control system.

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Populärvetenskaplig sammanfattning

I och med ökade krav om en övergång från fossila energikällor till förnyelsebara energikällor står energisystemet idag inför stora förändringar och utmaningar. Förnyelsebara energikällor är oftast mer väderberoende än fossila energikällor, vilket gör att det är svårare att förutspå energiproduktionen än tidigare. Detta bidrar till att elmarknaden blir alltmer svårbalanserad, där balansen mellan produktion och konsumtion är viktig för att upprätthålla ett välfungerande elnät. Samtidigt ökar användningen av elektrifierade fordon, vilket ställer högre krav på elnäten. Elmätare som möjliggör timmätning av elförbrukningen blir allt vanligare bland elkonsumenter, där tekniska lösningar och tjänster med syfte att få konsumenter att agera mer aktivt i sitt konsumtionsmönster kallas demand response eller förbrukningsflexibilitet. Det kan därmed finnas en nytta av att använda förbrukningsflexibilitet till att balansera den alltmer svängande energiproduktionen samtidigt som det kan användas till att minska belastningen på elnäten som ökar i och med elektrifieringen av viktiga samhällsfunktioner. Värmepumpar har identifierats som en möjlig förbrukningsflexibilitet, där byggnaders isolering gör att värmepumparna kan stängas av utan att förändra inomhustemperaturen för kunderna under en viss tidsperiod som är kritisk för energibalansen eller nätbolaget. Det här examensarbetet ämnar att utvärdera nyttan för nätbolag och balansansvarig att använda förbrukningsflexibilitet från värmepumpar i flerbostadshus samt att undersöka hur det påverkar slutkonsumenterna. Examensarbetet har utförts i samarbete med Vattenfall AB där nyttan för ett specifikt nätbolag och elprisområde har analyserats genom både intervjuer, analys av data samt kvantitativa simuleringar.

Resultaten visar att nyttan för nätbolag främst är möjligheten att sänka potentiella straffavgifter, minska sitt effektabonnemang till överliggande nät samt att få plats till att ansluta fler konsumenter till nätet utan att behöva bygga ut elnätet i lika stor grad. Nätbolaget kunde i genomsnitt spara 483 000 SEK per år genom att använda förbrukningsflexibiliteten till att minska straffavgifterna och effektabonnemanget, vilket kan likställas med 2800 SEK per flerbostadshus per år. Styrningen av värmepumparna gör att effekttopparna minskar för konsumenterna, medan deras energikonsumtion både kan minska och öka beroende på utomhustemperaturen när förbrukningsflexibiliteten utförs. Det rekommenderas därför att konsumenterna har ett elprisavtal där de betalar för effekt istället för energi och har ett rörligt timpris för att de ska få en minskad elkostnad av att bidra med sin förbrukningsflexibilitet.

Det finns flera marknader där de balansansvariga kan använda förbrukningsflexibilitet till att stabilisera energibalansen i elnäten. De marknaderna som identifierades som optimala för den här resursen var mFRR-marknaden och effektreservmarknaden. Genom att bidra till systemets energibalans får den balansansvariga ekonomisk ersättning av Svenska Kraftnät. Den här resursen resulterade i en genomsnittlig intäkt eller kostnadsreduktion på 2 699 000 SEK under en säsong i ett elprisområde på mFRR-marknaden, där en säsong representerar perioden 16/11 till 15/3. Den potentiella intäkten från effektreservmarknaden identifierades till 1 132 000 SEK i administrativ ersättning under samma säsong. Studien visar även att behovet av att minska konsumtionen inte behöver sammanfalla för nätbolaget och den som är balansansvarig i regionen. Om nätbolaget bestämmer sig för att minska konsumtionen när det är hög belastning i elnätet kan det istället resultera i ökade kostnader för den balansansvariga.

För att använda förbrukningsflexibilitet från värmepumpar är det viktigt att utvärdera de olika aktörernas roll och ansvarsområden. Samma resurs kan inte användas för olika syften samtidigt och det är därför viktigt att det finns en tydlig kommunikation mellan nätbolag och ansvarsområden. En vidareutveckling av studien är även att utvärdera potentiella praktiska implementeringsmöjligheter och kostnader för att analysera om det är praktiskt möjligt och lönsamt.

Acknowledgement and foreword

This master thesis is the last part of the Master’s Programme in Sociotechnical Systems Engineering at Uppsala University. The thesis has been conducted at Vattenfall AB at the Recource and Development department in the Data Analytics and ICT Solutions team. I would like to thank my mentors Anders Lindgren, Mats Hagelberg and Nader Padban at Vattenfall AB for continuous support through the project as well as my supervisor Joakim Widén at Uppsala University. I would also like to thank all employees at Vattenfall AB, Svenska kraftnät, Ngenic and Sustainable Innovation that have participated in interviews or provided data that has been valuable for the thesis.

The thesis has been written in close collaboration with Sabina Oehme, who has written her thesis during the same time at the same department. The purpose of Oehme’s thesis was to calculate the aggregated flexibility from heat pumps in multi-family buildings in a local grid as well as in a price area in Sweden. The calculated flexibility in Oehme’s thesis has been used in this thesis when evaluating the effects of demand response from heat pumps for the grid operators, end consumers and the balance responsibility party.

Rebecca Grill

Uppsala, maj 2018

List of terms

Additional price: Svenska kraftnät charges the BRP the additional price if the BRP's imbalance volumes contribute to the system's total imbalance. If the BRP's imbalance volumes do not match with the system's total imbalance, Svenska kraftnät pays the additional price to the BRP for their imbalance volumes.

Asymmetric product: A regulating product that only can be activated for either up- or down regulating purposes.

Balance regulation: Up or down regulation of production or consumption to stabilize the frequency level by performing primary, secondary or tertiary regulation or by using the power reserve.

Balance Responsible Party (BRP): A company that has the responsibility for the electricity balance for production and consumption for a certain group of customers.

Balance set-off: Economic settlement between the BRP and Svenska kraftnät where Svenska kraftnät calculates the BRP's imbalance costs for an electricity price region.

Controlling: When the heat pumps are controlled to turn off to reduce the power consumption. The power consumption curve during a controlling differs from the original power consumption curve for several hours, where it is lower during the first hours and generally higher during the following hours. The hourly change in power consumption that occurs during a controlling is defined as demand flexibility and can be seen in Appendix A for different outdoor temperatures.

Demand response: Changes in electricity consumption by the end consumers compared to their normal electricity consumption pattern. The purpose can for example be to reduce the grid load during critical periods or to reduce the consumption when the electricity prices are high.

Down regulation: Reduced production or increased consumption.

Electricity price region: One of the four electricity trading areas in Sweden, where each electricity price region has an individual spot price and additional price based on the supply and demand in each region.

Heat debt: Heat pumps need to be turned on to increase the indoor temperature to its nominal value for the end-consumers after they have been controlled to turned off. The energy consumption may therefore be higher than the original consumption curve when they are turned on, due to the heat debt.

Power reserve: Regulation capacity in production or consumption that can be activated within 15 minutes to stabilize the frequency level.

Primary regulation: Continuous automatic adjustment of the physical electricity balance in the Swedish power system by up or down regulation.

Regulation power: Power that Svenska kraftnät buys during the delivery hour to create an energy balance in the Swedish power system.

Secondary regulation: Automatic up or down regulation of the physical electricity balance in the Swedish power system by using the Automatic Frequency Restoration Reserves (a-FRR).

Symmetric product: A regulating product that can be activated both for up- and down regulating purposes.

Tertiary regulation: Consists of Manual Frequency Restoration Reserves (m-FRR), which manually stabilize the frequency level.

List of abbreviations

aFRR	Automatic Frequency Restoration Reserves
BRP	Balance Responsibility Party
DR	Demand Response
FCR-D	Frequency Containment Reserve for Disturbances
FCR-N	Frequency Containment Reserve - Normal
HP	Heat pumps
mFRR	Manual Frequency Restoration Reserves

Innehållsförteckning

1. Introduction

The energy sector is in the beginning of a shift where the centralized large-scale electricity production is decreasing, while the decentralized production of intermittent renewable energy sources is increasing. The increased level of intermittent sources in the electricity power system affects several different market actors. It is more difficult to forecast energy injection from renewable energy sources such as wind and solar and it is therefore more complicated to keep the energy balance on the electricity markets. In this way, the increasing level of intermittent energy sources leads to higher imbalance costs.

A promising solution for managing imbalances for electricity market actors is Demand Response (DR). The aim with DR is that end-consumers change their power consumption based on market signals. The thermal inertia in the building stock can be utilized to turn off heat pumps when the electricity consumption needs to be decreased, which could possibly contribute to maintaining the energy system balance as well as reducing the grid load in the near future. It is therefore interesting to analyze the potential economic benefits that this solution can generate for the Balance Responsible Party (BRP).

The BRP is responsible for the financial outcome of the Transmission System Operators (TSO) periodical balance settlement for the BRP. This settlement is calculated as the cost effect that arises from the hourly difference between procured and consumed power in the BRP portfolio. It is also interesting to evaluate the effects of this solution for the grid operators that potentially can decrease grid congestion and generate a more even grid load. This may result in economic benefits for the grid operators as they may be able to reduce their capacity subscription level and reduce the risk of exceeding the level and having to pay fines. It is therefore interesting to evaluate what value this service creates for the grid operators in order to analyze if it is a profitable business case to sell the flexibility that this DR solution generates. Another actor that would be affected by this solution is the end-consumer that may have their indoor temperature changed when the heat pump is regulated. An area that is interesting to investigate is therefore also how the end-consumer would be affected when the heat pump system is controlled.

1.1 Purpose

The aim of this master thesis is to evaluate the market potential for using demand response from heat pumps in multi-family buildings by utilizing the thermal inertia in the buildings. The purpose is firstly to evaluate the potential cost reduction it can generate for local distribution grid operators, in the form of reduced penalty fees and power subscription fees. These results are then analyzed from a consumer's perspective with the aim of evaluating the economic effects that using DR from heat pumps would have for end-consumers with hourly based electricity tariffs. Furthermore, the aim is to evaluate if it can lead to reduced imbalance costs by using DR instead of adjusting the energy balance on the intraday-market or paying imbalance fines. Potential markets such as the primary, secondary and tertiary market are also identified with the aim of determining the most suitable market products for this resource. This will be based on the characteristics of the flexibility such as how quick the heat pumps are to respond and how much power reduction the control system can generate. Finally, the purpose is to evaluate if these potential benefits can be combined to generate a profitable impact for several actors. The following more specific tasks will be performed:

1.2 Research objectives

1. Evaluate the potential economic savings that DR from heat pumps in multi-family buildings can generate for grid operators in the form of decreased penalty fees and power subscription fees.

2. Determine the optimal markets for the BRP to use DR from heat pumps and calculate the potential income from the resource on these markets.

3. Analyze how the end-consumers would be affected if the grid operator or the BRP controls the heat pumps.

1.3 Outline of the thesis

Chapter 2 contains the background information that is necessary to understand the framework of the study. The chapter describes how the Swedish electric power system is composed, the power exchange markets, the power regulation possibilities and the definition of demand response. The data that has been collected and the interviews and calculations that have been performed are then described in chapter 3. Chapter 4 illustrates the results in form of the market potential for demand response for the BRP and the grid operator and the effect the controllings may have on the end-consumers. This is followed by chapter 5 where a discussion of the results is performed. Finally, a conclusion of the results is summarized in chapter 6.

2. The Swedish electric power system

This section describes all the necessary background information about the electricity market in Sweden that is needed to understand the concept of the thesis.

2.1 The electricity market

The electric power system in Sweden consists of several market actors with different tasks and responsibilities. The flow of electricity is transmitted and distributed through three different levels of the grid that can be seen in figure 1. The Swedish national grid consists of 15 000 kilometers of power lines, where the power lines that are located closest to the large power stations are high voltage transmission lines. The electricity is then transported for long distances in the national grid until it has reached the regional grids that obtain voltage levels between 20 kV to 130 kV. Electricity-intensive industries such as paper mills often receive their electricity directly from the regional grid. The electricity is then transported from the regional grids to the local grids that provide smaller industries and households with electricity. The voltage level is gradually transformed to lower levels until it has reached 230 V, which is the normal voltage level in households (Södra Hallands Kraft). The different voltage levels in the different parts of the grid can be seen in figure 1 below.

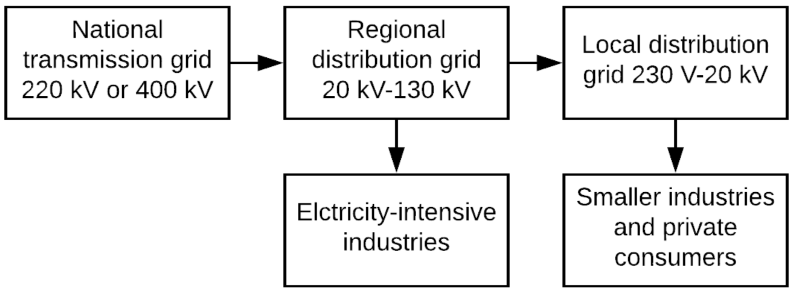

Figure 1. An overview of the Swedish power grid system (Södra Hallands Kraft).

2.1.1 Electricity producers

Electricity producers produce the electricity and transfer it to the grid they are connected to. Larger producers can connect to the national transmission grid where there is a minimal requirement of transferring 300 MW for the 400 kV grid or 100 MW for the 220 kV grid, whereas smaller producers can connect to the distribution grid (Svenska kraftnät, 2016e). The produced electricity is then sold to an electricity retailer that transfers it to the end consumers (Energimarknadsinspektionen, 2010). A prerequisite is that someone undertakes the economic responsibility that the electricity input is equal to the output. The producer can either take the balance responsibility by themselves by signing a balance agreement with the TSO or consult another company that act as the BRP (Energimarknadsinspektionen, 2014).

2.1.2 Transmission system operators

The transmission system is used for transferring energy over long distances from production sites to consumption areas (Södra Hallands Kraft). Svenska kraftnät is the transmission system operator (TSO) in Sweden and is therefore responsible for building new power lines when needed as well as maintaining the transmission grid in order to ensure a secure electricity supply. Furthermore, Svenska kraftnät has the overall responsibility to keep the energy balance between electricity production and consumption to prevent potential grid disruptions (Svenska kraftnät, 2016a). The TSO also works to simplify the electricity trading as well as to ensure that the trading is performed in free competition (Svenska kraftnät, 2017a).

2.1.3 Distribution grid operators

The distribution grids are divided into regional and local distribution grids. There are five companies that own the regional distribution grids in Sweden, consisting of; Ellevio, E.ON Elnät Sverige, Laforsen Produktionsnät, Skellefteå Kraft Elnät and Vattenfall Eldistribution. In the regional distribution grid, electricity is distributed to larger electricity-intensive industries such as paper and steel mill industries. There are approximately 1600 border points between the regional and the local distribution grids (Granath, Gustavsson, 2014).

The local distribution grid delivers electricity to smaller industries and private consumers (Södra Hallands Kraft). There are approximately 160 electricity companies in Sweden that administer the local distribution grids, where E.ON, Ellevio and Vattenfall together own half of the local grid and have approximately half of the consumers (Granath, Gustavsson, 2014). Consumers cannot decide their Distribution System Operator (DSO) but have the opportunity to decide their electricity retailer. In Sweden, all grid operators report their measures for electricity production and consumption to the electricity retailers, producers, BRP and to Svenska kraftnät that has the system responsibility. This gives the grid operators an important role in the balance set-off (Energimarknadsinspektionen, 2014).

2.1.4 Electricity retailers

While the grid operators control the physical transmission, the electricity retailers manage the economic trading of power and energy. The electricity retailers buy electricity from the producers and sell it to the users. There is free competition between the electricity retailers and the consumers can decide what retailer they want to sign their agreement with. A prerequisite for the retailer to be able to sell electricity is that someone undertakes the balance responsibility for the retailer’s customers by signing a balance agreement with

Svenska kraftnät. The retailer can either take the balance responsibility by themselves or consult another company that act as the BRP. (Energimarkndsinspektionen, 2014)

2.1.5 Balance responsibility party

The BRP is responsible for the financial outcome of the Transmission System Operators (TSO) periodical balance settlement for the BRP. This settlement is calculated as the cost effect that arise from the hourly difference between procured and consumed power in the BRP portfolio. The BRP aim to accomplish an energy balance by trading electricity for the production and/or consumption that the BRP has responsibility for. The balance responsibility can be divided depending on if it is a production or consumption balance responsibility. The BRPs plan their electricity trading in advance based on forecasts of the production and consumption. These predictions are based on weather forecasts as well as historical production and consumption data and are continuously updated when there is new climate information (Hagelberg, 2018). If any BRP has not delivered the expected power production or consumption during a certain hour, it is adjusted economically afterwards in the balance set-off (Svenska kraftnät, 2016c).

2.1.6 Electricity end-consumers

The electricity users withdraw the electricity from the grid and use it for different purposes. Electricity consumers consist of both private households as well as small and larger industries. To use the electricity, electricity users need to arrange two different agreements. The first agreement is between the user and a grid operator and enables the physical usage of the electricity, where the consumer pay a fee according to the agreement for using the grid. The second agreement is to an electricity retailer where the consumer pay a specific price for the amount of used electricity according to the agreement. Large consumers can decide to act as an electricity retailer by themselves and buy electricity directly from the Nordic electricity market while small consumers need to choose an existing retailer. (E.ON, 2018) (Energimarknadsinspektionen, 2014)

2.1.7 Electricity tariffs

While consumers pay fees to the electricity retailer and the local grid operator, local DSO's pay fees to the regional DSO's, who in turn pay fees to the TSO. These prices are determined by different kind of electricity tariffs. Local DSO's subscribe on a certain power level to the regional DSO, where the power subscription cost is determined in a regional grid tariff (E.ON, 2018). The used yearly power level that the local DSO is charged for is defined as the average of the two highest peak power periods that occur during two separate months during a year. If the DSO's yearly power level exceeds their power subscription level, they need to pay 1,5 times the subscription fee for each kW they exceed their subscription level (Vattenfall Eldistribution AB, 2018b). Since both the TSO and the DSO's have a natural monopoly in Sweden, the incomes are regulated by Energimarknadsinspektionen (Ei) to generate fair price levels (E.ON, 2018). Electricity users can either be charged by a fuse tariff or a demand-based tariff. Fuse tariffs are normally used by consumers that have a fuse level up to 63A or 80A. The pricing system consists of a fixed charge based on the fuse level, as well as a variable fee that is determined by the used amount of kWh (E.ON, 2018). A demand-based tariff on the other hand charges the consumers based on the highest peak power usage during a month as well as a fixed charge for the fuse level and a variable charge for the energy consumption. Demand-based tariffs are primarily used by large consumers such as industries and multi-family buildings that obtain fuses larger than 63A or 80A (E.ON, 2018). Some DSO's, including Sollentuna Energi och Miljö AB and Sala Heby Energi AB, have also started to provide demand-based tariffs for smaller consumers (Sollentuna Energi och Miljö AB, SHE).

Consumers can choose to have a set variable fee or have a variating variable fee that is higher during the winter week days between for example 06.00-22.00 and lower during the remaining time of the year. It is the variable fee the consumers pay to their electricity retailer (Vattenfall Eldistribution AB, 2018a). Since 2012, electricity consumers can also choose to be charged for their hourly consumption based on the spot price without any extra costs for a new electricity meter or hourly measurement costs. In this way, consumers can reduce their electricity costs by controlling their heating system based on the hourly electricity prices (Alpman, 2012). According to Bartusch et al. (2010), it is compulsory to expose consumers to hourly spot prices in order to enhance the potential for demand response. Berg, B. (2018), that is the CEO for Ngenic that currently aggregates demand flexibility from heat pumps in detached houses, also claims that Ngenic's customers need to have an hourly based tariff to use Ngenic's control system. Hourly variating costs that are based on the spot price are therefore regarded when analyzing how consumers are affected by using DR from heat pumps.

2.2 The power exchange

The Swedish electricity market consists of several marketplaces that are used for physical trading of electricity (EI, 2017). Nord Pool Spot holds the responsibility for the day-ahead market Elspot and the intra-day market Elbas, whereas Svenska kraftnät is responsible for the Swedish balancing market (Nord Pool, 2017a). Nord Pool is owned by Svenska kraftnät and the other TSOs in the Nordic and Baltic countries (Svenska kraftnät, 2016b). The electricity supply and demand vary between different regions, where the supply is higher than the demand in the northern parts of Sweden, while it is the opposite in southern Sweden (Svenska kraftnät, 2017a). The differences in supply and demand create various electricity prices in different regions. The day-ahead and intra-day market are therefore divided into various bidding areas, where Sweden consists of four different electricity price regions (Nord Pool, 2017a). If the available transmission capacity is large enough to compensate for the supply and demand differences by transferring capacity, it will result in similar electricity prices in the different electricity price regions. If the transmission capacity is not large enough, it will result in different electricity prices in the regions (Forsberg et al., 2014). The different electricity price regions can be seen in figure 2.

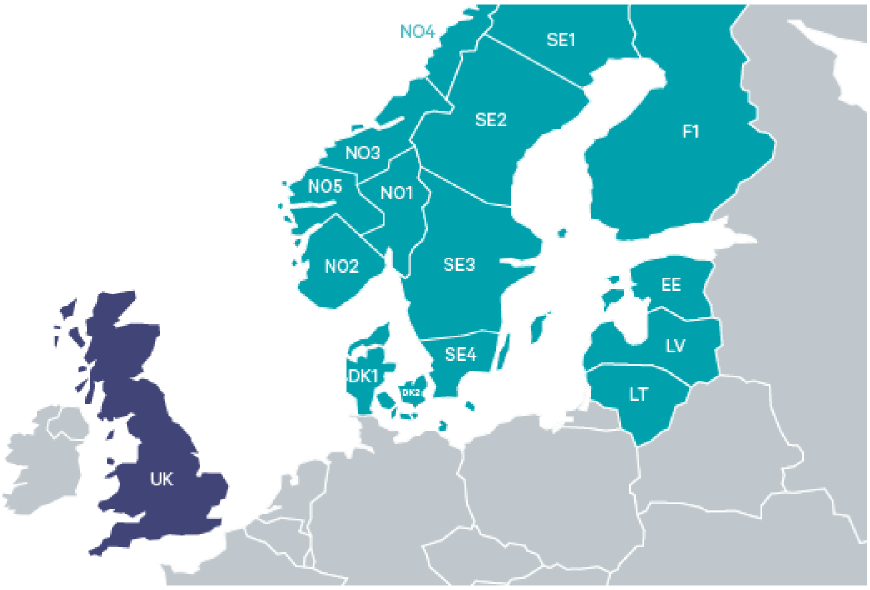

Figure 2. The Nordic electricity price regions (Nord Pool, 2017a).

2.2.1 Day-ahead market

The majority of electricity is traded on the day-ahead market, where the price is set for the following day and contracts are agreed on by sellers and buyers. There are currently around 360 members on the day-ahead market, where most members trade electricity every day. The sellers need to determine the amount of energy they can produce and at what hourly price they can produce it the following day. The buyers have to decide the amount of energy they will need to meet the demand and how much they can pay for it each hour. All bids have to be submitted before 12:00 CET for deliveries the next day and the hourly prices are then calculated and set after 12:42 CET to balance the opposing bids. If the available transmission capacity is reached, the electricity price is increased to decrease the demand in these areas. The trades are then settled once the hourly market prices have been determined. The power is then delivered to the buyers hour by hour according to the previously agreed power contracts with start at 00:00 CET the next day. (Nord Pool, 2017b)

2.2.2 Intra-day market

The intraday market consists of the Nordic, German, UK and Baltic electricity markets. The energy balance is normally secured at the day-ahead market but there are sometimes incidents or disturbances that cause an imbalance between the closing time of the day-ahead market and the delivery the following day. Disturbances in production or consumption may for example be caused by unexpected weather changes that affect the wind power generation or the electricity heat consumption. Producers and consumers can therefore trade energy volumes closer to the delivery time at the intraday market in order to settle the market balance again. The available capacity for the intraday trading are published at 14:00 CET and are then traded every hour until one hour before the delivery time. Prices are set continuously where the first bids are handled first and the best prices are prioritized. The intraday market plays a key role for enabling an increased amount of renewable energy sources since it is difficult to predict wind power on a day-ahead basis. (Nord Pool, 2017c)

2.2.3 Balance market

When the day-ahead and intraday market are closed, the physical electricity balance is controlled on the power regulation market. The BRPs may still be in imbalance during the delivery hour even though they have had the opportunity to trade electricity up to an hour before delivery on the intraday market. If the imbalance is not adjusted, it will contribute to frequency deviations that may cause disruptions in the system in worst case. Svenska kraftnät has the overall responsibility for ensuring that the production is equal to the consumption all the time in Sweden. To accomplish an energy balance, Svenska kraftnät has a balance service that is responsible for the balance market and perform balance regulation during the delivery hour and balance set-off after the delivery hour. The balance service trade regulation power with the BRPs during the delivery hour to adjust the frequency level. For smaller frequency deviations, the frequency level is automatically adjusted by primary control at electricity production stations. If there are larger frequency variations, the balance is adjusted manually by activating secondary or tertiary control. The prices for power regulation are determined by bids, where the BRPs offer bids if they are able to increase or decrease the production or consumption they have balance responsibility for to support the system (Energimarknadsinspektionen, 2014; Svenska kraftnät, 2018). The power regulation options are further explained in 2.3. In addition to the power regulation market, there is also a power reserve market during the winter months between November 16th to March 15th . The power reserve market is used when there is not enough electricity production in correlation to the consumption with the purpose of avoiding electricity black outs (Svenska kraftnät, 2018). The power reserve market is explained further in 2.3.4.

When Svenska kraftnät has received the measured data from the delivery hour, a balance set-off is performed. The balance regulation costs, and penalty fees are then divided between the BRPs that were in imbalance during the delivery hour (Energimarknadsinspektionen, 2014). Svenska kraftnät’s partner eSett Oy has taken over the operating responsibility for the balance set-off since 2017 (Svenska kraftnät, 2017).

2.3 Power regulation

The Transmission System Operators control the power system and ensure that the electricity production corresponds to the consumption every instant. The system frequency is 50 Hz when there is an energy balance in the Nordic power system. If the electricity consumption is larger than the production, the frequency decreases and needs to be regulated by an increased production or a decreased consumption. If it is the other way around, the frequency level needs to be regulated by a decreased production or an increased consumption. The balance can be controlled both automatically and manually by primary, secondary or tertiary control depending on the frequency level deviations (Svenska kraftnät, 2017b).

2.3.1 Primary control

The primary control system contains of the Frequency Containment Reserves (FCR), which are operating in order to balance the system within the normal frequency level and quickly respond to sudden load or production variations. These reserves are automatically activated within seconds in the event of a frequency deviation. FCR is divided into Frequency Containment Reserve for Normal operation (FCR-N) and Frequency Containment Reserve for Disturbances (FCR-D) (Entsoe, 2016). FCR-N is stabilizing the balance by compensating for imbalances within the allowed frequency band 49,9 > f < 50,1, whereas FCR-D is activated for larger deviations when the frequency drops below 49,9 Hz. FCR-N needs to be activated to 63% in 1 minute and fully activated in 3 minutes. FCR-D on the other hand must be activated to 50% after 5 seconds and reach 100% in 30 seconds (Svenska kraftnät, 2017c). There shall at least be 600 MW FCR-N in the synchronous system, where the power reserve is divided between Sweden, Norway, Finland and Eastern Denmark depending on the annual power consumption in each area the previous year (Entsoe, 2016). In Sweden, the required volume of FCR-N is approximately 200 MW, while the required volume for FCR-D is about 400 MW (Svenska kraftnät, 2017c).

2.3.2 Secondary control

When there is an imbalance between the production and consumption, it is adjusted by the primary control as previously described. There may still be frequency deviations from the nominal frequency of 50 Hz after the stabilization. The Automatic Frequency Restoration Reserves (aFRR) are then activated to restore the frequency to the nominal value. In the same time, the aFRR enables the FCR to release capacity for future imbalances. The aFRR is remotely controlled by a centralized controller and is activated within minutes. A specific volume of aFRR was agreed to be in the synchronous system each hour until the end of 2015, when the procurement was put on hold in Sweden until a potential agreement is made between all the Nordic TSOs (Entsoe, 2016). It was then agreed that aFRR should be used for imbalance peaks and it is now becoming more common in the Swedish power system. (Hagelberg, 2018)

2.3.3 Tertiary control

The tertiary control system consists of Manual Frequency Restoration Reserves (mFRR), which manually restore the frequency to its nominal value. Due to frequent congestions in the grid and a limited volume of aFRR, the Nordic power system is dependent on mFRR which is the main balancing reserve. The mFRR can be activated wthin 15 minutes and is used to handle the system’s imbalances. (Entsoe, 2016)

Figure 3 illustrates the different automatic and manual market products, if they correspond to primary, secondary or tertiary control as well as the approximate response time a demand response resource needs to have to participate in each market.

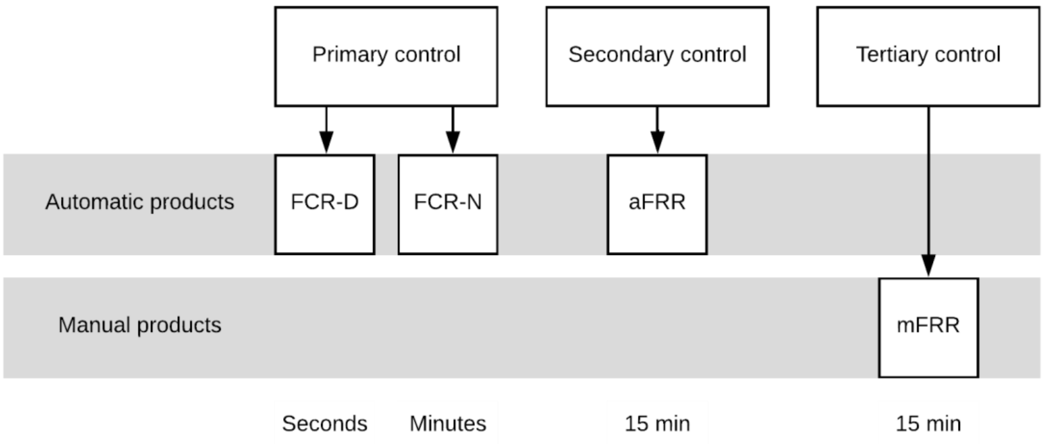

Figure 3. The frequency control system in the Swedish power system (Entsoe, 2016).

2.3.4 Power reserve

The power reserve has to be available every hour during the winter season between November 16th and March 15th. It needs to be available for 2 hours at the time with a maximal restoration time of 6 hours (Hagelberg, 2018).

2.3.5 Summary of the power regulation markets

A summary of the previously explained power regulation markets is illustrated in table 1. The table explains if the participating actor is reimbursed for power or energy on each market and the minimal bidding volume that each actor has to participate with to be allowed to enter the market. Table 1 also shows the required capacity that has to be available on each market and the maximum response time until the resource has to be activated and available on the market. Furthermore, table 1 shows if the market is used for both up and down regulation, for how long the resource needs to be available and how long in advance the trading is performed.

Table 1. Power regulation markets in the Swedish power system.

	FCR-N	FCR-D	a-FRR	m-FRR	Power reserve
Reimbursement	Power and energy product	Power product	Power and energy product	Energy product	Power and energy product
Min. bidding volume	0,1 MW	0,1 MW	5 MW	10 MW SE4: 5MW	SE3 and SE4: 5 MW
Required capacity in Sweden	200 MW	400 MW	100 MW	-	750 MW total (187 MW for consumption)
Activation time	63%: 1 min 100%: 3 min	5%: 5 sec 100%: 30 sec	100%: 2 min	100%: 15 min	100%: 15 min
Symmetric product	Yes	Yes	No	No	No
Traded availability	1 hour	1 hour	1 hour	1 hour	2 hours
Time frame for trading	One or two days before operation	One or two days before operation	Once a week for following week	45 min before operating hour	Procured by season 16/11-15/3

(Entsoe, 2016; Svenska kraftnät, 2017c; Hagelberg, 2018)

2.4 Demand side management

Demand side management (DSM) includes all electricity management activities that are performed on the demand side of the energy system (Aduda et al., 2016). Clark Gellings firstly defined DSM as:

"DSM is the planning, implementation and monitoring of those utility activities designed to influence customers use of electricity in ways that will produce desired changes in the utility's load shape, i.e., changes in the time pattern and magnitude of an utility's load." (Gellings, 1985)

There are four subcategories within DSM called energy efficiency, time of use, demand response and spinning reserve and six techniques within DSM called peak clipping, valley filling, load shifting, strategic conservation, strategic load growth and flexible load shape (Logenthiran et al., 2014). This thesis focuses on demand response (DR), which is a characterization of DSM that is used to specifically reduce peak power demand (Gellings, 2017). The three most common techniques within DR are peak clipping, valley filling and load shifting. Gellings (2017) defines peak clipping as a reduction of demand during peak power and valley filling as an increase of demand during off-peak periods. He defines load shifting as technologies that move existing peak loads to off-peak periods (Gellings, 2017). The focus in this thesis is load shifting, which Oehme (2018) explains further in her thesis.

DR can be used for different purposes for different market actors. Consumers can for example use DR to reduce their electricity costs (Hong et al., 2012), while grid operators can use it to avoid expensive constructions of under-utilized transmission lines and distribution networks (Logenthiran et al., 2014). Furthermore, balance responsibility parties can use DR to reduce the energy imbalances in the power system (Hagelberg, 2018).

2.5 Heat pumps as a flexible load

DR can be used by collecting demand flexibility from consumers that have the availability to increase or decrease their load. Larger industries can trade flexibility individually, while consumers with smaller loads such as multi-family buildings with heat pumps can not trade individually due to too small electricity loads. An aggregator can instead aggregate the demand flexibility from multiple smaller consumers into larger volumes and participate on the electricity market by placing bids on different marketplaces for electricity trading or to system operators (Energimarknadsinspektionen, 2017). Several studies identifies heat pumps as a potential possibility for demand response (Aduda et al., 2016; Fischer et al., 2016; Hong et al., 2012). Oehme (2018) has calculated the aggregated flexibility from heat pumps in multi-family buildings in a local grid area and in SE3, that has been used in this thesis to evaluate the market potential. The flexibility is defined as the load deviation curve, which is a curve of the hourly difference of the power consumption when the HP are controlled compared to the original power consumption curve when they are not controlled.

3. Methodology

In the following section, the quantitative and qualitative methods that were used to generate the results are introduced and motivated. First, an overview of the method choices are introduced. The overview is then followed by a more detailed description of the data and chosen methods for each case study.

3.1 Overview of methodology

The working process can be divided into three main parts. The first part included project planning, literature studies and basic information collection. The second part consisted of interviews, market analysis and model development. The last part consisted of simulations of the results and analysis of the economic effects for the different market actors. The report has been written continuously during all three process parts, but the majority of the text has been produced during the third part of the process.

The study consists of two parts; interviews and case studies. The interviews have been performed with employees at Vattenfall AB, Svenska kraftnät, Ngenic and Sustainable Innovation. The purpose with this part was to receive a deeper understanding for heat pumps, the electricity market and the balance market as well as to discuss assumptions that have been made in other projects and validate the results of this study against other projects. The second part consisted of two case studies. The first case study aimed to evaluate the profitability to use DR from heat pumps for local grid operators, where a local grid in a large city region with grid congestion issues was investigated. Hourly consumption data in the local grid as well as hourly temperature data were analyzed to estimate the potential flexibility during high grid load and in that way the potential possibility to decrease the highest yearly peak power. Furthermore, this case study was used to evaluate how this control system would affect the end consumers. The second case study aimed to analyze the profitability for BRPs and the price area SE3 was then investigated since this area needs to import energy to stabilize the energy balance. Several interviews with a BRP were performed and hourly data for the additional prices in SE3 was analyzed to calculate the potential economic savings. An illustration of the described methods can be seen in figure 4.

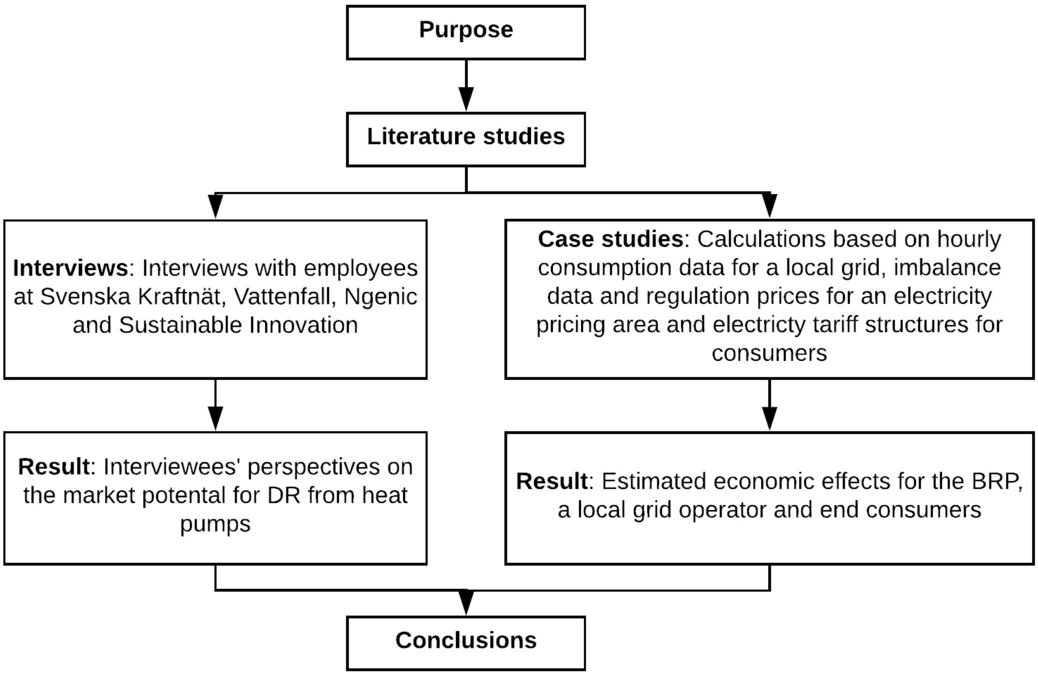

Figure 4. Overview of the major parts of the methods and how they correlate to the purpose and conclusions of the study.

3.2 Pre-study

The pre-study primarily consisted of literature studies about demand response from heat pumps, the electricity market and the balance market. Furthermore, the author participated in a seminar about demand response where perspectives from the BRP, grid operators and industries were presented and discussed. Interviews were also performed with employees at Vattenfall AB and Svenska kraftnät to quicker understand the concepts of the balance market as well as to understand the opportunities and weaknesses with heat pumps. Mats Hagelberg, who is BRP for the consumption area at Vattenfall AB, has been the main source for information about the balance market in Sweden. Two employees at Svenska kraftnät were interviewed in the pre-study to gather information about current regulations for DR as well as future possibilities for using DR. The interview with Svenska kraftnät was semi structured and the questions were sent to the respondents before the interview. According to Andersen (2010, pp 167-168), semi structured interviews are suitable when the interviewee is familiar to the area but is open for new perspectives from the respondents. The interviews that were performed in the pre-study are described in table 2.

Table 2. Information about the interviews that were performed in the pre-study.

Respondent	Organization	Position	Date and place
Mats Hagelberg	Vattenfall AB	Senior Sourcing Manager, BRP	Regularly meetings Solna
Linda Thell Zarah Andersson	Svenska kraftnät	Analyst Market Design Analyst	2018-02-20 Phone interview, Solna
Nader Padban	Vattenfall AB	Senior R&D engineer	Regularly meetings Solna
Anders Lindgren	Vattenfall AB	Senior R&D engineer	Regularly meetings Solna
Per-Olof Nylén	Vattenfall AB	Project Manager	2016-02-16 Solna
Cecilia Ibánez-Sörenson	Vattenfall AB	Program Manager, R&D	2018-02-20 Solna
Magnus Berg	Vattenfall AB	Customer Solutions Portfolio Manager	2018-02-28 Solna

3.3 Case study 1: Local grid operators

The local grid area that is investigated in case study 1 is located in a large city-region and consists of 174 multi-family buildings with heat pumps.

3.3.1 Interviews about the market potential for grid operators

Several semi-structured interviews were performed to gather more detailed information about grid operators and the benefits demand response can generate for the grid operators. Information about the respondents and the time and place for these interviews are described in table 3.

Table 3. Information about the interviews that were performed to gather information about the market potential for grid operators.

Respondent	Organization	Position	Date and place
Fredrik Carlsson	Vattenfall AB	R&D Portfolio Manager, Distribution	2018-03-05 Solna
Anna Nilsson	Vattenfall Eldistribution	Business Analyst	2018-03-12 Solna
Joachim Lindborg	Sustainable Innovation	Technical Manager	2018-03-29 Phone interview, Solna
Björn Berg	Ngenic	CEO	2018-04-18 Uppsala
Yvonne Ruwaida	Vattenfall Eldistribution	Business Strategist	Regularly meetings Solna
Per Sundberg	Vattenfall Eldistribution	Customer and Market Analyst	2018-05-03 Phone interview, Solna

3.3.2 Data and assumptions

Different data was required to enable calculations of the potential cost reduction for grid operators. The data that is used in the calculations is summarized below:

- Total hourly electricity consumption data in a local grid located in a larger city region for the previous 3 years.
- Amount of measure points in the local grid
- Type of region grid tariff in each measure point
- Prices for region grid tariffs in 2018
- Hourly outdoor temperature in the region where the local grid is located
- Demand flexibility in the local grid based on the outdoor temperature

The hourly consumption data has been collected for the years 2015-2017, where 2015 and 2017 had mild winters while 2016 was a cold year (SMHI, 2018). Since the results show that the electricity consumption is strongly correlated to the outdoor temperature, it is beneficial to analyze years with both mild and cold winters. The hourly consumption data includes all measure points in the local grid. The measure points have different power subscription levels and there are two different types of tariffs among the measure points in the investigate grid area. Some assumptions were therefore made to determine a general power subscription price in the local grid for all measure points. The equations (3.1), (3.2) and (3.3) explains how the general power subscription in the local grid was calculated, while equation 3.4 explains how the penalty fee was calculated. Since there are two different types of tariffs in the local grid, the quota of each tariff was first calculated. The quota of measure points with tariff X was determined as

$$Q_x = \frac{P_x}{P_{tot}} \tag{3.1}$$

Where P_x is the power subscription level in the measure points with tariff X and P_{tot} is the total power subscription in all measure points together. The quota of measure points with tariff Y was determined as

$$Q_y = \frac{P_y}{P_{tot}} \tag{3.2}$$

Where P_y is the power subscription level in the measure points with tariff X and P_{tot} is the total power subscription in all measure points together. The general power subscription fee in the local grid area was determined as

$$F_{tot} = Q_x F_x + Q_y F_y \qquad \text{[SEK/kW]} \tag{3.3}$$

Where Q_x is the quota of measure points with tariff X, F_x is the power subscription fee for tariff X, Q_y is the quota of measure points with tariff Y and F_y is the power subscription fee for tariff Y. The general power subscription fee F_{tot} was calculated to 142 SEK/kW. The penalty fee for a local grid operator if they exceed their power subscription level is 1,5 times larger than the power subscription level and was therefore determined as

$$F_p = 1{,}5\ (F_{tot}) \qquad \text{[SEK/kW]} \tag{3.4}$$

The penalty for the local grid operator was determined to 213 SEK/kW according to equation (3.4) if they exceed their power subscription level.

The demand flexibility for the local grid has been collected from Oehme (2018) who has simulated the flexibility in this local grid for the outdoor temperatures +10°, 5°, 0°, -5°, -10° and -15° Celsius. When determining the flexibility, she has calculated with the amount of multi-family buildings that currently obtain heat pumps in this grid area.

3.3.3 Calculations

Determination of power subscription levels

The potential cost reduction is dependent on the power subscription level that the local grid obtains. Grid operators have different margins but normally decide a level that is as low as possible but still above their normal peak power in order to avoid penalty fees. Some grid operators also subscribe on a power level that is higher than their normal peak power to be able to connect more customers to the grid in the future without changing the subscription level, since that is not always possibly due to grid congestion issues (Sundberg, 2018). To be able to easier apply the case study results on other grid operators with different margin levels, three different power subscription levels were determined in discussion with Ruwaida (2018) and analyzed. The levels that were analyzed were 180 MW, 185 MW and 190 MW. The local grid has exceeded 180 MW in 6 of the previous 10 years, 185 MW in 4 of the 10 last years, while it never has exceeded 190 MW during the previous 10 years.

Peak power reduction

When calculating the potential power subscription fee and penalty fee reduction in 2015-2017, the reduction potential of the peak power was first analyzed. In order to do so, the peak power were sorted from the highest to the lowest to prioritize a reduction of the highest peak power. Oehme (2018) identified an optimal controller that was suitable for this case study, which manually turns off the heat pumps once when a high peak power occurs. The hourly flexibility from the controller for each temperature can be find in Appendix 1. Figure 5 illustrates an example of the day with the highest hourly peak power in 2017 where this controller was used to minimize the highest peak power.

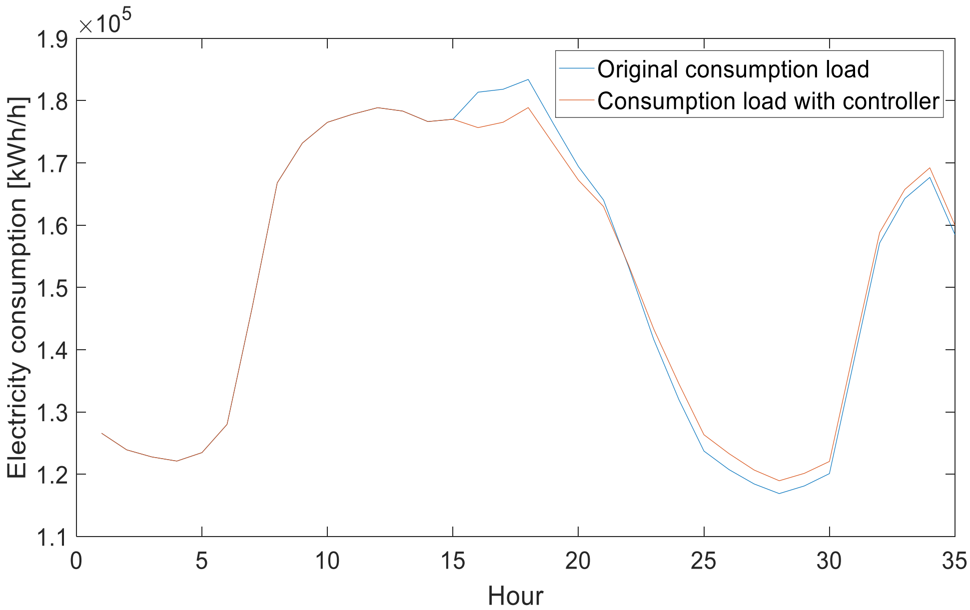

Figure 5. The most critical day with the highest peak power in 2017 when the outdoor temperature was -5° degrees Celsius. The blue line shows the original consumption curve, whereas the red line illustrates the consumption curve when the controller is applied.

Figure 5 shows that the maximum peak power during the time period can be avoided with the controller. Furthermore, it illustrates the re-generation time where the consumption curve with the controller has a higher consumption when the heat pumps are started again. Figure 6 shows a different example that illustrates the day with the highest peak power in 2016. The graph shows that there are two peak power periods with a relatively small interval in between.

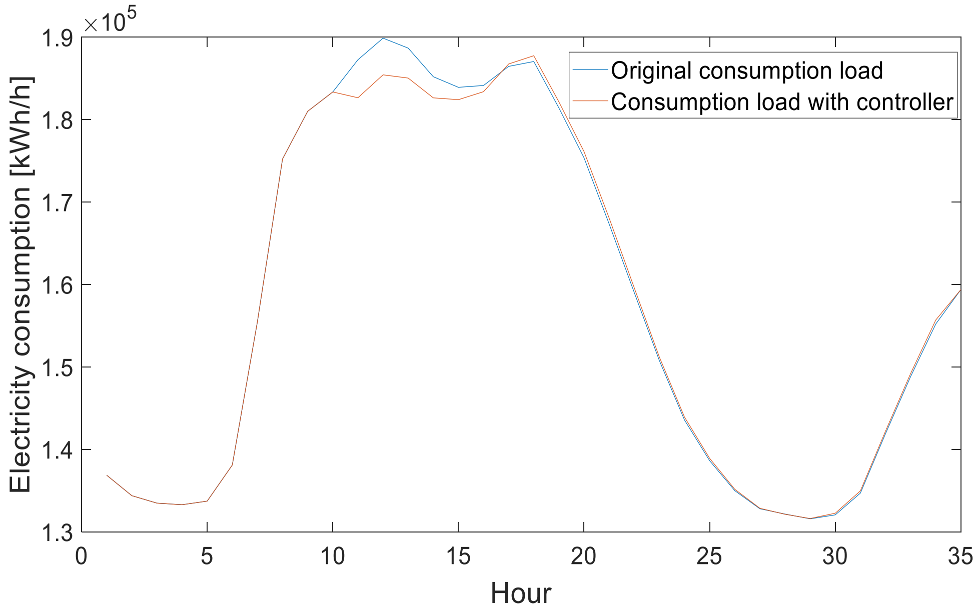

Figure 6. The most critical day with the highest peak power in 2016 when the outdoor temperature was -10° degrees Celsius. The blue line shows the original consumption curve, whereas the red line illustrates the consumption curve when the controller is applied.

Figure 6 shows that the standard controller only minimizes the first peak power period but not the second one. In order to minimize the highest peak power as much as possible, it is therefore necessary to divide the available flexibility between the peak power periods. Equation (3.5) below shows how the flexibility has been optimized in the calculations to minimize both peaks in order to minimize the highest peak during the time period. The equation aims to calculate the unknown quota of the flexibility that needs to be applied for each peak to minimize both peaks.

$$\mathrm{Pp}_1 - \alpha \mathrm{Q} = Pp_2 + H_d - \alpha(1 - \mathrm{Q}) \tag{3.5}$$

Where Pp_1 is the first peak power, α is the available flexibility, Q is the quota of the flexibility, Pp_2 is the second peak power and H_d is the heat debt. Equation (3.5) is modified to equation (3.6) to calculate the quota Q as

$$\mathrm{Q} = \frac{Pp_1 - H_d - Pp_2 + \alpha}{2\alpha} \tag{3.6}$$

When equation (3.5) and (3.6) was used to determine the quota of the flexibility that should be used for each peak, it results in another manipulated consumption curve that can be seen in figure 7, where the highest peak is lower than in figure 6.

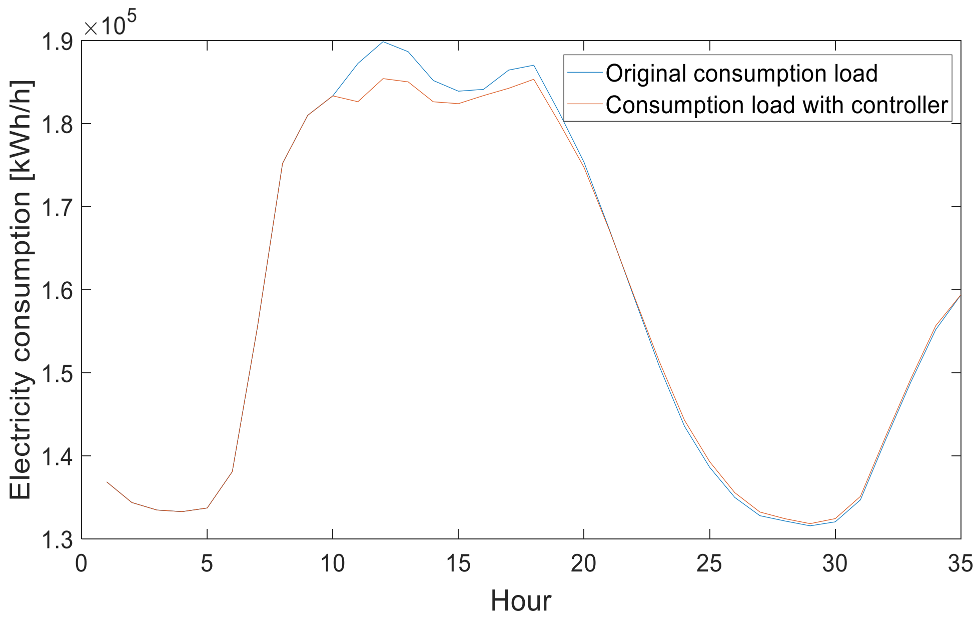

Figure 7. The most critical day with the highest peak power in 2016 where the flexibility is divided between the peaks according to equation (3.5). The blue line illustrates the original case whereas the red line shows the consumption curve with the controller that divides the flexibility between the peaks.

Figure 5 and figure 6 show that it is necessary to divide the available flexibility between the time periods when there is two peaks during a control cycle. The available flexibility was therefore divided between the periods according to equation (3.5) when there were two peak power periods during a control cycle in the calculations. To simplify the calculations and to realize more realistic results, the available flexibility was only divided twice during the same control cycle. To further optimize the peak power reduction, it may be beneficial to divide the flexibility more times. However, future prognosis are normally not exactly equivalent with the outcome and dividing the flexibility several times based on the outcome data may result in an overestimation of the resource.

Effect for end-consumers

The electricity heat load for the local grid was divided by the amount of buildings in the grid to generate the electricity heat load in one multi-family building during 48 hours at the outdoor temperature 0°C. Two days that were critical for the local grid was then chosen to evaluate the effect a control signal would have for one building during that time period. The controlling was performed during the hours with the highest consumption in the local grid in order to calculate the hourly electricity heat load that was needed if a controller was used. To calculate the hourly electricity heat cost with and without controller, the spot price was multiplied with the electricity heat load for each hour.

3.4 Case study 2: Balance market

The electricity price region that is investigated in case study 2 is SE3 and the location of SE3 can be seen in figure 2. SE3 consists of 10146 multi-family buildings that obtain heat pumps.

3.4.1 Interviews about the market potential for the BRP

Several interviews were performed to gather more detailed information about the balance market and the benefits demand response can generate for the BRP. Information about the respondents and the time and place for these interviews are described in table 4.

Table 4. Information about the interviews that were performed to gather information about the balance market.

Respondent	Organization	Position	Date and place
Mats Hagelberg	Vattenfall AB	Senior Sourcing Manager, BRP	Regularly meetings Solna
Linda Thell Zarah Andersson	Svenska kraftnät	Analyst Market Design Analyst	2018-02-20 Phone interview, Solna

3.4.2 Data and assumptions

To be able to compare the incomes from the mFRR market, the intraday market and the power reserve market, the time period November 16^{th} to March 15^{th} has been chosen for all the markets since that is when the power reserve has to be available. Different data was required to enable calculations of the potential cost reduction for the BRP. The data that has been collected and used in the calculations is summarized below:

- Additional regulation prices in SE3 2014-2017
- Weighted outdoor temperature in SE3 2016-2017
- Spot prices in SE3 2014-2017
- Intraday prices in SE3 2016-2017
- Exchange rates EURO/SEK 2016-2017
- Demand flexibility in SE3 based on the outdoor temperature
- Repeatability for the flexibility based on the outdoor temperature

3.4.3 Calculations

The calculations for the mFRR market and the intraday market were performed similar to the calculations for the grid operator and can be seen in 3.3.3. The exception is that the resource was not divided into two parts since the BRP does not have the same prognosis predictions of the additional price as the grid operator has of the power consumption.

mFRR

The potential income from the mFRR market was calculated for when the BRP placed bids when the up regulating price was above 500 SEK/MW, 100 SEK/MW and 50 SEK/MW. Since it is difficult to predict when there will be up regulation in the Swedish power system, bids were placed every time the up regulation price was above for example 100 SEK/MW, independent on the following hourly prices. The full available resource was used in each case and never divided between different hours in order to illustrate a realistic situation, where the BRP normally does not know the price prognosis. If two periods of high up regulation prices occurred close to each other, the resource was only used again if the repeatability time had passed. When the heat pumps are controlled to turn off, it affects the power consumption for a certain amount of hours depending on the outdoor temperature. The change in power consumption compared to the original power consumption that occurs during a controlling is defined as demand flexibility and can be seen in Appendix A. Since the power consumption is affected for several hours, the incomes/costs for the BRP is also calculated for all these hours.

Intraday market

If the intraday price is higher than the spot price, it is possible to turn off the heat pumps to decrease the consumption and sell the resource on the intraday market. In this way, the BRP can sell the electricity for a higher price than it was bought for. The income potential from the intraday market has been calculated according to equation (3.6). Due to time constraints, the incomes from the intraday market were only calculated for one season: November 16th 2016 to March 15th 2017. To be able to compare the incomes from the intraday market with the mFRR market, the same amount of bids were placed on the intraday market as on the mFRR market. The income potential was calculated as

$$I_i = Pr_i E - Pr_s \qquad \text{[SEK]} \qquad (3.6)$$

Where Pr_i is the intraday price, E is the euro exchange rate and Pr_s is the spot price.

When placing bids, the hours with the largest differences between the intraday price and the spot price were identified first. The resource was then applied at these hours first, with no consideration to the following hours after the hour with high income potential. When the same amount of bids had been implemented as on the mFRR market, the total income was calculated where a bid could generate either an income or a cost depending on how the heat debt correlated with the prices.

Power reserve

The incomes from the power reserve market was calculated as

$$I_p = C_a H + C_c N \qquad [\text{SEK}] \qquad (3.7)$$

Where C_a is the administrative hourly compensation for participating on the power reserve market, H is the amount of hours during the season, C_c is the compensation for one call off during the season and N is the number of call offs during the season.

The administrative compensation for the power reserve varies but was for the calculations approximated to 15 SEK/MWh in discussion with Hagelberg (2018). The power reserve has to be available the entire season which equalizes to an income of 43200 SEK/MW during a normal season with 2880 hours. The compensation from Svenska kraftnät to the BRP if the power reserve is used was for the calculations approximated to 4000 SEK/MWh in discussion with Hagelberg (2018).

Since the resource has to be available for two hours, the average volume of the flexibility for the first two hours was calculated for each temperature. The repeatability for the resource at each temperature was gathered from Oehme (2018). Two hours were then eliminated from the repeatability at each temperature to generate the rest time since the resource has to be activated for two hours on the power reserve market. The resource volume and the rest time for the resource depending on the outdoor temperature can be seen in table 5.

Table 5. The resource volume and the rest time depending on the outdoor temperature for the power reserve market.

Outdoor temperature	Resource volume [MWh/h]	Rest time [hours]
15°C	13,1	8
10°C	38,1	5
5°C	52,4	7
0°C	64,5	8
-5°C	86,4	13
-10°C	118	18
-15°C	150	23
-20°C	150	28

Since the rest time had to be minimized to a maximum of six hours, the rest time was divided into equal parts until it was less than six hours, whereby the resource volume was divided the same amount of times to generate an equal resource volume for each controlling. The resource has to exceed the volume that the BRP participates on the power reserve market every six hours which is the reason why it has been divided into equal parts. If the volume is divided into two parts for example, it means that half of the heat pumps can be turned off first and the other half can be turned off after the rest time of six hours. The available resource volume for each outdoor temperature can be seen in table 6.

Table 6. The available resource volumes and rest times for the resource when fulfilling the requirements for the power reserve market.

Outdoor temperature	Resource volume [MWh/h]	Rest time [hours]
15°C	6,5	4
10°C	38,1	5
5°C	26,2	3,5
0°C	32,2	4
-5°C	28,8	4,3
-10°C	39,3	6
-15°C	37,4	5,8
-20°C	29,9	5,6

4. Results

This section presents the results from the calculations and the qualitative interviews. First, the market opportunities are introduced in terms of quantitative benefits for the electrical grid operators, the end-consumers and the BRP. This is followed by a discussion of implementation possibilities for the service.

When the heat pumps are controlled to turn off, it may result in economic savings both for the consumers, the grid operators and the balance responsible party if it is up regulation. If the heat pumps are controlled to turn on, it may only result in economic savings for the balance responsible party if it is down regulation (Hagelberg, 2018). Consumers are either interested in reducing the energy or power consumption depending on their tariff type, which only can be accomplished by turning off the heat pumps.

4.1 Case study 1: Local grid operators

Results from interviews

According to Nilsson (2018) who works at the distribution department at Vattenfall and currently investigates the opportunities for grid operators to utilize DR, DR from heat pumps in multi-family buildings primarily generates benefits for the local grid operators. Furthermore, she clarifies that the largest potential for grid operators to benefit from DR is to reduce the penalty fees when exceeding the power subscription level or to be able to reduce the fuse level which leads to lower monthly subscription fees. She also identifies a decreased amount of power losses as a result from regulating the power usage, but believe there are larger potential economic savings in reducing the penalty fees or the power subscription. Lindborg (2018) identifies two ways for grid operators to regulate the power usage; base regulation and peak shaving. He clarifies that base regulation is performed continuously to optimize the daily power usage, which may enable a lower power subscription fee for the grid operators. Peak shaving on the other hand, is only performed rarely when the peak power is exceptionally high in order to avoid or decrease the penalty fees for the grid operators. Lindborg (2018) explains that unusual high peak power normally correlates with longer periods of cold weather, which normally occurs approximately once every five years. He points out that how often a grid operator exceeds the power subscription level and has to pay a penalty fee depends on how large the grid operators' trading margin is and that it is therefore difficult to determine how often it occurs (Lindborg, 2018). Local grid operators pay approximately 200 000 SEK/MW in subscription fee per year to the regional grid operators. If they exceed the subscription level, they owe the regional grid operator approximately 300 000 SEK/MW that is above the agreement level (Berg, B., 2018). It is therefore important to optimize the choice of subscription level to minimize the fixed cost and in the same time avoid penalty fees by not exceeding the chosen level.

Sustainable Innovation, where Lindborg works, started a project called Klokel in 2014 in collaboration with Upplands Energi and Ngenic. The purpose with the project was to connect 500 heat pumps from Upplands Energi's electricity consumers in detached houses to Ngenic's control system. The consumers that connected their heat pumps with the control system could then save energy by optimizing their inner house temperature and turn the heat pumps off when they were away from the house for longer periods. In the same time, Upplands Energi had the possibility to reduce peak power by turning their customers' heat pumps off when the grid space was limited. Since the project started in 2014, Upplands Energi have controlled the heat pumps twice; once in 2016 and once during a long period of cold weather in 2018. They estimated that they aggregated about 1 MW by controlling heat pumps for about one hour in 350 houses during the peak in 2018, which saved them about 300 000 SEK in penalty fees. When discussing if it is more profitable to acquire a higher power subscription level and use DR to avoid penalty fees or use DR to decrease the subscription level, Lindborg (2018) suggests that the fuse level may play a larger role in the future. He clarifies that the energy price is becoming cheaper with the increased level of wind and solar power while the power is becoming more expensive. The power subscription fee may therefore increase, which makes the utilization of DR for decreasing the power subscription more interesting (Lindborg, 2018). However, the grid capacity may be reached or close to be reached in some areas which makes it difficult for grid operators to increase their power subscription level. For this reason, Ruwaida (2018) means that local grid operators may subscribe on more power then they need in order to be able to connect more customers to the grid in the future.

There may be one or several border points between a local distribution grid and a regional distribution grid. The local distribution grid subscribes on a certain power level in each border point, as well as a total power level for a group of border points in the grid. It is therefore important to not exceed any border point subscription power level as well as the total subscription level for such groups of border points (Sundberg, 2018). The cost for exceeding the total subscription level is larger since that includes the power level in a group of border points and this is the subscription level that is used in the following calculations.

4.1.1 Correlation between grid congestion and the outdoor temperature

The flexibility increases when the outdoor temperature is cold (Fischer, 2016) and it is therefore interesting to first illustrate the correlation between high power consumption and the outdoor temperature. This correlation is illustrated during two different years in figure 8 and figure 9.

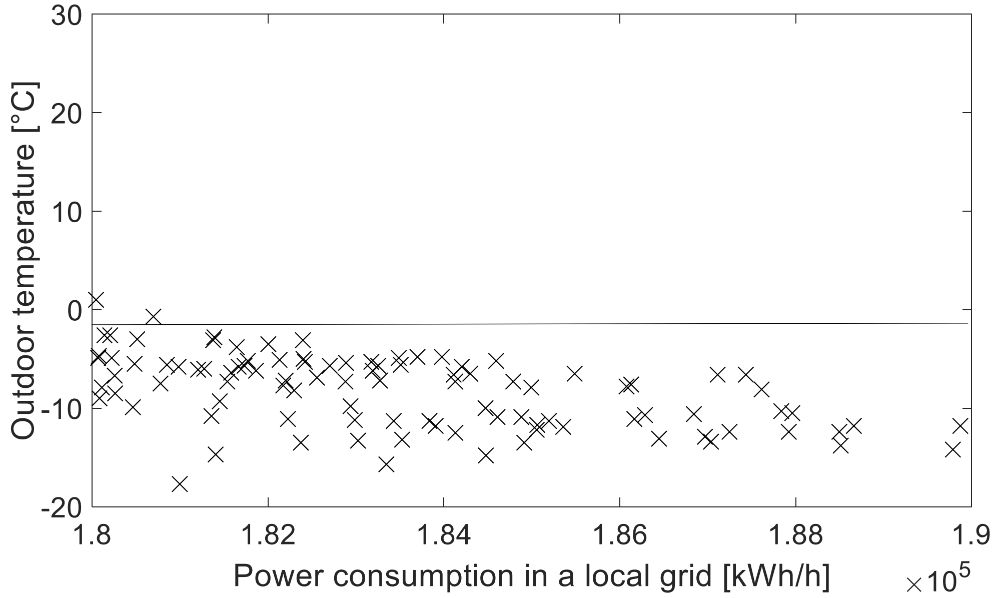

Figure 8. Power consumption in a local grid in correlation to the outdoor temperature during the 100 hours with the highest power consumption in this grid area in 2016.

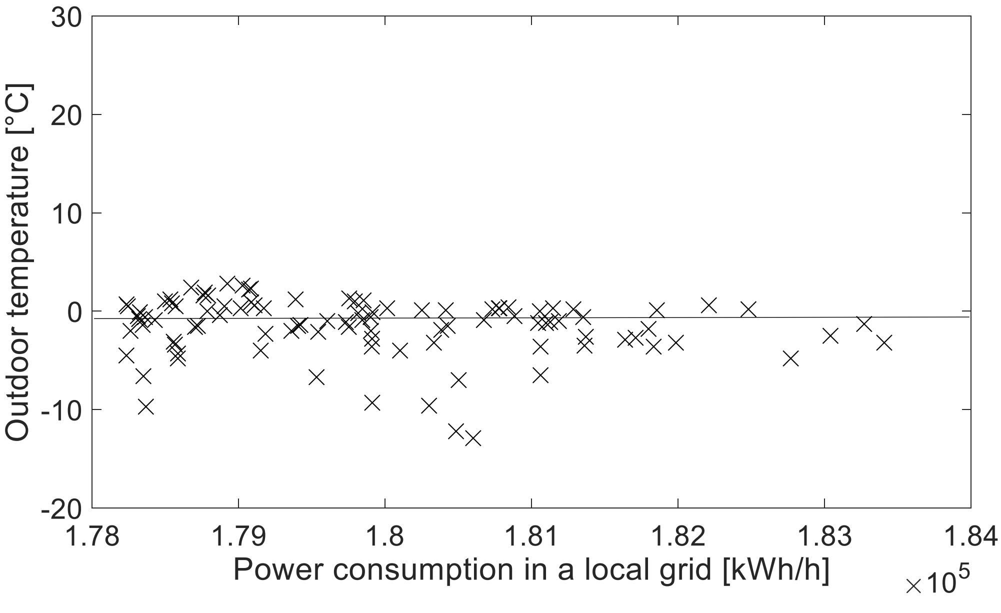

Figure 9. Power consumption in a local grid in correlation to the outdoor temperature during the 100 hours with the highest power consumption in this grid area in 2017.

The figures above show that high grid load are correlated to cold temperatures, which can be explained by the fact that the heat demand is higher during cold temperatures. According to Fischer et al (2016), approximately 60% of heat pumps are turned on when the outdoor temperature is 0°C, 80% when it is -5°C and 95% when it is -10° degrees outside. This means that the potential of turning off the heat pumps to reduce the grid load during the most critical hours is generally high.

4.1.2 Potential peak power reduction for a grid operator

The yearly used power for a local grid is defined as the average between the two highest peak power periods that occurred during two separate months during one year. Figure 10 illustrates the possible peak power reduction of the average between the two highest peak power periods during three different years.

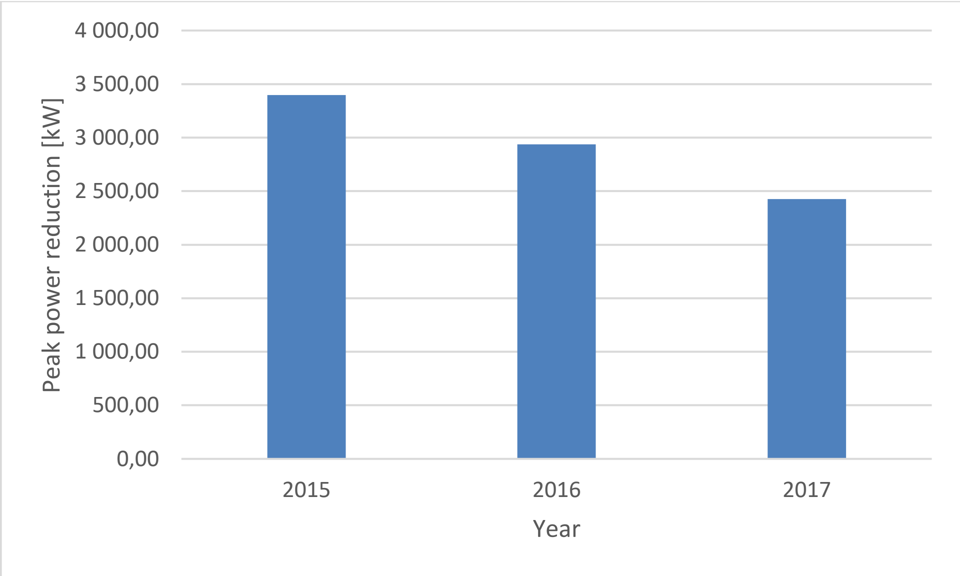

Figure 10. Potential peak power reduction in the local grid in 2015, 2016 and 2017.

Figure 10 shows that the possible peak power reduction in the local grid was 2,4 MW in 2015, 2,9 MW in 2016 and 3,4 MW in 2017. This corresponds to an average yearly peak power reduction of 2,9 MW. The average power usage between the two largest peak power periods during two separate months in the local grid with and without controller is illustrated in figure 11.

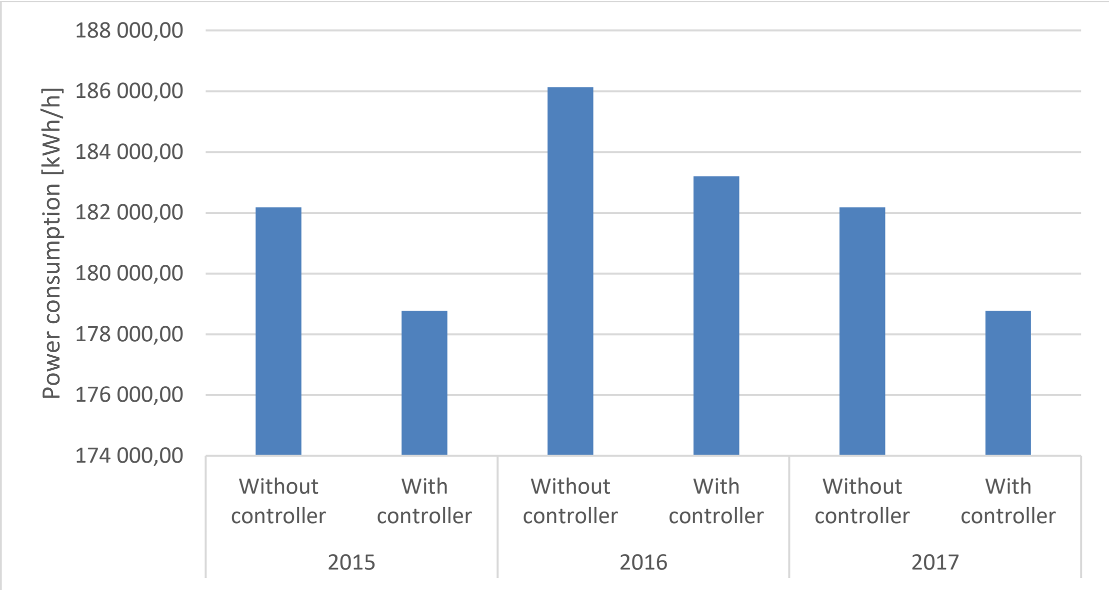

Figure 11. The average between the two highest power peaks in a local grid during two separate months in 2015, 2016 and 2017 with and without controlling the heat pumps in the local grid area.

4.1.3 Yearly cost reduction for a local grid operator

The yearly costs for the grid operator with and without controller can be seen in figure 12. The costs were determined based on the hourly consumption data in 2015-2017 and whether they would have a power subscription level of 180 MW, 185 MW or 190 MW. The fees only include the power subscription fee and potential penalty fees and therefore for example not the set fee, energy transfer fee or the measurement fee. The power subscription fee reduction is calculated given with the assumption that the grid operator would keep the same margin to the subscription level as in the original case. For example, if they would subscribe on 190 MW and have a peak power of 187 MW in the original case and the potential power reduction was 4 MW with the controller, they could reduce their subscription level to 186 MW and still have 3 MW in margin.

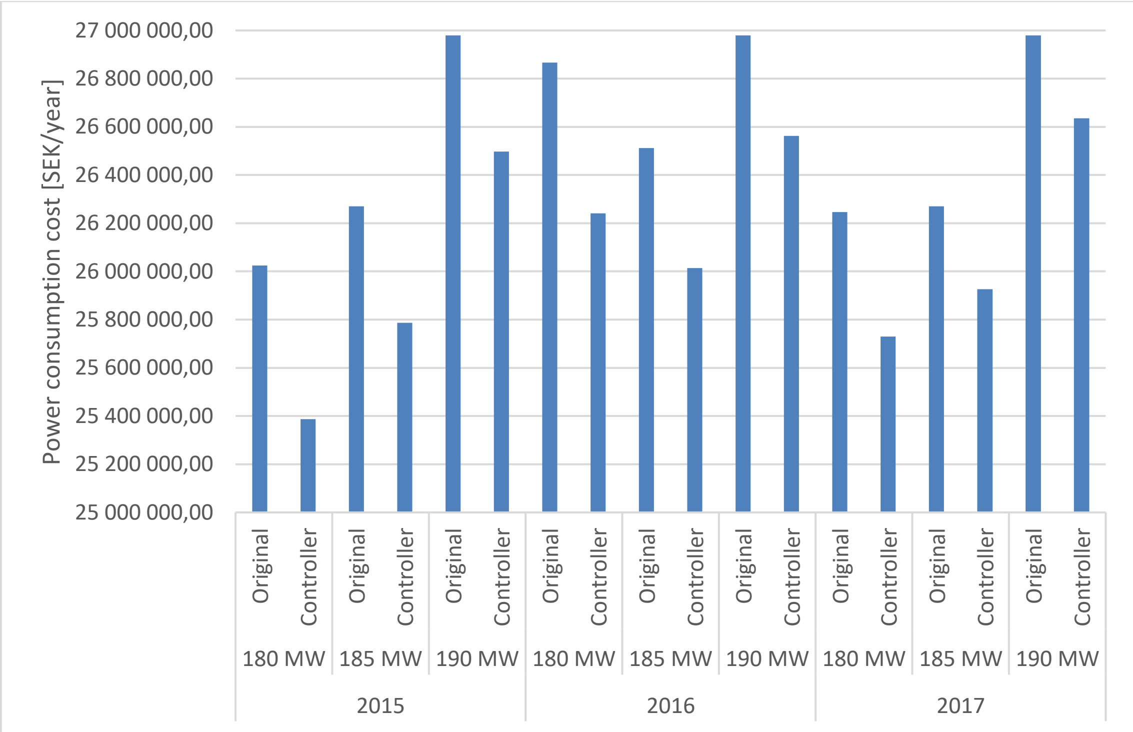

Figure 12. Yearly power consumption costs for the local grid in 2015, 2016 and 2017 if they would subscribe on 180 MW, 185 MW and 190 MW with and without controlling the heat pumps.

Figure 12 shows that it would have been optimal to subscribe on 180 MW in 2015 and 2017, while it would have been cheaper to subscribe on 185 MW in 2016. The reason why it would have been cheaper to subscribe on a higher level in 2016 is because the peak power was higher that year and the penalty fees are then more expensive than to increase the subscription level. Table 7 illustrates the cost reduction that arises from penalty fee reduction and subscription fee reduction for the different power subscription levels.

Table 7. The possible cost reduction of the power subscription fee and the penalty fee for the local grid operator in 2015, 2016 and 2017 depending on if they would subscribe on a power level of 180 MW, 185 MW or 190 MW.

	180 MW	185 MW	190 MW
2015 Subscription fee reduction	173 000 SEK	483 000 SEK	483 000 SEK
Penalty fee reduction	464 000 SEK	0 SEK	0 SEK
2016 Subscription fee reduction	0 SEK	256 000 SEK	417 000 SEK
Penalty fee reduction	626 000 SEK	242 000 SEK	0 SEK
2017 Subscription fee reduction	0 SEK	344 000 SEK	344 000 SEK
Penalty fee reduction	517 000 SEK	0 SEK	0 SEK

The total yearly cost reductions including both penalty fee reductions and power subscription fee reductions for each power subscription level can be seen in figure 13.

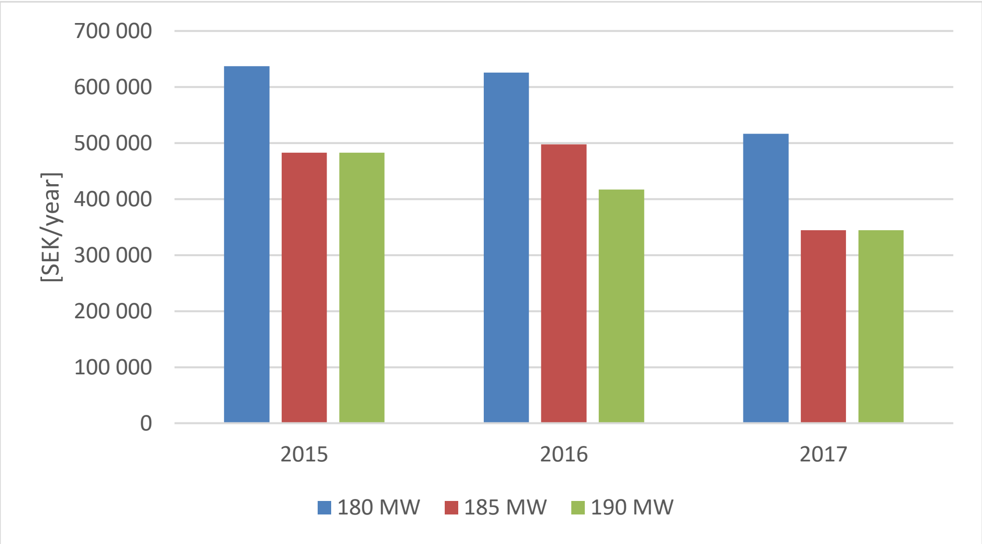

Figure 13. Total yearly cost reduction including the power subscription fee reduction and the penalty fee reduction for a local grid operator depending on if they would subscribe on 180 MW, 185 MW or 190 MW.

The average cost reduction per year including all the three different subscription levels and the three different years was calculated to 483 000 SEK/year, which equalizes to 2800 SEK per multi-family building per year. If an aggregator aggregates the flexibility and sell it to the grid operator, the implementation cost needs to be maximum 5600 SEK per house in order to have a payback time of less than two years, not including potential operating costs. If they require a payback time of three years, the implementation costs can not exceed 8400 SEK, when the operating costs not are included. The case study was performed on a local grid in a larger city region with relatively large buildings, which means that grid operators in areas with smaller multi-family buildings may have a lower income per house.

The reason why the potential cost reduction is larger for a power subscription of 180 MW is because the grid operator exceeded this level in each of the three years when the controller was not used. The choice of this subscription level therefore resulted in penalty fees in the original case that could be eliminated or reduced by controlling the HP. When choosing the optimal subscription level, Sundberg (2018) claims that a grid operator normally choose a level that exceeds their normal yearly peak power to avoid the penalty fees. It is therefore reasonable to believe that the real subscription level is higher than 180 MW.

4.1.4 Economic effects for end-consumers

Results from interviews

The economic impacts on the consumers from controlling the heat pumps depends on their electricity tariff type and for what purpose the heat pumps are controlled. Larger multi-family buildings obtain larger heat pumps and therefore a greater amount of flexibility, which makes it more profitable to install the control systems in larger multi-family buildings. Buildings that acquire a fuse level of 80 A or higher normally has a demand-based tariff and pay for the largest peak power as well as energy consumption and fuse level (E.ON, 2018, Vattenfall, 2018). Since the purpose for the grid operators is to reduce the peak power, it correlates to the desire for consumers with a demand-based tariff to reduce their electricity bill. According to Carlsson (2018), it is not possible to compensate consumers that agree to letting an aggregator control their heat pumps. Grid operators have to offer the same choice of tariffs to all electricity consumers, regardless on their contribution to a more sustainable grid. However, it is possible to form a bilateral agreement between the grid operator and a specific consumer that allows economic incentives.

In Håkansson’s (2018) interview study of property owners and BRPs about drivers and challenges of DR from heat pumps, heat pumps were reported to be most common in locations not covered by a district heating network, as well as in properties with special needs. However, one reason for wanting to install geothermal heating or solar hybrid is when the prices of district heating are increasing. By interviewing property owners from different areas with properties of different sizes, Håkansson (2018) identified that owners strongly argue to remain in control of e.g., heating or ventilation, which could potentially clash with the concept of controlling heat pumps externally. They prioritize tenants' comfort and were worried about how they would counter complaints if the tenants complained about indoor temperature differences that occurred from an external control system. Håkansson (2018) points out that the property owners in the study are positive and willing to make changes toward more energy-efficient solutions, but that one hard challenge is negotiating with the residents' association. The residents' association has the tenants in focus and is concerned about changes (including investments in controlling systems) that would increase the rent. The property owners in the study made it clear that they must have the tenants on board and engage them in new projects to be able to make any changes. Regarding envisioned flexibility, the property owners believe that it is more difficult today to predict the heat consumption behavior, since people are at home more evenly over the day than before. Håkansson (2018) clarifies that working hours were more fixed a few years ago, while more people work from home today or have more flexible work hours, which makes it more difficult to predict and control heat pumps. A few larger property owners reported already subscribing to weather services or having their own measurement systems to be able to predict the consumption and plan ahead to create more even transitions. They therefore do not see the same potential benefits of an external control system as much as smaller property owners do, who do not have the time and resources to actively engage in demand response themselves.

According to Berg, B. (2018) consumers save around 15% of their heat consumption by using Ngenic's control system for heat pumps, where heat consumption equalizes approximately 60% of consumers' total electricity consumption. With these estimations and a smart control systems, consumers can reduce their electricity consumption with 9%.

Steen et al. (2016) performed a case study to analyze how hourly electricity prices would affect consumers' incentives for DR when they had an energy-based tariff and a power passed tariff and how each tariff would affect the DSO's. The results showed that consumers that scheduled their load could save up to approximately 1190 SEK/year with an energy-based tariff and 1270 SEK/year with a demand-based tariff depending on the volume of the flexible load. They also concluded that the grid load could be increased if more than 25% of the consumers with an energy-based tariff adjusted their consumption based on hourly prices, while it could be decreased by 4% if the same amount of consumers used a demand-based tariff. Furthermore, the voltage variations, transformer overloading and active power losses increased when consumers with both tariffs changed their consumption pattern based on prices. The impact was however larger when consumers used energy-based tariffs (Steen et al., 2016). Another aspect to take into consideration is that load planning based on the hourly prices can affect the market spot price, which could lead to increased balancing costs (Hagelberg, 2018).

Results from calculations

Figure 15 shows an example of how the electricity heat load in a multi-family building in the local grid from the case study changes during 48 hours when there was a need from the local grid to control the HP.

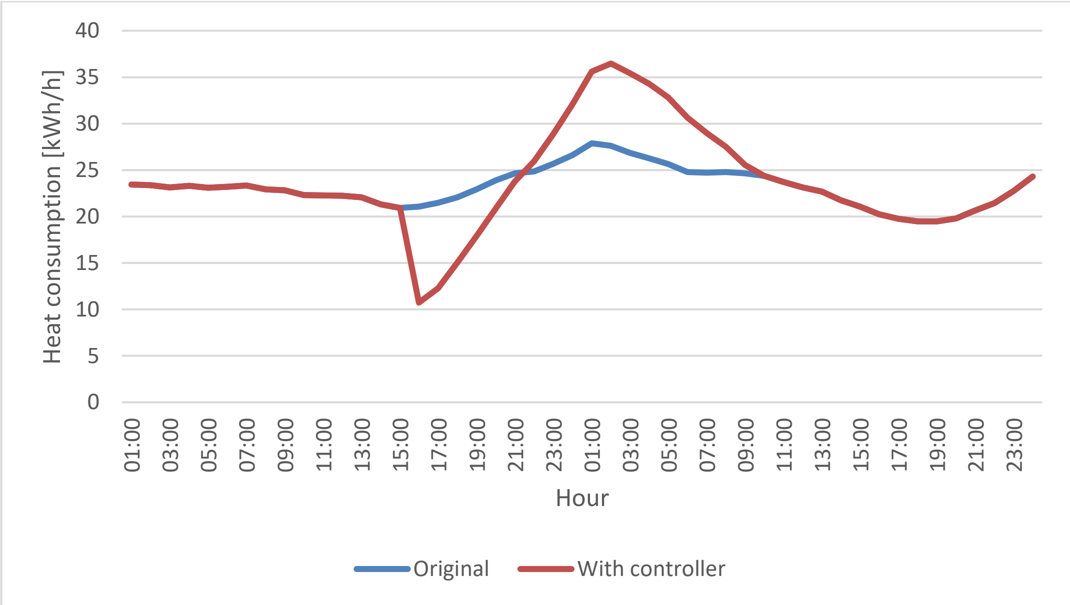

Figure 15. An example of how the electricity heat load changes in one building during 48 hours when a controller is used when the outdoor temperature is 0° degrees Celsius.

The area between the lines below the blue line in figure 15 illustrates the reduced energy that is used during the controlling compared to in the original case, whereas the area above the blue line shows the increased energy that is used during the heat debt. The total energy that is needed to run the heat pumps when controllings are performed may be lower or higher than in the original case depending on the outdoor temperature. When it is higher than in the original case, it can generate increased expenses for consumers that obtain fuse tariffs that charge consumers based on their energy consumption. Figure 16 shows how the hourly electricity heat cost varies for one building when a controlling was performed for consumers with hourly based tariffs.

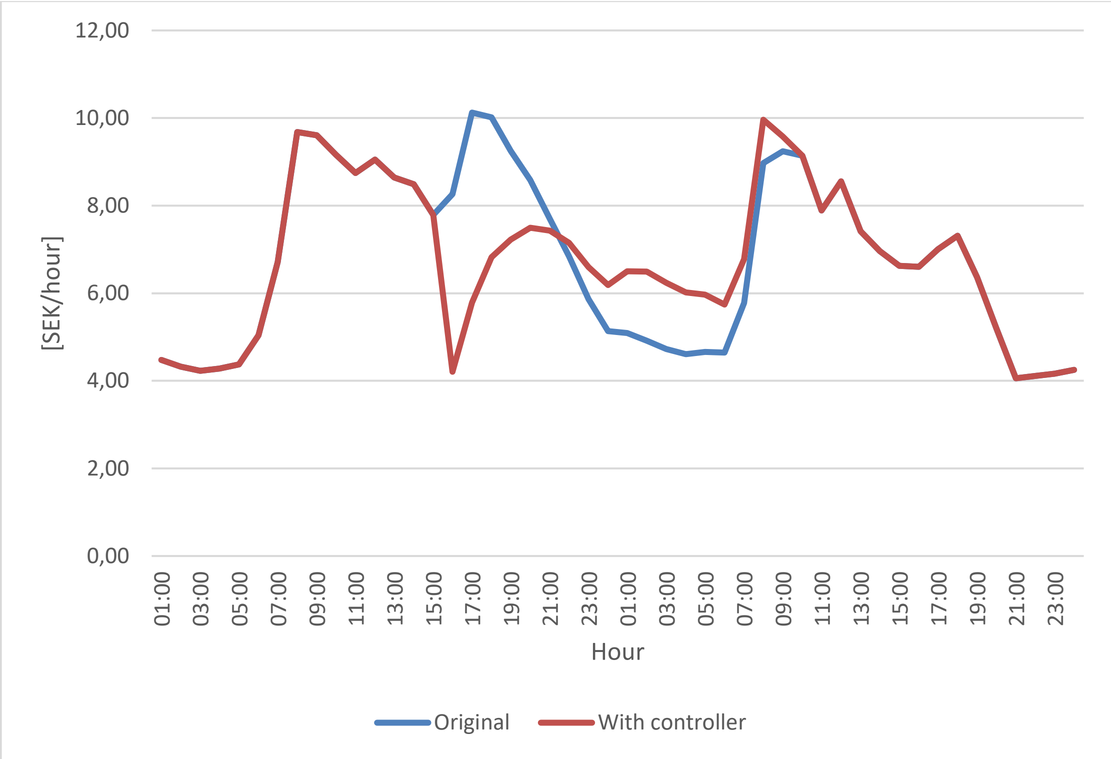

Figure 16. The hourly electricity heat cost for the building in figure 15 with and without controller during 48 hours when the outdoor temperature was 0° degrees Celsius.

Figure 16 shows that the need to control the HP was correlated to the highest hourly heat cost for the building, which therefore was lowered as a consequence of the controlling. However, the regeneration time causes a higher hourly price than in the original case. The heat consumption price was in total 2,25 SEK cheaper for this building during this time period when the controlling was used, even though figure 15 suggests that the total energy consumption may be slightly larger when the controlling is used. The reason is because the higher spot prices correlated to when the local grid needed to turn off the HP. The hourly spot price is composed by supply and demand, which means that high demand and low supply generates high spot prices and low demand and high supply generates low spot prices. It is therefore reasonable to believe that high spot prices often are correlated to hours with grid congestion, although it may have other explanations as well such as lower supply from wind power for example. When high spot prices correlate to grid congestion, consumers can expect a lower electricity cost when local grid operators use the demand flexibility since the heat consumption is shifted to cheaper hours. As previously mentioned, this is only the case for consumers that obtain hourly based electricity tariffs. Furthermore, if the HP are controlled to minimize the peak power in the local grid, it may also minimize the peak power for the consumers. If consumers' peak power is reduced, they may be able to lower their fuse level and consumers with demand-based tariffs may be able to lower their power fee. If the BRP controls the HP to minimize the imbalance costs, it may also result in lower balance costs for the consumers in a long-term perspective since the balance costs is part of the electricity bill (Hagelberg, 2018).

4.2 Case study 2: Balance market

There has been up- or down regulation in 77% of the hours in the Swedish power system during 2014-2017, which means that the frequency level has needed to be stabilized during 77% of the time. Up regulation correlates to a need of increasing the frequency level which can be made by increasing the energy production or decreasing the consumption. Down regulation means that the frequency level needs to be reduced, which can be accomplished by decreasing the production or increasing the consumption. Figure 17 shows the amount of hours with up and down regulation in SE3 in Sweden.

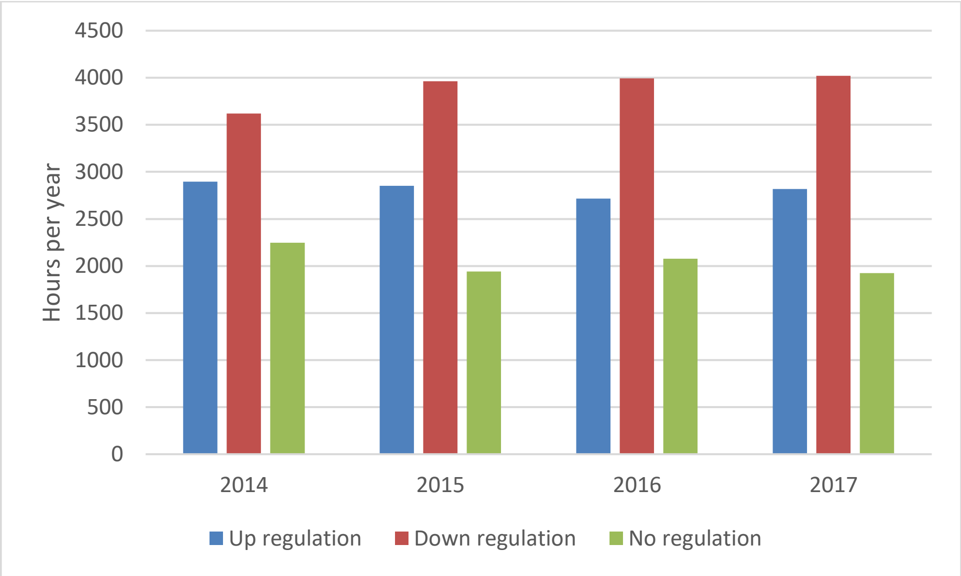

Figure 17. Amount of hours with up and down regulation as well as the amount of hours without any need for balance regulation in SE3 during 2014-2017.

As can be seen in figure 17, there are normally fewer hours of up regulation compared to hours with down regulation. Figure 18 illustrates the average hourly price for up and down regulation during this period that Svenska kraftnät debit or credit the BRP for depending on if they support or counteract the system’s total imbalance.

Figure 18. The average hourly price for up and down regulation in SE3 during 2014-2017. The positive price represents the up regulation price while the negative price represents the down regulation price during the same period.

The total average up regulation price during 2014-2017 was 65,61 SEK/MWh while it was -59,34 for down regulation. The average price is therefore generally higher for up regulation than for down regulation. According to Hagelberg (2018) it is important for the BRP to minimize the costs during the most critical hours with the highest additional prices by minimizing the imbalance volumes or by helping the system by for example reducing the consumption when it is up regulation. Figure 19 shows the average additional prices for the 10 hours with the highest up and down regulation prices.

Figure 19. The average hourly price for up and down regulation during the 10 hours with the highest additional prices in SE3. The positive price represents the up regulation price while the negative price represents the down regulation price during the same period.

Although the average up and down regulation prices were relatively similar, figure 19 shows that the peak prices during the period were a lot higher during up regulation compared to down regulation. The highest noted up regulation price in SE3 during the period occurred in 2015 and was 17700 SEK/MWh, while the average of the 10 hours with the highest up regulation prices during 2014-2017 was 5200 SEK/MWh. The highest down regulation price in SE3 occurred in 2016 and was 1700 SEK/MWh. The average of the 10 hours with the highest down regulation prices during 2014-2017 was -1300 SEK/MWh.

When there is a need for down regulation, the production level in hydro power stations is normally decreased. DR is normally not used for down regulation since that would mean an increased consumption level, which may generate higher costs for grid operators and electricity consumers as well as a negative impact on the climate (Hagelberg, 2018). When the temperature is below -5° degrees, 80% of the heat pumps are switched on, which means that the potential for switching on more heat pumps during the winter months is relatively low (Fischer et al., 2016). There is as previously mentioned also a desire from the grid operators to not further increase the peak power during the cold winter months since the power availability is limited.

However, there may be an opportunity for using DR from heat pumps for down regulation during the spring. When the snow is melting during the spring, the water flows through the power stations, which creates an overload of power that is hard to predict. There is therefore a need for either decreasing the power production or increasing the consumption during these occasions. Since it is warmer during the spring, the grid load is normally lower and it is therefore possible to increase the consumption without harming the grid (Hagelberg, 2018). In the same time, approximately 35% of the heat pumps are switched on when it is 5° degrees, which creates a higher potential to use DR from heat pumps for down regulation during this time period than during the winter (Fischer et al., 2016). However, using heat pumps for down regulation means that the pumps are turned on when they do not need to, which causes higher electricity costs for other market actors (Hagelberg, 2018).

If DR is used for up regulation instead, it may also generate economic savings for other actors aside of the BRP. When heat pumps are controlled for consumption reduction purposes, it also reduces the grid load and may result in lower electricity costs for consumers. The highest potential is therefore to turn off heat pumps when it is up regulation. Table 8 describes when the BRP makes a profit and loses money depending on if it is up- or down regulation and if they have a production or consumption surplus as well as the application possibilities for heat pumps.

Table 8. Information about when DR from HP can be used on the balance market.

	Production surplus	Consumption surplus
Up regulation	Profit – possibility to increase incomes by turning off heat pumps	Loss – possibility to reduce costs by turning off heat pumps
Down regulation	Loss – possibility to reduce costs by turning on more heat pumps	Profit – possibility to increase profit by turning on more heat pumps
	Production surplus	Consumption surplus

Based on previous arguments, this thesis will only investigate the potential of using heat pumps for up regulation purposes. According to Oehme (2018), heat pumps have a response time of 6 minutes, which is too long to participate on the FCR-N, FCR-D and the aFRR market. The maximum response time for the mFRR and the power reserve market is 15 minutes and it is therefore possible to participate on these markets if the resource fulfills the volume requirements. Another profitability opportunity is to reduce the heat consumption during hours when the intraday price is higher than the spot price. In this way, the BRP can sell the resource for a more expensive price than it was bought for (Hagelberg, 2018). The following sections describe these three market possibilities for the BRP to use DR from heat pumps during up regulation.

4.2.1 M-FRR

As previously mentioned, it is possible to use DR from heat pumps on the m-FRR market when it is up regulation either by increasing incomes when the BRP has a production surplus or by reducing costs when it has a consumption surplus. High up regulation prices should be prioritized since that generates the largest profit, independent on whether there is a consumption or production surplus for the BRP. The volume of the flexibility is strongly correlated to the outdoor temperature since a larger amount of heat pumps are switched on during cold temperatures than during warmer temperatures (Oehme, 2018) (Fischer, 2016). It is therefore interesting to analyze the correlation between the highest up regulation hours and the outdoor temperature. This correlation is illustrated for two different years in figure 20 and figure 21.

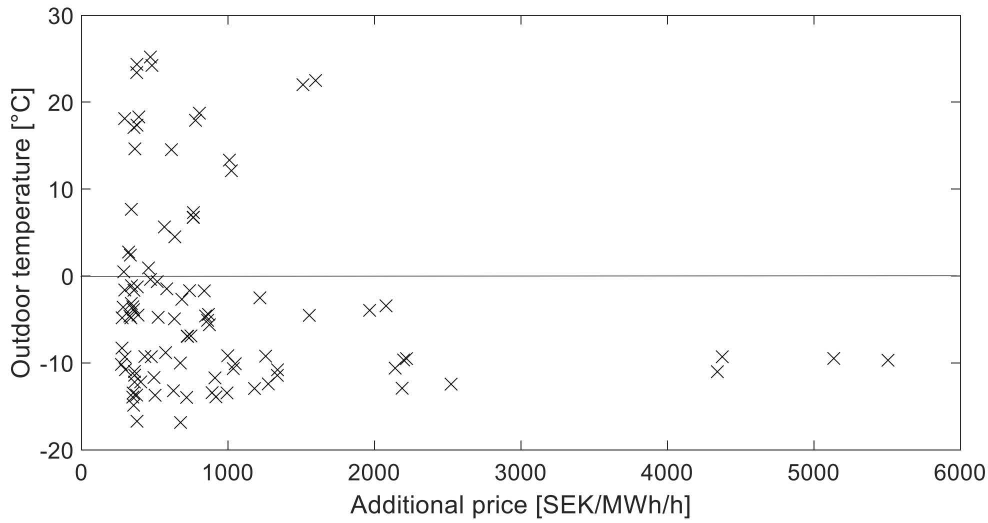

Figure 20. The correlation between the up regulation prices and the weighted outdoor temperature during the 100 hours with the highest up regulation prices in SE3 in 2016.

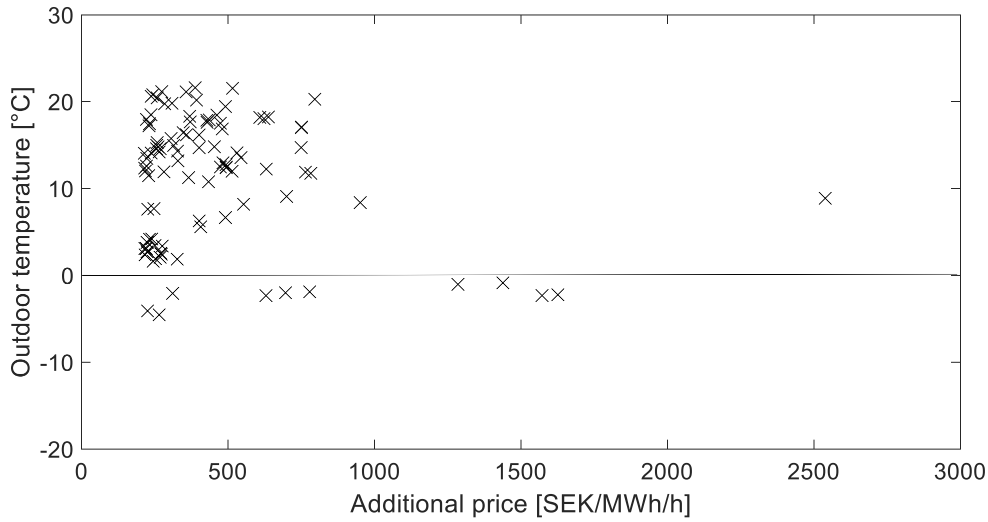

Figure 21. The correlation between the up regulation prices and the weighted outdoor temperature during the 100 hours with the highest up regulation prices in SE3 in 2017.

Figure 20 and figure 21 show that the highest up regulation prices are not directly correlated to specific outdoor temperatures. During 2016, the temperature varied between -20°C and 30°C while a majority of the most critical hours for the BRP had a temperature above 0C in 2017. The outdoor temperature was above 10°C in several of the critical hours for the BRP during both years. High temperatures generate a low flexibility from HP since a majority of the HP are turned off already and therefore can not be turned off again for controlling purposes. When the outdoor temperature is above 10°C, only 15% of the heat pumps are turned on, which means that the potential flexibility from HP is 15% of the maximal flexibility that occurs during cold temperatures (Fischer, 2016).

Figure 22 shows the potential incomes from the mFRR market in SE3 between November 16th and March 15th during three different seasons. As can be seen in figure 20 and figure 21 above, several of the hours with the highest up regulation prices occur when the temperature is above 10°C which may occur during the rest of the year between March 16th and November 15th. The yearly potential incomes from the mFRR market may therefore be higher than illustrated below but this time period was chosen to be able to compare the potential incomes from the mFRR market with the power reserve market. The outdoor temperature during the rest of the year is warmer and the available flexibility from HP is therefore smaller so the potential seasonal incomes should not be scaled up to generate a yearly income.

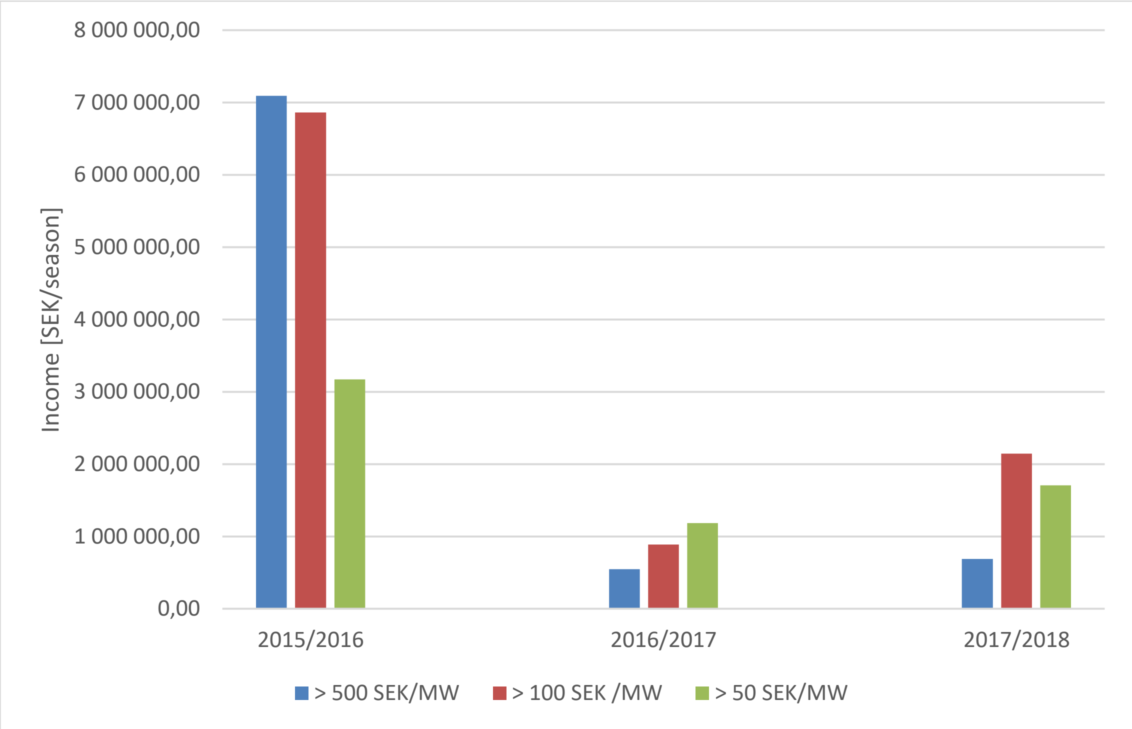

Figure 22. Potential incomes from the mFRR market in SE3 when the BRP provides bids when the up regulation price is above 500 SEK/MW, 100 SEK/MW or 50 SEK/MW between November 16th and March 15th during three different seasons.

Different amount of bids were placed on the mFRR market during the different seasons when placing bids above the certain price levels. The average amount of bids that were placed per season for the certain price levels can be seen in table 9. One controlling is performed during several hours and affects the costs/incomes for the BRP during all these hours in these calculations. The length of a controlling and the volume of the demand flexibility each hour during the controlling can be seen in Appendix A. If the controlling of the HP generates a reduced consumption during several hours of up regulation prices, it generates reduced costs or increased incomes for the BRP during all these hours in these calculations. If the heat debt occurs during up regulation prices on the other hand, it generates increased costs or reduced incomes for the BRP while down regulation prices during the heat debt generates reduced costs or increased incomes.

Table 9. The average number of controllings that were needed during one season to bid when the up regulation price was above 500 SEK/MW, 100 SEK/MW and 50 SEK/MW.

Bid level	Average number of controllings during one season
>500 SEK/MW	9
>100 SEK/MW	25
>50 SEK/MW	48

In 2016/2017, the incomes were increased when the amount of bids were increased. In 2017/2018, the incomes were more than doubled when controlling the HP during up regulation prices above 100 SEK/MW compared to 500 SEK/MW. The reason may be that there were many hours with up regulation prices between 100 SEK/MW and 500 SEK/MW and only a few hours that exceeded 500 SEK/MW.

In 2015/2016, the maximum income was obtained when DR only was used for hours with up regulation prices above 500 SEK/MW. When DR was used more often for up regulation prices above 100 SEK/MW, the seasonal income was reduced by approximately 200 000 SEK, while the income was less than half when bids were placed above 50 SEK/MW compared to bids above 500 SEK/MW. One reason why the income potential was reduced when more controllings were used may be that the BRP miss the hours with extraordinarily high up regulation prices when using the flexibility for hours with lower prices. The flexibility from HP has a certain repeatability for different outdoor temperatures and can not be used straight after a previous controlling, since the HP need to be switched on for a certain time period to restore the indoor temperature. When high up regulation prices of for example 2000 SEK/MW occur close after lower prices of for example 60 SEK/MW, it is then not possible to control the HP during the higher prices if the flexibility was already used for the hours with lower prices. It is therefore crucial to determine an optimal price level when the flexibility should be used on the mFRR market.

Another reason why more bids generated a lower income during this season may be the heat debt that occurs after the flexibility is used. When a HP has been controlled to turn off while it would have been turned on during normal circumstances, it needs to be switched on afterwards to restore the indoor temperature as previously mentioned. The energy from the HP that is used to restore the heat debt may be larger than the energy that was reduced when the HP was controlled to turn off. If there are still up regulation during the heat debt period, it may result in larger costs than incomes for the BRP depending on the prices in correlation to the heat debt. If there are down regulation during the re-generation time, the incomes are increased since an increased consumption during down regulation decreases the BRP’s costs or increases its incomes depending on if the BRP has a production or consumption surplus. It is possible to predict the size and length of the heat debt based on the outdoor temperature and the used flexibility and the BRP can therefor trade electricity ahead for the heat debt hours. However, it is difficult to know ahead if there will be up or down regulation in the power system and it is therefore difficult to know if the heat debt will generate an increased cost or income. If the heat debt correlates to grid congestions, it may not be possible to transfer more electricity to the HP which could decrease the indoor climate below the comfort zone for the customers. If the grid congestions allow for an increased electricity transfer to the HP during the heat debt, it may be expensive for the BRP to buy the needed amount of electricity since the prices may be higher during times of grid congestion.

The regulation prices vary and are not only correlated to the weather but also other circumstances such as the function of large production stations and grid transfer availabilities. If a nuclear reactor is broken down or the wind is stronger than predicted or the electricity transfer availabilities to other countries are congested, it may result in extraordinary high up or down regulation prices. A reason why the income potential was larger in 2015/2016 may be that the highest up regulation price was 17720 SEK/MW compared to 2079 SEK/MW in 2016/2017 and 2926 SEK/MW in 2017/2018. In 2015/2016, there were 23 hours with up regulation prices above 1000 SEK/MW compared to 4 hours in 2016/2017 and 9 hours in 2017/2018.

An important factor to take into consideration is that there are several BRPs in SE3 that are responsible for the energy balance for different consumers. A BRP has to participate with a minimal power volume of 10 MW in SE3 on the mFRR market, which may be difficult to achieve for BRPs that are responsible for a smaller amount of consumers. However, Svenska kraftnät is discussing different possibilities to lower the requirements to simplify for demand response to participate on the mFRR market (Thell, 2018; Andersson, 2018). Hagelberg (2018) also suggests that BRPs can use the resource for internal balancing purposes if the resource is too small to participate on the mFRR market.

4.2.2 Intraday market

The intraday prices are set closer to the delivery hour and may therefore differ from the day-ahead prices. Larger disturbances in electricity production stations between the closing time of the day-ahead market and the delivery hour may result in higher intraday market prices than the previously set day-ahead market prices (Hagelberg, 2018). There is therefore income potential to use the flexibility from heat pumps to reduce the consumption and sell the previously purchased power on the intraday market. In this way, it is possible to earn the difference between the day-ahead price and the intraday price for the flexibility that can be aggregated from heat pumps. The income potential from the intraday market during the season 2016/2017 can be seen in figure 23, with the same amount of controllings as on the mFRR market during this season in the previous section.

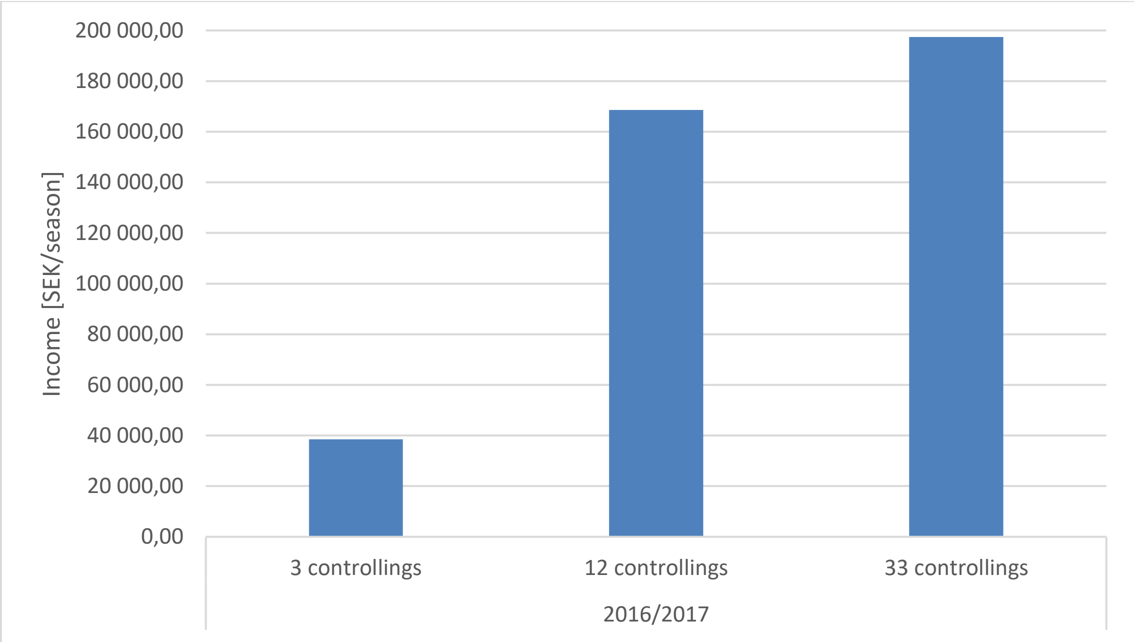

Figure 23. Potential incomes from the intraday market between November 16th 2016 and March 15th 2017 when performing the same amount of controllings that were used in the previous example on the mFRR market.

A comparison between the incomes from the intraday market and the mFRR market with the same amount of controllings is illustrated in figure 24.

Figure 24. Potential incomes from the intraday market compared to the mFRR market between November 16th 2016 and March 15th 2017 when performing 3, 12 and 33 controllings during the season.

4.2.3 Power reserve

The volume of the power reserve was calculated based on the outdoor temperature during the three different seasons and the fact that it has to be available for two hours with a maximum of six hours rest time until it has to be available again. The resource has to be available 95% of the time between November 16th and March 15th. The available demand flexibility in SE3 for the power reserve market based on the outdoor temperature can be seen in figure 25.

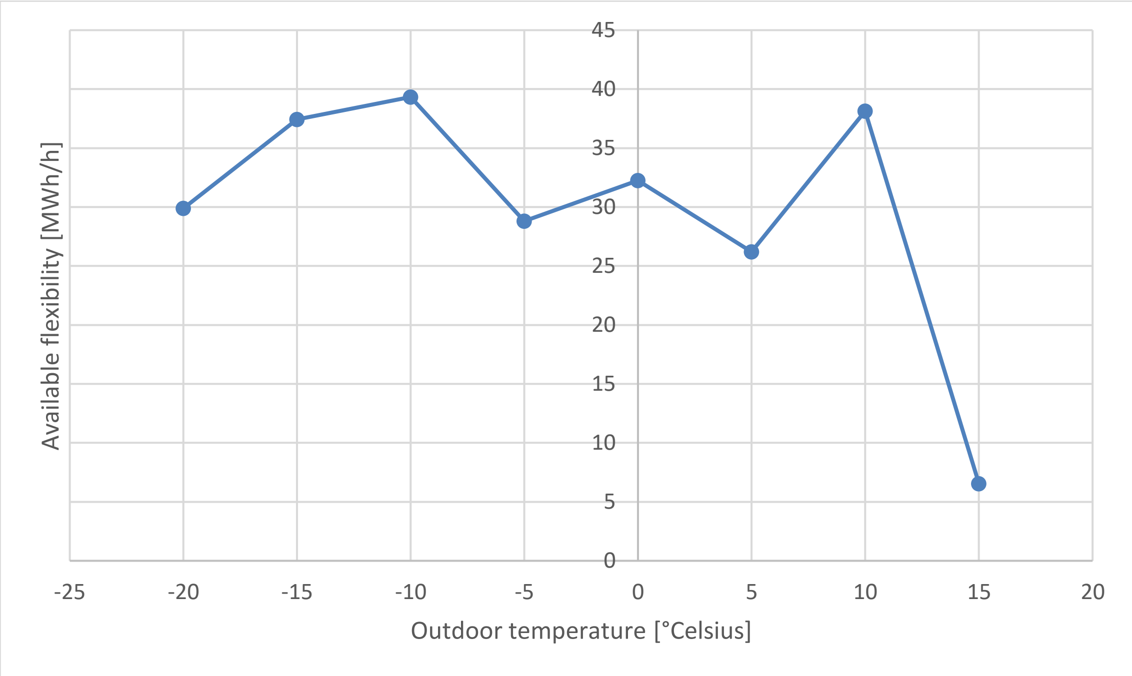

Figure 25. The available demand flexibility in SE3 on the power reserve market based on the outdoor temperature when the resource is available for two hours at the time with a maximum of six hours rest time.

The resource is smallest when the outdoor temperature is 15° Celsius, but this temperature was never reached during the seasons 2015/2016, 2016/2017 and 2017/2018. The smallest available resource is therefore reached when the temperature is 5° Celsius, where this temperature occurred in more than 5% of the total hours in each of the three seasons. The volume of the resource for the outdoor temperature 5°C was calculated to 26,198 MWh/h. Rounded off, 26 MWh/h is therefore the highest demand flexibility that could be aggregated from heat pumps in multi-family buildings in SE3 used on the power reserve market. The potential income from using this capacity on the power reserve market can be seen in figure 26.

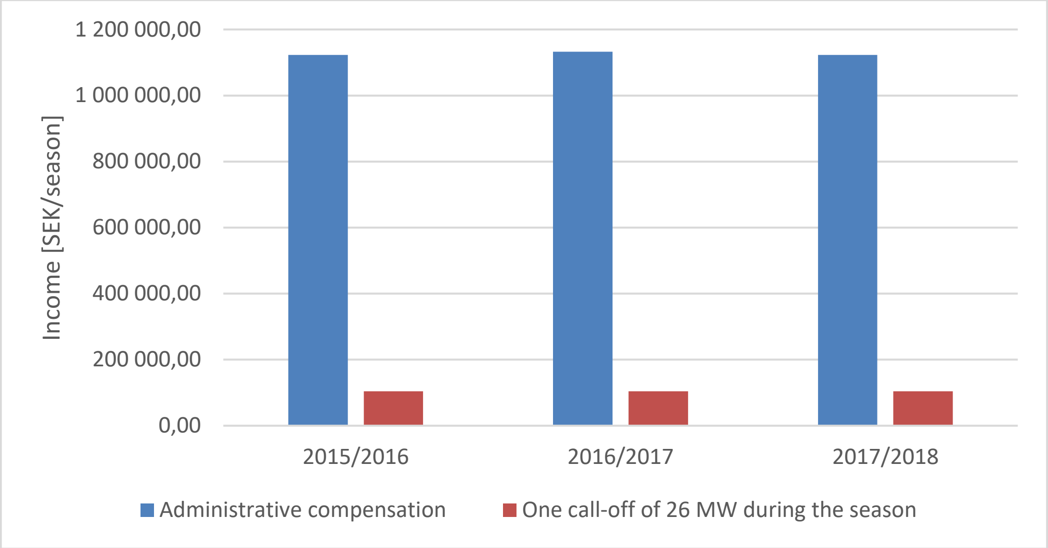

Figure 26. Potential income from participating on the power reserve market with the aggregated demand flexibility from all heat pumps in multi-family buildings in SE3. The total compensation consists of an administrative compensation as well as a compensation for each call-off of the resource.

The administrative compensation was calculated to 1 132 560 SEK/season during 2015/2016 and 2017/2018 and 1 123 200 SEK/season during 2016/2017 since 2016 was a leap year. If the entire resource of 26 MW was to be called-off, it would have resulted in a compensation of 104 000 SEK per call-off. According to Hagelberg (2018) there are normally maximum one call-off per year and the figure therefore shows the compensation from one call-off. Worth to note is that there are several BRPs in SE3 that are responsible for different consumption loads, where figure 26 shows the income potential for all BRPs in this sector in SE3. If one BRP is responsible for 25% of the consumption load for example, it would have a demand flexibility of 6,5 MWh/h which is higher than the current minimal requirement of 5 MW to participate on the power reserve market in SE3. BRPs that are responsible for smaller parts of the consumption load may struggle to exceed the requirement of 5 MW. The controlling of the heat pumps could also be optimized to maximize the resource volume. The available resource for 5°C was 52 MWh/h for the first two hours with a total of 6 hours of positive flexibility and a rest time of seven hours until the same resource was available again. Since the maximum for the rest time is six hours, the resource had to be divided into two parts. If the original resource was lowered or positive for a shorter time than six hours, the repeatability may be shorter and the resource would then not have to be divided into two parts which may result in a larger resource.

A problem when entering the power reserve market is that Svenska kraftnät requires real time measurement of the resource (Hagelberg, 2018), which may be expensive to implement for each heat pump. However, it is possible to predict the aggregated resource volume based on the outdoor temperature for a certain amount of heat pumps.

4.3 Correlation between grid operators and BRP

Since grid congestions is becoming a larger problem, using DR to reduce the grid load may be more common in the future. It is therefore interesting to see how the BRP would be affected if the HP were turned off with the aim of reducing the grid load. Figure 27 and figure 28 show how often the BRP is affected positively and negatively if the grid operator would control the HP during the 100 hours with the highest grid load during two different years.

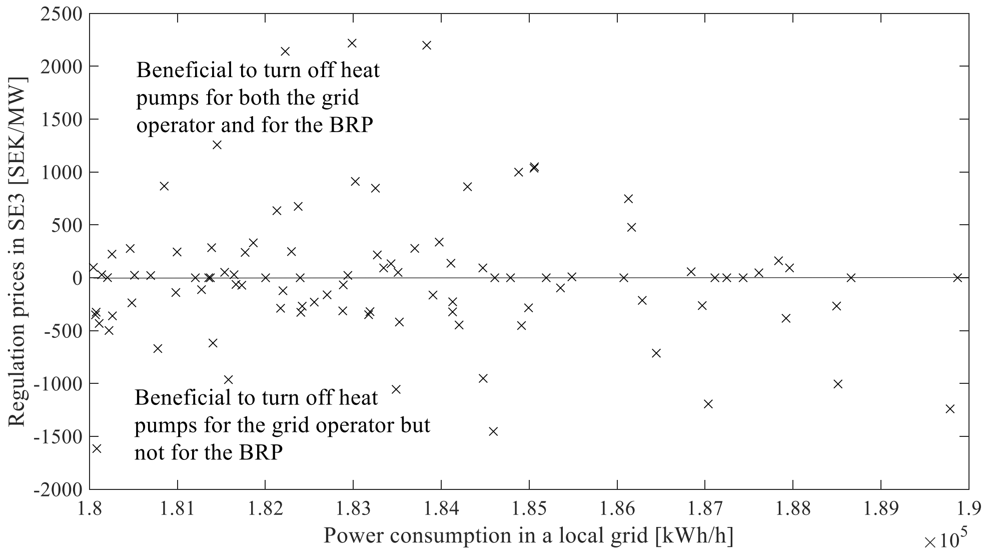

Figure 27. The additional prices in SE3 during the 100 hours with the highest peak power in 2016 in the investigated local grid that is located in SE3.

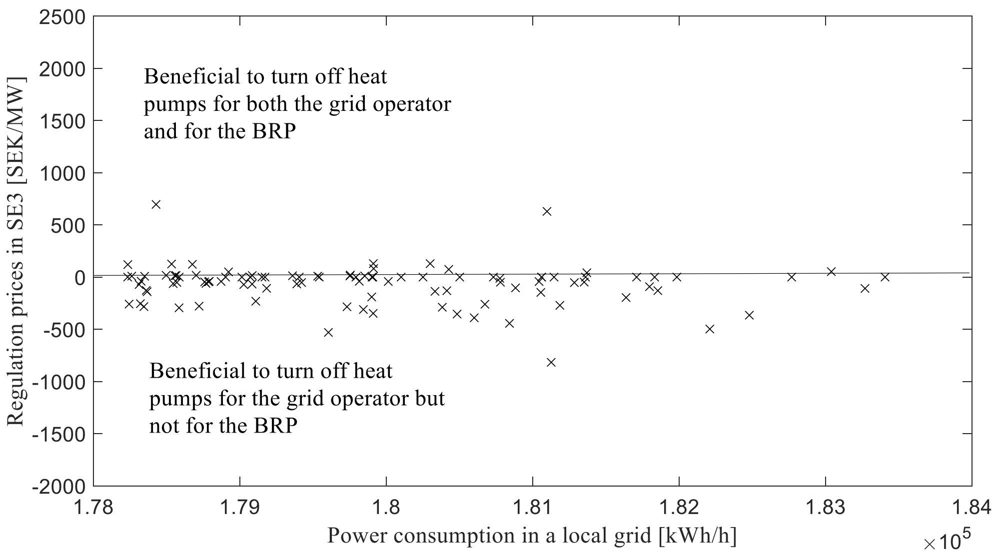

Figure 28. The additional prices in SE3 during the 100 hours with the highest peak power in 2017 in the investigated local grid that is located in SE3.

Figure 27 and figure 28 shows that there are both up and down regulation in SE3 during the most critical hours for the local grid in 2016 and 2017. In 2016, a few of the hours with the highest grid load in the local grid occurred during hours with down regulation prices around 1000 SEK/MWh. If an aggregator decide to reduce the grid load during these hours, it will result in high hourly costs for the BRP if the BRP is not aware of the consumption changes and can trade into balance. In 2017, the down regulation prices were not as high as in 2016 during the critical hours for the grid operators, but a majority of them occurred during down regulation. The need to control the heat pumps for this grid operator and for the BRP did not correlate in this case. It is therefore important that the aggregator communicates with the BRP when a larger demand flexibility is used in order to reduce the power consumption.

If the BRP wants to use DR from HP to reduce the imbalance costs, it is important to investigate how the heat debt will affect the grids. If the heat debt occurs during hours with a high grid load, it may not be possible to turn on the heat pumps again to stabilize the indoor temperature, which may result in cold indoor temperatures for the consumers. It is important to keep a comfortable indoor climate if the consumers are going to agree to install the control systems that allows DR from their HP (Håkansson, 2018). It is therefore important that the BRP is aware of any current grid congestion issues and choose to control the HP when the grid load is not extraordinary high. To minimize the risks of grid congestion, the BRP should control HP from different grids in SE3 since that decreases the heat debt in each grid compared to if all HP that are being controlled are located in the same grid.

4.4 Technical implementation possibilities

As previously mentioned, the income for the local grid was calculated to 2776 SEK/multi-family building per year. The potential income per house needs to be considered when choosing a suitable technical solution. There are currently several different technical solutions with different prices available on the market. NIBE, that is one of the larger HP manufacturers in Sweden, has a system called Uplink that consumers have had the opportunity to connect their HP to during the last five years. The system can optimize consumers' heat consumption with a recent update based on the Nordpool spot prices and the predicted heat and hot water consumption in order to reduce consumers' electricity cost (Kroon, 2018). Ngenic is a different actor that have developed a control system that optimizes consumers' indoor climate and currently acts as an aggregator. They have previously decreased Upplands Energi's peak power by controlling HP in detached houses when the grid operator had grid congestion issues (Berg, B., 2018). The software developer Enervalis has recently partnered with ABB to deliver their Smart Energy Management module and Schneider has a solution called EcoStruxure that optimizes the energy management. Other product suppliers that have products that optimizes the energy consumption is for example Siemens and Bosch (Lindgren, 2018).

5. Discussion

This section provides a discussion of the findings and methods that are described in the previous sections. First, a general discussion of the values that the service brings to the different market actors is provided as well as an analysis and validation of the implementation costs. The stakeholder values and implementation costs are then compared in relation to each other to discuss the potential profitability. Finally, an analysis of potential effects from changes in laws and regulations is performed.

The demand flexibility can only be used once and not several times for different purposes during the same time. It is not possible to for example participate on the power reserve market during one season and then place bids on the mFRR market or reduce the grid load with the same demand flexibility. It is therefore important to choose the optimal market for the resource. However, the BRP and the grid operator could divide the resource between them and the BRP could choose to participate with part of the resource on the power reserve market and place bids on the mFRR market with the other part. The case study shows that the mFRR market and the power reserve market provided higher economic profit for the BRP than the intraday market. It is therefore advisable for the BRP to use the resource on the mFRR market or the power reserve market to generate the highest income or cost reduction. The up regulation prices had a large variation between the seasons, which resulted in a large variation of potential incomes between the seasons. It is important to choose the right hours to control the HP on the mFRR market since the heat debt may result in a higher cost rather than income depending on if it is up or down regulation during the hours after the controlling. The BRP may choose to always place bids when the up regulation price is above a certain price level. The results varied and showed that it was most profitable to place bids over 500 SEK/MW in 2015/2016, 100 SEK/MW in 2016/2017 and 50 SEK/MW in 2017/2018. In general, it is important to not choose the price level too low since the BRP then may miss the extraordinary high up regulation prices.

The average income from the different seasons was higher on the mFRR market than on the power reserve market. However, using the demand flexibility on the mFRR market may result in grid congestion problems in the local grid. If the grid load during the heat debt exceeds the grid capacity level, it may result in indoor temperatures below the comfort level for consumers. To avoid this problem, it is necessary that the BRP has information about the different grid capacity levels and the grid consumption prognosis. It is also advisable that the BRP controls HP from different grids during the same time to not synchronize all the HP in one grid since that can create grid congestions. If the BRP uses the resource on the power reserve market on the other hand, the resource would rarely be used and the risk of causing grid congestion problems would be lower than if the resource was used on the mFRR market or the intraday market. If the BRP uses the resource to reduce the imbalance costs, it may have positive effects for the consumers in a long-term perspective, since a small part of the electricity bill consists of imbalance costs.

The results show that the need to control the consumption load does not always occur in the same time for the BRP and the grid operator. Many of the hours with the highest power consumption in the local grid occurred during hours with down regulation prices. If the grid operator decides to turn off the HP during these hours, it will result in higher costs for the BRP if it is not aware of the consumption change. It is therefore important with clear communication between the grid operators and the BRPs to avoid that the market actors counteract each other.

The grid operator could minimize the average between the two highest peaks that occurred during two separate months during a year with an average of 2,9 MW, which equalizes to 16,78 kW/building. This possibility generates an average cost reduction of 483 000 SEK/year or 2800 SEK/building per year including a reduction of both the penalty fee and the power subscription fee to keep the same margin to the power subscription as without the controlling. However, some grid operators may choose to not reduce their power subscription in order to be able to connect more customers to the grid in case it is not possible to increase the subscription level in the future. If the grid operators control the HP, it can generate either lower or higher energy consumption for the consumers depending on the outdoor temperature since the heat debt depends on the outdoor temperature. Even though the energy consumption may be larger, it may still result in a lower electricity price for the consumers if they have a demand-based tariff or pay their variating costs based on the hourly spot price. When a grid operator decreases the peak power in the local grid by turning off the HP, it is reasonable to think that the consumers' peak power will be reduced as well. Consumers with demand-based tariffs may therefore be able to reduce their peak power fee as a consequence of the controllings. When the power consumption is high in the local grid, the spot price is normally higher than normal since the spot price is composed by supply and demand. It is therefore advisable that consumers are charged by the hourly spot price for their variating costs or obtain demand-based tariffs if they control the HP.

Technical solutions that control the HP can also generate a more comfortable indoor climate for the consumers, where the consumers could choose to lower the indoor temperature while they are away for longer periods to save electricity. In this way, it is possible to improve the comfort level for the consumers while an aggregator can control the HP during peak power. It is important to keep the consumers' perspective in mind and to be able to promise that the control will not cause an indoor temperature below or above a certain level. Otherwise, consumers may not agree to let an external actor control their heat system. Worth to keep in mind is that if consumers install technical solutions that act on price signals, it may have negative effects for the BRP since the spot price is composed by supply and demand. If the demand is changed based on the price, the price is not market oriented anymore.

6. Conclusion

This section concludes the key findings from the results and discussion by answering the research questions. Recommendations for future studies are also provided in the end of the section.

The demand flexibility from HP can only be used for one purpose at the same time, although it may result in positive or negative impacts for other actors during the controlling. The results show that the grid operator in the case study can reduce their highest peak power with an average of 2,9 MW during a year, which equalizes to 16,78 kW/building. This possibility generates an average cost reduction of 483 000 SEK/year or 2800 SEK/building per year including a reduction of both the penalty fee and the power subscription fee. To generate these cost reductions, it is important with an accurate and reliable consumption prognosis system. A reduction of the peak power in the local grid may generate lower electricity costs for consumers with demand-based tariffs and for consumers that are charged by the hourly spot price for their variating costs.

The power reserve market and the mFRR market are considered the most suitable market for using DR from HP in multi-family buildings. The average income potential from the mFRR market when placing bids when the up regulation price was above 50 SEK/MW, 100 SEK/MW and 500 SEK/MW was calculated to 5 710 000 SEK/season in 2015/2016, 874 000 SEK/season in 2016/2017 and 1 513 000 SEK/season in 2017/2018. To optimize the income from the mFRR market, it is advisable to place bids when the up regulation price is above 100 SEK/MW to minimize the risk of missing the high up regulation prices but also place enough bids to generate a high income. The available demand flexibility for the power reserve market from HP in multi-family buildings was calculated to 26 MW, which generates an income of 1 133 000 SEK/season in administrative compensation and 104 000 SEK per call off.

The control need for the grid operator and the BRP did not always correlate though several critical hours for the grid operator occurred during hours with high down regulation prices. If the heat debt that occurs after a BRP has controlled the HP for the mFRR market occurs during grid congestion, it may result in lower indoor temperatures for the consumers since the grid capacity may not allow for all HP to turn on in the same time. It is therefore important with a clear communication between the BRP and the grid operators about when the controllings should be performed.

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Appendix A

Hourly demand flexibility depending on the outdoor temperature in the investigated local grid [kWh/h].

Hour	-20°C	-15°C	-10°C	-5°C	0°C	5°C	10°C	15°C
1	-10165	-9480	-7738	-5069	-3297	-2324	-1894	-651
2	-7594	-8526	-7672	-4544	-2715	-2036	-1592	-575
3	-4066	-6472	-6702	-3725	-2017	-1614	-1226	-440
4	-1952	-4579	-5271	-2619	-1562	-1211	-902	-391
5	-303	-3155	-3408	-1472	-1046	-868	-617	-348
6	115	-807	-990	-398	-510	-292	-336	-217
7	122	410	1101	735	535	249	118	-6
8	1278	438	1660	1939	1013	806	437	86
9	119	383	1650	2597	1543	1093	719	179
10	109	463	1560	2624	2230	1543	813	154
11	92	409	1620	2661	2519	1878	827	219
12	80	328	1673	2407	2427	1983	846	255
13	72	252	1583	2085	2560	2066	840	268
14	84	172	1560	1950	2612	1983	967	257
15	105	46	1575	1895	2392	1722	895	257
16	74		1635	1876	1713	1261	861	233
17	33		1505	1721	9234	716	913	181
18			1456	1610	397	281	935	1567
19			1501	1621			747	130
20			1789	1579			683	102
21			1773	1546			551	58
22			1622	1133			321	39
23			1802	481			72	50
24			1846					81

Hourly demand flexibility depending on the outdoor temperature in SE3 [kWh/h].

Hour	-20°C	-15°C	-10°C	-5°C	0°C	5°C	10°C	15°C
1	-169040	-159160	-123686	-92350	-68351	-55465	-39852	-13433
2	-129825	-140252	-112303	-80531	-60627	-49326	-36430	-12730
3	-79264	-104959	-89463	-63133	-46343	-39270	-30567	-10925
4	-32836	-67548	-64124	-43579	-32896	-29007	-24250	-8964
5	31	-30465	-34338	-23995	-19409	-18467	-17346	-68367
6	11938	5665	-3218	-3836	-5516	-8254	-10636	-4705
7	11978	18720	27883	16772	7753	2443	-3395	-2258
8	11602	18337	39525	38253	21833	13493	3522	-862
9	11043	17710	39268	53071	36439	23671	8258	45
10	10427	17261	38381	53202	51426	33068	10898	722
11	9788	16010	36061	51596	59344	40549	13309	1398
12	9355	12600	29902	45979	57091	44518	15847	1710
13	8886	7601	24579	40079	52097	46470	17279	1918
14	7840	1366	20091	34555	45496	44996	18385	2024
15	6092		14284	29961	36487	38930	18924	2385
16	3179		7412	25260	26171	30116	19004	2756
17			1986	20334	15541	21352	19087	3067
18			2729	14762	3654	11611	19169	3431
19			7018	10149		1773	18776	3674
20			10984	9660			16724	3892
21			13745	8884			13715	4211
22			17388	4686			9419	4334
23			21319				3728	4350
24			24391					4370