

Peak Shaving Potential of Demand Side Response in a Local Energy Community

LUND UNIVERSITY

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Thesis for the degree of Master of Science in Engineering
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This master thesis for the degree of Master of Science in Engineering has been conducted at the Division of Efficient Energy Systems at the Faculty of Engineering, Lund University, in collaboration with E.ON Energy Networks AB, Malmö. Supervisor at E.ON Energy Networks: Peder Kjellén; Assistant supervisor at E.ON Energy Networks: Staffan Sjölander; Supervisor at LU-LTH: Asst. Prof. Kerstin Sernhed; Examiner at LU-LTH: Assoc. Prof. Per-Olof Johansson Kallioniemi.

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Abstract

The introduction of renewable power generation and increased electrification puts higher demands on the power grids as many of these sources, such as wind- and solar power, are intermittent. One way to handle this is the use of demand side response (DSR), which is a technology that has received an increased interest the last few years. DSR is to change customer electricity consumption over time, for example to hours with lower consumption and thereby reducing high loads on the power grid.

The purpose of this thesis is to investigate the potential of DSR to decrease power peaks on a daily basis over an entire year in a local energy community (LEC). An LEC is a concept defined by the European Commission, which allows household customers to act as an aggregated load with a common measuring- and connection point to the overlying grid. A fictive LEC with 200 household customers is assumed and has the following controllable units; heat pumps (HPs), electric vehicles (EVs) and photovoltaics (PVs) with batteries. These units are simulated in two ways; first, a base simulation of the load patterns from the units when they are not subject to DSR. Then, a DSR simulation in which DSR of the units is used. The simulations are done in order to investigate the change in daily load curve and peak power change when using DSR. The peak powers are measured both per month and annually and defined as the highest measured power during one hour.

Simulations of three cases with different shares of units are made, leading to varying results. It is found that for each unit the annual peak power in the LEC is decreased by 2 - 6 % using controllable HPs, 15 - 43 % with distributed EV charging and 2 - 10 % using PV with batteries. Combining all units, the annual peak power is decreased by 16 - 40 %. Looking at monthly distribution, the highest potential for peak shaving is during summer where the peak power in June/July is decreased by 35 - 68 %. The lowest potential is during winter, where the peak shave is between 13 - 40 %.

Using the results from the simulations, an economic analysis is done. It is assumed that the LEC is charged according to how a company connected to the low voltage grid is charged today, which normally is based on peak power. Tariffs from three different distribution system operators are compared, two Swedish and one German. It is assumed that the LEC needs to invest in; control units for the HPs, EVs and the batteries as well as a central control system. With this assumption there is no profitability with current cost levels. Removing the cost for the central control, there is a payback time between 11 - 25 years with the different tariffs. Further, when removing also the battery (from both simulation and economic calculation) the payback time is between 3 - 9 years.

Keywords: battery, clean energy package, demand side response, electric vehicle, heat pump, local energy community, peak shaving, photovoltaics.

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Lund, June 7, 2018

Jakob Ingvar-Nilsson
Lisa Sandblom

List of abbreviations

BEV	Battery Electric Vehicle
BESS	Battery Energy Storage System
CEP	Clean Energy Package
COP	Coefficient of Performance
DHW	Domestic Hot Water
DSO	Distribution System Operator
DSR	Demand Side Response
EV	Electric Vehicle
FLH	Full Load Hours
HP	Heat Pump
LEC	Local Energy Community
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaics
SCOP	Seasonal Coefficient of Performance
SoC	State of Charge
TSO	Transmission System Operator

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Chapter 1

Introduction

With a rapid introduction of new technologies and an ongoing transition towards a more renewable energy sector, new challenges are emerging which demands innovative solutions for both producers, businesses and consumers on the energy market. The installed capacity from renewable generation will likely continue its fast increase over the next years (International Energy Agency, 2017b). This development is in line with internationally agreed goals which sees to decrease greenhouse gas emissions from the energy sector. However, this trend adds new challenges due to the nature of most renewable generations as they cannot be scheduled to produce electricity according to current consumption.

Since a future scenario includes more intermittent power, i.e. power generation that cannot be planned due to their dependency in weather, the power system will be in need of more balancing components. To handle peak powers during cold winter days, the Swedish Transmission System Operator, Svenska Kraftnät, procures a power reserve. Today there is both a reserve capacity that can be started on demand and consumption flexibility in terms of larger industries that can decrease or shut down their consumption (Svenska Kraftnät, 2017b). In the winter 2016/2017, the reserve in Sweden was 994 MW, out of which 34 % was in the form of consumption reductions (Svenska Kraftnät, 2017a). According to Svenska Kraftnät, the demand for flexibility will be substantially larger in the future. The introduction of demand side response (DSR), the action of changing or moving the customer energy consumption, will therefore have an increasingly important role (Svenska Kraftnät, 2017b).

Today DSR of electricity consumption is rarely used, but there are examples of its implication. One example is load control of electric vehicle charging for companies and housing cooperatives (Krafrtringen, n.d.-a; Vattenfall, n.d.). However, this is not in the context of being a balancing component on the transmission power grid as the reserve capacity described above. Instead, DSR can be desirable from an energy utility perspective to decrease the peak load on the electricity grid. The daily household consumption of energy follows a clear pattern with two peaks during the day; one in the morning and one in the evening (Broberg, Brännlund, Kazukauskas, Persson, & Vesterberg, 2014). By reducing these peaks, i.e. peak

shave, the load on the grid is decreased, grid utilization is increased and reinvestments in the grid could be postponed (ABB, n.d.; Kjellén & Sjölander, 2018).

Strategies to face the challenges connected to a renewable energy system are partly described in the “Clean Energy for all Europeans” package (CEP) prepared by the European Commission. One part of this is the introduction of *local energy communities* (LECs)¹ which is a way to increase customer involvement and local ownership on the energy market (European Commission, 2017). A clear definition of LECs, their rights and obligations have not been implemented at the time of writing this thesis. The proposed package of legislations, CEP, emphasizes the importance of customer engagement in the new energy system, where one action of the customer can be participation in DSR. In this thesis, the LEC is regarded as a residential area with single houses, whereas in reality it could involve other types of customers or buildings.

In addition to the intermittent electricity production, the use of electricity might change as electric vehicles (EVs) are introduced and photovoltaic cells (PVs) are added on rooftops together with a home battery. This change depends on several factors like weather, charging need, time of day etc. However, the spontaneous behaviour of residents could give rise to high power peaks if, for example, the residents charge their vehicles at the same time. This could possibly be avoided if the consumption can be moved in time, i.e. the customer consumption is flexible. This is also true for household electricity units with high electricity consumption, such as washing machines, dishwashers, water heaters or heat pumps. However, DSR of some appliances could interfere with customer comfort if residents wishes to use their units while it is subject to load control. In addition to this, customers might need an incentive to participate in DSR. This points to the necessity of also investigating the profitability for customers using DSR.

The CEP also opens up for other types of actors to take place on the electricity market, for example aggregators. An aggregator can combine customer loads, potentially through load control, or customer small-scale electricity production and offer it on electricity markets. An independent aggregator could be a competition to energy distributors and suppliers. Hence, it is in the interest of established market players, for example DSOs, to look into the potential of DSR themselves and possibly provide this service for their customers.

Against this background, it is interesting to investigate how the electricity consumption profile might change in the future and how power peaks can be reduced by using demand side response in a way that does not disturb customers daily life.

¹ The LEC is connected to the distribution grid and shall not be confused with a *local energy system* (LES) where there should be production, storage and consumption as the LES needs to be able to operate in isolated mode (Schwaegerl & Tao, 2014).

1.1 Purpose and research questions

The purpose of this thesis is to investigate to what extent the use of demand side response can contribute to peak shaving in a local energy community. The demand side response aims to reduce daily peaks over the entire year. Further, existing tariffs related to peak power will be studied and applied to the local energy community.

To fulfill the purpose of this thesis, the following research questions will be answered:

1. What is the demand side response potential of the following units:
 - (a) heat pumps?
 - (b) electric vehicles?
 - (c) photovoltaics with batteries?
2. What is the demand side response potential in a local energy community to contribute to peak shaving on an aggregated level?
3. Using three real capacity tariffs, two Swedish and one German, what is the economic outcome if applied to a local energy community using demand side response?

1.2 Disposition

This thesis consists of three main parts; a literature study of the units used for DSR, a simulation of the load patterns from the units both with and without using DSR and finally an economic analysis of the LEC's cost and payback time when investing in control systems for the units. It is disposed as follows: *Chapter 2: Background* explains the context of the introduction of LECs and the concept of demand side response. *Chapter 3: Methodology* describes the overall method of the thesis. Next, *Chapter 4: Demand response units*, is the result of the literature study where the units for demand response are explained in terms of technical basics, market and theoretical potential of demand side response. *Chapter 5: Simulation of units* in detail describes the method for simulation and the result from this is displayed in *Chapter 6: Result and analysis of simulation*. In *Chapter 7: Sensitivity analysis* three parameters in the simulation are altered in order to examine how the results changes. Then, the main results from the simulations are used in an economic calculation to find annual savings for customers using DSR as well as payback time which is found in *Chapter 8: Economic analysis*. The results of the simulation and economic analysis are discussed and questioned in *Chapter 9: Discussion*. Conclusions and recommendations for future work is presented in *Chapter 10: Conclusions*.

Chapter 2

Background

The following chapter aims to put local energy communities into context and further elaborate the need for demand side response. First, the political incentives for customer engagement on the energy market is presented. Secondly, a more in-detail definition of demand side response is provided as well as the current and future development of a flexibility market. Then, some perspectives on customer attitude on DSR are mentioned. Lastly, an overview of previous studies on DSR is presented.

2.1 Political incentives

When working towards a more environmentally friendly society, reducing greenhouse gas emissions from the energy sector is of high importance as the consumption of energy is responsible for 25 % of the world's accumulated emissions (Intergovernmental Panel on Climate Change, 2015). The European Union (EU) has several goals in the energy sector. One of these is the 2030 Energy Strategy where the main goals are to decrease the greenhouse emissions, increase the share of renewable energy and increase the energy efficiency in the union (European Commission, n.d.-a). One way to realize the European goals are through the strategy described in the following section. On the national level, the Swedish Energy Agreement is of relevance.

Clean Energy for all Europeans

In order to achieve the 2030 Energy Strategy goals, the European Commission presented the Clean Energy for all Europeans package (CEP) in 2016. The CEP is a package of measures which not only sets out a path for the countries in the union to work after, but also intends to

make EU a global leader in the transition towards renewable energy production, energy efficiency and cutting the greenhouse gas emissions. Further, the package intends to elevate the importance of the customers in this transition. This means a more transparent and open energy market where customers can make active choices of their supply as well as produce and sell their own energy. In this energy transition, customers will take an active part (European Commission, 2017).

The CEP consists of eight different legislation proposals. One of these contains the proposal of the Electricity Directive (2016/0380(COD)) (European Commission, n.d.-b). This proposal is of importance to this thesis, as it lays out a legislative and political framework necessary for creation of LECs. In this context, an LEC is described by the European Commission as “*a geographically confined community network that may operate in an isolated mode or be connected to the public distribution network*”. In the CEP, it is stated that customers participating in an LEC are, among other things, entitled to own, establish and manage an energy community in order to fully utilize the potential of local production and storage. An LEC may also encourage active engagement such as the use of demand side response. The members are entitled to fair and transparent charges for their participation and, alongside with distribution system operators (DSOs) and transmission system operators (TSOs), participate in ancillary services depending on technical possibilities (European Commission, 2017).

All in all, the CEP describes how LECs, DSOs and TSOs can cooperate and benefit from each other in order to encourage and enable the participation of more active customers on the energy markets in the progress towards the 2030 Energy Strategy goals (European Commission, 2017).

The Swedish Energy Agreement

Currently, hydro- and nuclear power dominate the Swedish electricity generation and accounts for approximately 80 % of the power generation, producing equal amounts. Other types of power sources are wind power, 10 %, thermal power, 9 %, and solar power of 0.05 % (SCB, 2017). However, this mix will change in the future since the parliament has set a goal to have a 100 % renewable electricity system. Despite this, it is not clear if, when and how fast the nuclear power will be dismantled (SOU, 2017:2). However, there are decisions taken regarding two of the oldest reactors that they will be decommissioned during 2019 and 2020 (Vattenfall, 2017).

In 2016, five out of eight parties in the Swedish parliament agreed on a long term plan for the Swedish energy sector, called ”The Energy Agreement”. The overall goals, related to electricity production, from the agreement are:

- Zero net emissions of greenhouse gases by 2045

- 100 % renewable electricity production by 2040
- Decide on an energy efficiency goal between 2020-2030¹

Among other strategies to achieve these goals, implementation of new technologies is mentioned. It will be easier to produce, store and trade electricity amongst customers. Micro-production of electricity and possibilities to increase energy efficiency will, during the time of the agreement, be incentivised (The Swedish Government, 2016a).

The agreement enables the development of technology which can increase customer participation in the energy market while decreasing the dependency on centralized power plants. It also allows participants on the market, such as utilities who need long term conditions, to initiate projects which can contribute to the desired development.

2.2 Demand side response

Customers today use electricity according to patterns in their everyday life. Turning on lights, cooking food and washing clothes all takes place according to accustomed patterns in the society. However, this habit depending consumption in households is only one part of the total electricity consumption, as many single houses uses electricity also for heating. Household electricity includes activities such as cooking, cleaning, illumination and entertainment, while heating covers space heating and domestic hot water (DHW) consumption. A common distribution over the two categories is 30 % household electricity and 70 % electricity for heating. The average total consumption of electricity for a single dwelling using electric heating in Sweden is 22 000 kWh per year (Swedish Energy Agency, 2017d; E.ON, 2017).

In the coming years, customers will to a larger extent produce their own electricity and drive cars powered by electricity compared to what they do today (Transport Analysis, 2017b; Lindahl, 2016). This introduction may add significant amounts of loads which potentially could be moved, using load control, in time without affecting the customers. Load control could potentially be used for many household appliances. Control of heating systems is, compared to household electricity, usually not noticed by the customer unless the temperature in the house drops too much (Sernhed, 2004). Household electricity may however also be controlled, but can have undesirable effects on customer comfort. In this perspective, household electricity can be seen as a less suitable option for load control, see *Figure 2.1* (Vanhoudt et al., 2014). The change of loads over time is called demand side response (DSR) (Svenska Kraftnät, 2017b).

¹ It was later decided that the energy efficiency goal is to increase the energy efficiency by 50 % to 2030 compared to 2005 (The Swedish Government, 2016b).

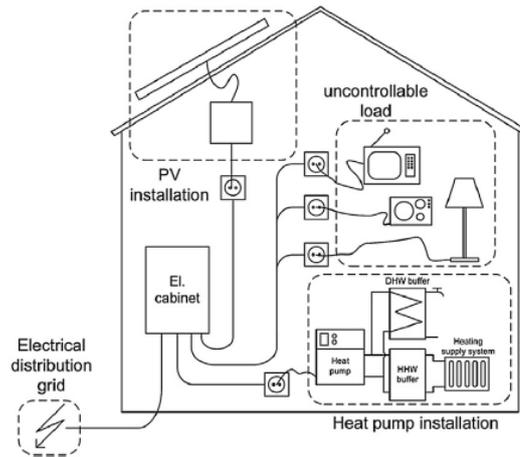


Figure 2.1: Example of household loads which may or may not be controlled using demand side response (Vanhoudt et al., 2014).

Depending on what the control contributes to, there are different names which more or less describe the same activity. In this thesis, demand side response is the same as load control, terms which may also be used in an equivalent manner. Two types of DSR can be defined:

Implicit DSR: price-based DSR where the customer reacts to a price signal. This requires that the customer has a time varying price of electricity. By being flexible the customer would be able to reduce their total energy cost (Alvehag et al., 2016).

Explicit DSR: active or autonomous load control where customer load is displaced in time. One purpose of this load shifting is grid benefits. Another aspect is that the displaced energy may be offered to different energy markets. For explicit DSR the customer load is more strictly controlled (Alvehag et al., 2016).

DSR can achieve two purposes, either negative control or positive control. Negative control means that power is decreased. Incentives for this can be to decrease peak powers or to match current local production when it falls short of local consumption. Positive control is used to increase consumption during times when this is desired, for instance when local production from renewable generation exceeds local consumption. This can be achieved by charging electric vehicles, home batteries or other energy storage solutions such as power-to-gas (Stadler, 2008). This thesis focuses on *explicit DSR* and how it can be utilized to achieve peak shaving using *negative control*.

2.2.1 DSR on the Nordic market

The Nordic electricity market is in several ways interconnected; physically through grid connections and economically through the joint energy marketplace Nord Pool. To further develop this collaboration, a common internal energy market for end-users is being developed

by the Nordic Energy Regulators (Swedish Energy Markets Inspectorate, 2017b). In addition to this, the four Nordic TSOs have also decided to harmonize the different Nordic balancing markets (Energinet, Fingrid, Statnett, & Svenska Kraftnät, 2017). For example, this includes harmonizing of national legal framework and minimizing market barriers (Svenska Kraftnät, 2017b). However, it is yet to be decided exactly how this will be implemented (Energinet et al., 2017).

A way to make it easier for more participation on the balancing market is to allow aggregation of smaller resources, who themselves cannot make a bid on the balance market. The bidding limit in terms of power is today higher than what a household could supply. The Nordic TSOs argue that for small units, such as households, it is necessary that an upper hand aggregates them into one to enter the balance market (Energinet et al., 2017). An aggregator is, in the proposal of the Electricity directive, defined as “*a market participant that combines multiple customer loads or generated electricity for sale, for purchase or auction in any organized energy market*”. An aggregator can be independent, i.e. not connected to an energy supplier or another type of actor on the market. Hence, a customer can engage in a contract with an aggregator, without consent from their energy supplier (European Commission, 2017). This provides a reason for the DSOs or electricity utilities to themselves develop these kinds of services (Energinet et al., 2017). The aggregation of resources could be realized through LECs and thereby possibly offering the flexibility from LECs on balancing markets.

2.2.2 Customer attitude on DSR

The supply of electricity is today taken for granted in Sweden. The introduction of DSR can thus be perceived as a large adjustment for some customers. To be able to achieve flexibility on the energy market, household customers play a vital role. It is therefore important to take into account how customers experience different DSR measures. In this section results from three different studies made in Sweden, where the customer perspective was included, are shortly presented.

The electricity use in households has a clear load profile with two peaks; one during the morning and one during the evening, see *Figure 2.2*. It is during these peaks where power reduction may be interesting in the perspective of this thesis. However, surrounding loads on the grid needs to be taken into consideration when deciding a peak shaving strategy.

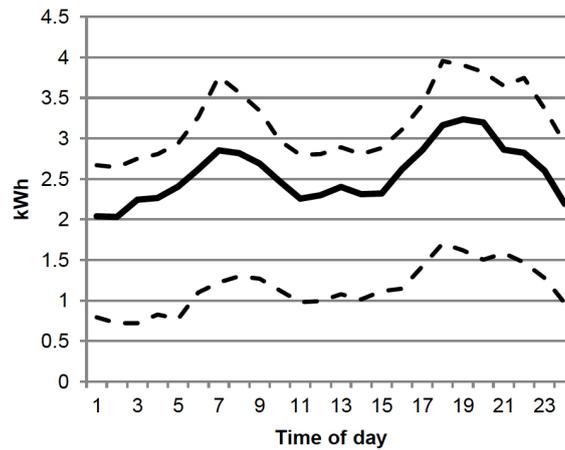


Figure 2.2: An example of household electricity use during a February weekday in Sweden. The continuous line is median use and the dashed lines are eightieth (top) and twentieth (bottom) percentile (Broberg et al, 2014).

The Swedish Energy Market Inspectorate conducted a survey on households attitudes towards offering flexibility. The load control was set out between 7-10 in the morning and/or 17-20 in the evening. The entities of control was heating systems and household electricity usage such as washing machines and dishwashers. The results showed that a general opinion was that a limitation in the energy use was seen as something negative and that participation should be compensated. It also showed that the households were more positive to control of their heating compared to a control of household electricity usage. The reason for this was stated to be that the households were less affected when controlling only heating whereas their daily life would be disturbed when controlling household electricity (Broberg et al., 2014).

In a different study, which investigated customer incentives to participate in a local energy system, household heat pumps and hot water boilers were the controllable units. In the study it was concluded that the customers in general were positive towards DSR. A majority of the customers wanted to contribute with flexibility. Those who did not want to participate were of the opinion that they did not have enough information or insights in order to contribute. On the other hand, customers had a negative approach towards participating if it required any investments or a large engagement (Ingelsson Wendell & Rydberg, 2017).

In a study from 2004, ten households were subject to load control of their electricity based heating and water heater during periods of mainly 1 - 4 hours at a time. Nine out of ten said that this type of load control was acceptable and that the maximum indoor temperature drop should be 2 - 3°C. Some kind of financial compensation was also stated to be a prerequisite for participation (Sernhed, 2004).

2.2.3 Previous studies on DSR

A great number of studies have investigated the potential of demand side response in power grids with different objectives. However, the focus of many studies have been to decrease the cost for customers using a time-of-day tariff, i.e. a varied hourly price (Saele & Grande, 2011; Mathieu, Dyson, & Callaway, 2012; Alimohammadisagvand, Jokisalo, Kilpeläinen, Ali, & Sirén, 2016). These prices are typically higher during peak hours, providing an incentive to decrease power peaks or move consumption to lower consumption hours. The control is then set to follow the current electricity price; if the price is high, the consumption is reduced.

In addition to this, studies have investigated DSR of heat pumps (HPs) with various purposes. For example, DSR of HPs in combination with different internal heating systems (radiators and underfloor heating) was studied to compare the thermal inertia and through that the potential of DSR for these specific heating systems (Arteconi, Hewitt, & Polonara, 2013).

For electric vehicles (EVs), the potential of DSR for bidirectional power flow such as vehicle-to-grid has been studied (Soares, Morais, Sousa, Vale, & Faria, 2013). Another approach has been that customers can choose when the load control should be done and on which appliances, including EVs, by setting a maximum power limit per household (Shao, Pipatanasomporn, & Rahman, 2012). There are also cost-based DSR studies for EVs in order to decrease peaks in the grid (Tan, Yang, & Nehorai, 2014).

Using DSR of home batteries connected to photovoltaic (PV) systems has been studied (Lorenzi & Silva, 2016). However, only the PVs are more rarely studied which could be explained by the simple fact that only PV is not suitable for DSR. As PV is a power generation source, it can only decrease peaks if the peaks occur during the time that the PV is producing.

Studies investigating the potential of combining all of these specific units - HPs, EVs and PVs with batteries - have not been found. Information about demand response of these units individually are found in *Chapter 4: Demand response units*. The contribution of this thesis is thus to examine the potential of demand side response for these household units in combination. Further, these units have been selected as they, when properly controlled, interfere very little with customer comfort with respect to both use patterns and customer involvement of the control.

Chapter 3

Methodology

This chapter describes the overall method of how each of the earlier formulated research questions were answered.

3.1 Literature study

To answer research question 1; *"What is the demand side response potential of the following units? (HP, EV and PV with battery)"*, a literature study was conducted in two parts. In the first, google scholar and other scientific search engines were used to find scientific articles regarding the different units; heat pumps (HPs), electric vehicles (EVs) and photovoltaics (PVs) with batteries. Key findings were technical background and demand side response potential for each unit. This included results such as power demand, use patterns and earlier studies of DSR of the units.

In the second part of the literature study, current and future forecasts on the prevalence of the units were investigated. This was needed to develop three cases, where one of them was based on a 2030 prognosis. The purpose of using different cases was to investigate the outcome when residents in an LEC had different shares of units and how it affects peak powers on an aggregated level. The basis of the cases are stated below:

- Low case: based on current occurrences of HPs and on forecasts for the year 2030 for EV and PV.
- Medium case: middle case between low and high case.
- High case: maximum occurrences of all units.

The reason for using the prognosis outcome in the low case was due to the relatively low projections for EVs and PVs. The forecasts used for EV and PV inputs were done by two

government charged agencies; the Transport Analysis and the Swedish Energy Agency and were both focused on the year 2030. For the HPs, such forecasts could not be found. Therefore, the low case was decided to correspond to the current prevalence of HPs.

The findings from the literature study is found in *Chapter 4: Demand response units*.

3.2 Simulation

A simulation of an LEC was made to answer research question 1 and research question 2; *"What is the demand side response potential in a local energy community to contribute to peak shaving on an aggregated level?"*. Simulations were made for HPs, EVs and PVs individually and in combination. The simulation model was built in Python, using the development environment Spyder. In addition to this, VIP-Energy was used to simulate HPs and System Advisor Model was used to simulate PV production.

Two types of simulations were done; a base simulation and a DSR simulation. The difference between the two is that in the base simulation, the units (HPs, EVs and PVs with batteries) were uncontrolled and in the DSR simulation the units were controlled. A detailed description of the simulation method is presented in *Chapter 5: Simulation of units*. Simulated aggregated load profiles of the LEC were obtained in the three cases (low/medium/high) to visualize how load control affects the LECs power outtake and compare the cases to each other. To put the simulated numbers into context, a base load of household electricity, referred to as "original load", was used as a basis in all simulations which consisted of real electricity consumption data from 96 households with hourly measurements.

The results from the simulation are presented in *Chapter 6: Result and analysis of simulation*. A sensitivity analysis was also done on parameters that were considered to have high impact on the end result. This is found in *Chapter 7: Sensitivity analysis*.

3.3 Economic analysis

The economic analysis was performed to answer research question 3; *"Using three real capacity tariffs, two Swedish and one German, what is the economic outcome if applied to a local energy community using demand side response?"*. The two Swedish tariffs were chosen as they had differences in how peak powers were charged, while the German tariff was chosen to further widen the perspective of how tariffs can differ in how the electricity distributors charge their customers. With the three tariffs, the economic potential of peak shaving could be investigated using the results from the simulations.

The analysis aimed to compare the energy expenses for the low, medium and high case in the base and DSR simulation respectively. Results were obtained which showed how DSR may decrease energy expenses on an annual basis in the three cases in absolute (SEK/EUR) and relative (%) numbers. With given results, a payback time for the necessary DSR investments could be calculated.

Since the batteries were a large investment, an additional payback time calculation was done called "No battery". In this, batteries were excluded from both the simulation and the investment cost.

The compared tariffs have been anonymised and therefore no references are included for the pricing. This was done on request by E.ON Energy Networks. Also when displaying the cost of the central control system, the source is anonymous by request. The economic inputs, equations used and results of the economic analysis is presented in *Chapter 8: Economic analysis*.

Demand side response units

This chapter intends to lay out the technical basics of the units, the demand response potential as well as the current market share and future projections. The purpose of the findings in this chapter is to later be used to estimate proper inputs in the simulations of the units. Therefore, a summary of the learnings is presented in each of the unit sections.

4.1 Heat pumps

Heat pumps (HPs) are devices engineered to convert energy from one medium to another. The mediums varies in different types of HPs; normally air-to-air, air-to-water or water-to-water. Different types of HPs are suitable in various conditions, and the choice of HP depends on parameters such as annual average temperature, heated area, heating demand and geographical area. It also matters what type of internal heating system that the building has, i.e. if it is waterborne or not. An air-to-air HP is only used for space heating and is suitable where the annual average temperature is high. An exhaust air HP, reuses the ventilated air in a house to reheat the house's heating system, and requires mechanical ventilation. Exhaust air HPs can be air-to-air or air-to-water HPs (Swedish Energy Agency, 2014). Air-to-water and water-to-water HPs can be used for domestic hot water (DHW) usage in addition to the space heating. Air-to-water HP may, much like air-to-air HPs, be limited by outdoor temperatures meaning that they are less efficient when the outdoor temperature is low. In colder climates, water-to-water HPs are more suitable as these can extract heat from the surrounding ground, sea or lake water where the seasonal temperatures does not vary as much as the surrounding air temperature does (Värmepump.se, n.d.). A water-to-water HP does however put higher demands on the surroundings and geological conditions and increases the financial investments compared to an air-to-air HP, as these for example require a drilled hole into the underlying bedrock or a coil to be dug down in the ground.

The HP considered in this thesis is an air-to-water HP. HPs using air (air-to-air or air-to-water) are most common in Sweden (Swedish Energy Agency, 2017c) and for the purpose of also heating domestic hot water, an air-to-water is most suitable.

A HP is an efficient device for heating purposes as the output of thermal power can be up to five times the amount of the input of electric power. This factor is called coefficient of performance (COP) and normally varies between 2 and 5 in modern HPs, see *Equation 4.1*. A COP of 4 indicates that 1 kWh electricity is needed to obtain 4 kWh of heat. As the performance of HPs strongly depend on the temperatures of the working fluids, the COP varies depending on outdoor temperature in the case when an air-to-air or air-to-water HP is used. However, this change in COP can be harmonized by a seasonally adjusted COP, called seasonal coefficient of performance (SCOP). The SCOP value of a HP will give a more fair evaluation of its actual performance over a year, especially at locations which demand a lot of heating during seasons with low outdoor temperatures (Polarpumpen, n.d.).

$$COP = \frac{P_{thermal}}{P_{electric}} \quad (4.1)$$

The power output of a HP is controlled by indoor and sometimes also outdoor temperature. Temperature sensors, which measures indoor and outdoor temperatures, are coupled to the HP. Together these sensor measurements can, using algorithms, decide the thermal output power from the HP in order to maintain a comfortable indoor temperature. Traditionally, HPs are step controlled, meaning that the HP can deliver thermal power at one or several power levels. This is a simple technique which has drawbacks as the HP is limited to pre-determined power levels. Modern HPs are normally inverter controlled, meaning that the power is more variable. This increases efficiency, saves energy and is able to maintain an even more stable indoor temperature since the HP can to a larger extent fine tune the power output (Polarpumpen, 2015).

4.1.1 DSR potential of HPs

As earlier described, the energy consumption from space heating in a typical single house in Sweden is a significant part of the total energy demand. A HP can, if actively controlled, shift demand of energy over time. Depending on the thermal inertia of the house, thermal energy can be stored in the house for several hours without affecting the comfort of the residents (Vanhoudt et al., 2014). This makes HPs suitable units for DSR (E.ON, 2017; Wang et al., 2013). Three different case studies regarding DSR of HPs are presented below, which all have specific prerequisites.

Negative control of HPs may reduce the overall peak power when curtailing power demand or completely deactivating the unit during a period. This manipulation of the HP control will affect the indoor temperature, as the house loses an essential part of its thermal power

contribution (Ranstorp, 2018). In a Swedish study, the heat source to a single house was turned off for eight hours which caused the indoor temperature to drop 2°C. The house was built in 1956 and had a size of 106 m². The outdoor temperature was around 0°C. The study showed that the indoor temperature drop depends on parameters such as outdoor temperature, building type and size, residents and living patterns (Fransson, 2017).

Several other studies have been conducted in the area of HPs and DSR. Load control of a HP was evaluated in an Northern Ireland detached household by Arteconi, Hewitt & Polonara (2013). The studied house covered a ground area of 100 m², the outdoor temperature was -3°C and the indoor temperature was set to 21°C. The heat was delivered by air-to-water heat pumps in two different designs, one underfloor heating system and one radiator system. In *Figure 4.1*, the potential power supply from underfloor ($Q_{underfloor}$) and radiator ($Q_{radiators}$) heating systems are presented together with the house's nominal energy demand (Q_{house}) at various outdoor temperatures. As radiators, in contrast to an underfloor heating system, offer a low thermal inertia, the HP was dimensioned to match the house's nominal thermal power demand in the case of a radiator heating system. When an underfloor heating system was used, the HP was under dimensioned, see *Figure 4.1*. The study showed that an actively controlled HP decreased the overall energy demand by 2 and 4.5 % in case of an underfloor and radiator heating system respectively (Arteconi et al., 2013). Peak shaving was not investigated in this study. Results from this study is presented in *Table 4.1*.

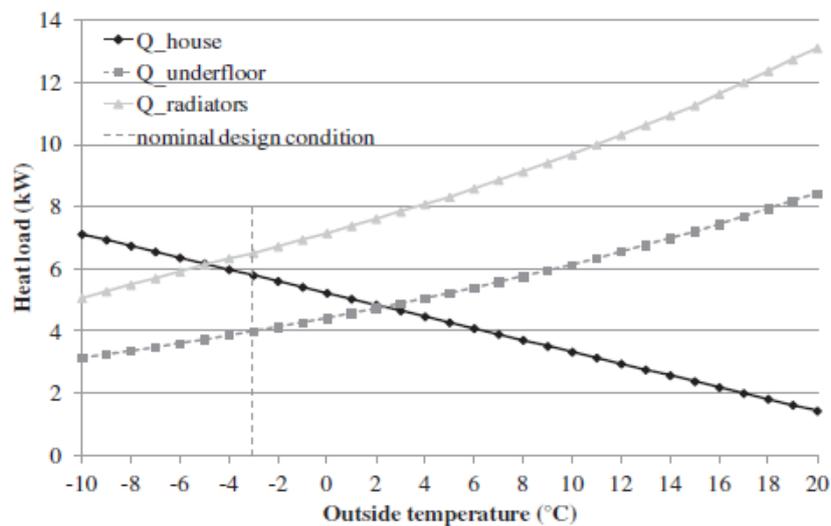


Figure 4.1: Thermal loads and potential power supply from underfloor and radiators respectively in a Northern Ireland study (Arteconi et al., 2013).

In a Belgian study from 2014, the potential of demand response of a HP was investigated. The main purpose was to find whether a HP could contribute to peak shaving and maximize self consumption from PV and a small wind power plant. The tests were conducted during two different weeks during the winter, one cold week and one averaged tempered week. The HP in the set-up supplied both energy for space heating and domestic hot water (DHW). Two different types of storages were available, one DHW tank of 300 l and a buffer storage tank for space heating of 400 l. The studied house was a two store detached house with a total

heated floor area of 134 m² and an annual heat demand of 11 280 kWh. The measurement for peak shaving in this study was one percent peak (OPP). The OPP was defined as the highest one percent peak power measured during intervals of 15 minutes over the entire test period. The test showed that the HP was able to decrease OPP. During the coldest week, the OPP decreased by 3 %. During the average week, the OPP was reduced by 18 % with the same set-up. Furthermore, the study showed that active control of the HP increased the total energy consumption. During the colder week, the HP consumption increased by 8 %, while in the average week consumption increased by 10 %. This concluded that load control is capable of peak power reduction, but could also increase overall energy demand (Vanhoudt et al., 2014). Results from this study is also presented in *Table 4.1*.

Table 4.1: Comparison between two studies on active control of heat pumps in single homes (Vanhoudt et al., 2014; Arteconi et al., 2013).

	Vanhoudt et al., 2014		Arteconi et al., 2013	
	Cold week	Average week	Underfloor heating	Radiator heating
Heated area	134 m ²		100 m ²	
Conditions	Winter, Belgium		One year, Northern Ireland	
Annual energy demand	11 280 kWh		3800 kWh	2500 kWh
Heat pump type	Air-to-water		Air-to-water	
Heat pump size	11 kW _{th}		4.7 kW _{th}	6.5 kW _{th}
OPP change	- 3.2 %	- 17.6 %	-	
Change in energy consumption	+ 8.2 %	+ 10.2 %	- 2 %	- 4.5 %

The energy use for heating purposes in buildings is likely to decrease in the future. Today the average energy use for a newly built house (between 2011-2015) is 74 kWh/m² whereas the average energy use for all building years is 107 kWh/m² (Swedish Energy Agency, 2017c). This development is likely to proceed as requirements on energy performances of all types of buildings are constantly updated in order to increase energy efficiency. Parallel to this is a continuous development of HPs. New models are increasingly energy efficient and the Ecodesign directive promotes the most efficient HPs (BUILD UP, 2017). More energy efficient buildings combined with higher COP of HPs decreases the energy use, and therefore the potential of DSR of HPs may also decrease (Rydén et al., 2015).

The HPs will, during load control, not run in optimal design conditions and thus not deliver optimal performance. After periods of deactivation, a HP needs to reheat the internal and external system. This means that the temperature of the flow lines, radiators and room all may decrease during times of deactivation. In addition to this, the decrease in room temperature will trigger an increased opening of the radiator valves, which in its turn will increase the flow through the radiators. Combined, these factors increases the HPs' power output. This effect is called *rebound effect*, meaning that a HP after deactivation will increase its power output until steady state is reached, see *Figure 4.2* (Ranstorp, 2018).

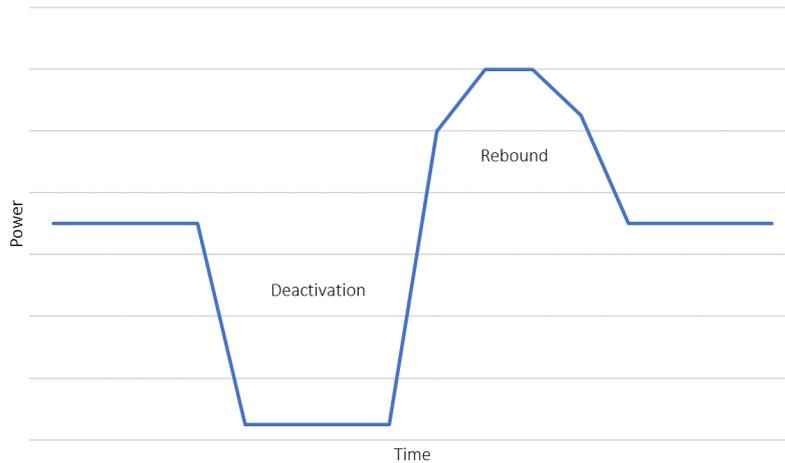


Figure 4.2: Theoretical example of a rebound effect after deactivation of a heat pump.

The rebound effect means that an actively controlled HP will require a sophisticated control strategy in order to be a valuable addition for the DSR (Georges, Cornélusse, Ernst, Lemort, & Mathieu, 2017). If aggregated with the purpose of peak shaving, too many HPs can not be deactivated and activated at the same time as this only will move the peak in time. Instead, HPs can be deactivated and activated again in groups in order to maximise utilisation of actively controlled HPs and decrease the aggregated rebound effect.

This section has clarified some of the methods that can be used when controlling heat pumps. The following learnings will be used later in the simulations:

- A modern house in Sweden should be able to maintain indoor temperature within reasonable boundaries when the heating source is turned off.
- An actively controlled heat pump may increase or decrease overall heat pump energy consumption.
- The deactivation of a heat pump triggers a rebound effect when the device is reactivated. This causes the heat pump to increase its power output during a shorter period.
- On an aggregated level, it might not be appropriate to deactivate all heat pumps at the same time.

4.1.2 Current market and future projections of HPs

Future projections of the amount of heat pumps were not possible to find. Today, heat pumps exist in almost half of all single houses. For houses built between 2011-2015, 50 % have HPs, according to the Swedish Energy Agency. This also includes HPs in combination with another heating source such as biofuels or pellet stoves. The distribution between these are unknown (Swedish Energy Agency, 2017c).

Heat pumps have in the last few years steadily increased in numbers in single houses in Sweden (Swedish Energy Agency, 2017c). In newly built houses it is the most common type of heating system in Sweden, much due to its increasing COP and versatility (Birgersson, 2017). One estimation is that 38 % of single houses in Sweden uses only a HP for heating purposes¹.

For electricity demanding products on the market, such as HPs, there is an EU directive on Ecodesign (2009/125/EG). This ensures that the energy efficiency of products is increased over time, and that the products with the highest energy demand disappear from the market (Swedish Energy Agency, 2017a). The directive sets minimum requirements on performance of the products. For example, the minimum seasonal coefficient of performance, SCOP, was 3.42 in 2015 for air-to-air HPs (Nordsyn, 2015).

4.2 Electric vehicles

Electric vehicle is a generic term for vehicles that uses electricity in their operation. Chargeable EVs includes both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) where the latter is most common in Sweden (Power Circle, n.d.-a). The difference between the two is that BEVs only runs on a chargeable battery, whereas a PHEV in addition has a combustion engine that can be used when the battery is emptied (Swedish Energy Agency, 2017b). A third type often mentioned is hybrid electric vehicles (HEVs), but these are not externally chargeable. Instead, HEVs uses both a combustion engine and a battery that only is powered by excess energy from the combustion engine (Miljöfordon, 2017). In this thesis, only chargeable EVs are considered; BEVs and PHEVs.

The charging time of an empty battery depends on the power of which it is charged and battery capacity (Power Circle, n.d.-c). The charging can be divided into three categories depending on charging power: normal, semi-fast and fast charging. At home, normal charging is mostly used since people can charge over night - fast charging might not always be necessary. Faster charging is more common at public charging stations, for example close to highways (Swedish Energy Agency, 2017b). Common values for different types of charging - voltage, current and charging power - are shown in *Table 4.2*.

¹ HPs are classified as electric heating. In 2016, electric heating was the single most common energy source for space heating and DHW, accounting for 30 % of the single houses. Out of these, 70 % were using an air-to-air, air-to-water or an exhaust air HP. This means that 25 % used only a HP for heating purposes. In addition to this, 13 % of all single houses used only a lake or geothermal HP (Swedish Energy Agency, 2017c). Hence, 38 % used only HPs for heating in 2016. Note that the use of these HPs could also include heating of DHW.

Table 4.2: Charging voltage, current and power for different types of charging (Power Circle, n.d.-c).

Type of charging	Voltage and current	Charging power
Normal		
- AC	230 V, 10 A	2.3 kW
- AC	230 V, 16 A	3.7 kW
Semi-fast		
- AC	400 V, 16 A	11 kW
- AC	400 V, 32 A	23 kW
Fast		
- AC	400 V, 63 A	43 kW
- DC	400 V, 125 A	50 kW

It is recommended that customers who wish to charge their EV at home install a charging box. It is specially designed for charging of EVs with increased safety compared to the regular wall socket. This should be compatible with the EU standard mode 3 type 2. The mode refers to the requirements of the charging station and the type refers to the charging socket. It can be used for charging in both 1- and 3-phase and also supports communication between vehicle and charging box (Svensk Energi, 2014). Charging is limited by the main fuse, in houses it can typically be 16 A (Elsäkerhetsverket, 2017). It should however be mentioned that charging with 16 A and 230 V (3.7 kW) while also using other household electricity possibly could result in over-current if the appliances are connected to the same phase (Leisse, 2018). In two other theses conducted at E.ON, which examined future EV load, a charging power of 3.7 kW was used (Persson & Forsström, 2017; Philipson & Lavin, 2017).

The size of the battery, and thereby the possible travel distance, differs between BEVs and PHEVs. Two of the most common plug-in hybrids today are Mitsubishi Outlander and Volkswagen Passat GTE (Power Circle, n.d.-a). Their battery capacities are 12 kWh and 9.9 kWh, allowing a travel distance of 35.9 and 39.1 km each if the battery was fully charged from start (Teknikens Värld, 2017). The three most common BEVs are Tesla Model S, Nissan Leaf and Renault Zoe (Power Circle, n.d.-a). The battery sizes are in some cases optional and are shown in *Table 4.3*. Most manufacturers also offer a charging box to enable safer and faster charging. This is also shown in *Table 4.3*. In the case of the PHEVs, they do not offer specific charging boxes but recommends installing one for safety and for faster charging than from the wall socket. The PHEVs are limited in charging power and can not charge at higher powers than 3.7 kW (Mitsubishi, n.d.; Volkswagen, n.d.). Note that faster charging using a charging box is only possible if the main fuse allows it, otherwise the fuse needs to be upgraded.

Table 4.3: Compilation of the three most common EVs and their battery sizes.

	Battery capacity (kWh)	Charging box (kW)	Source
PHEV			
Mitsubishi Outlander	12	3.7	(Teknikens Värld, 2017; Mitsubishi, n.d.)
Volkswagen Passat GTE	9.9	3.7	(Teknikens Värld, 2017; Volkswagen, n.d.)
BEV			
Tesla Model S	75 - 100	11 - 16.5	(Tesla, n.d.-a, n.d.-b)
Nissan Leaf	40	7	(Nissan, n.d.)
Renault Zoe	22 - 41	7.7	(Renault, n.d.-a, n.d.-b)

4.2.1 DSR potential of EVs

For a simple charging model, it can be assumed that the EV starts to charge as soon as it is parked. This is called uncontrolled charging. If the power flow only goes in one direction, as in grid-to-vehicle, this is called unidirectional charging (Grahn, 2013) and usually gives the highest power load (Habib, Kamran, & Rashid, 2015). This would typically occur when the residents come home from work during the weekdays which most often is before 18.00. Or equivalent; most travels occur between 16.00-17.00 (Holmström & Wiklund, 2015). This is also supported by the fact that most charging takes place during night time (Svensk Energi, 2014). This assumption for uncontrolled charging has been used in other theses (Persson & Forsström, 2017; Philipson & Lavin, 2017) and papers (Shao et al., 2012).

How much the battery needs to be charged depends on the travel distance. The average Swedish car travels 12 240 km per year (Transport Analysis, 2017a). Distributing this evenly over the year results in a travel distance of 33.5 km/day. This is shorter than what the two most common PHEVs can travel on a fully charged battery, as mentioned in the previous section. Due to this, it is reasonable to not distinguish between BEVs and PHEVs in this thesis since all would be able to travel an average distance each day without the need to charge during the day. A usual assumption for the energy consumption of EVs are 2 kWh per 10 km (Montin, Björck, Adsten, & Haegermark, 2013; Persson & Forsström, 2017; Philipson & Lavin, 2017).

When including the DSR for EVs, an external charging strategy is used, meaning that the charging is controlled by an external actor such as an aggregator (Grahn, 2013). One common strategy is valley-filling, which means that the load is shifted to time periods when consumption is low. This is typically during the night (see *Figure 2.2*). However, this must be locally coordinated so that a new peak does not arise. This type of strategy could be either centralized or decentralized. In the centralized strategy, an operator or aggregator decides the way the EVs are charged to optimize the total charging. In a decentralized charging strategy,

the users decide their charging pattern. This could be done by using a time-of-day tariff as in implicit DSR (Ma, Callaway, & Hiskens, 2013).

E-mobility, partly financed by the Swedish Energy Agency, has stated load control strategies for a situation where many vehicles are charged at the same time. This mainly refers to public charging at a charging station, but could be applied to an LEC since these vehicles are connected to the same grid connection point. The purpose of the strategies below is to have an even charging profile. The different strategies mentioned are as follows:

- Equal charging power to all vehicles. This power is the highest power that all vehicles simultaneously can have without creating a too high load on the system.
- The vehicle last plugged in gets the highest power, i.e. charging longer time enables lower charging power.
- Some charging points gets low power and some charging points get higher power. This could be made possible by offering a lower price on the low power points.

(Power Circle, n.d.-b).

The following learnings will be used later in the simulations:

- Uncontrolled charging would start when arriving home from work.
- The travel distance of 33.5 km/day would result in a charging need of approximately 7 kWh per day when using the consumption of 2 kWh per 10 km.
- Load should be shifted to hours with lower consumption, i.e. during night time.
- The most simple charging strategy is that all vehicles charge at the same power.

4.2.2 Current market and future projections of EVs

The price of the EVs is related to the price of the batteries (International Energy Agency, 2017a). EVs have seen a positive development the last few years, much thanks to the rapid decrease in battery prices from 1 000 dollars/kWh in 2010 down to 230 dollars/kWh in 2016 (Frankel & Wagner, 2017). Bloomberg New Energy Finance projected that in 2026 the price of batteries in the EVs will have dropped to 100 dollars/kWh and will by then be competitive to combustion engine cars (Bloomberg New Energy Finance, 2017). While it is clear that there is a fast increase in the amount of sold BEVs and PHEVs in the recent years, it is still not clear whether EVs will disrupt the car market as it is known today or if they simply will be an add on to the traditional combustion engine cars.

Every other year, the Swedish Energy Agency makes forecasts over the future energy system, with regards to current policies and instruments. In the latest report the scenarios are predicted until 2050 but only results from 2030 are presented in this thesis. Different scenar-

ios were made in the report. One of them was called "low electricity price" and was based on continued low prices of both electricity certificates and fossil fuels (Swedish Energy Agency, 2017g). According to one of the project leaders, Susanne Lindmark, this is the most probable scenario (Lindmark, 2018). In the "low electricity price" scenario, the estimation was 3.8 % EVs. In a different scenario, "more EVs", fossil fueled vehicles were assumed to be phased out over a longer period (after 2050). In this scenario, the amount of EVs was 17.6 % in 2030 (Swedish Energy Agency, 2017g).

The Swedish authority Transport Analysis has also made a prognosis for the development of the Swedish vehicle fleet. In the analysis, future subsidies and legislations were disregarded. This projection resulted in 19 % EVs in 2030 (Transport Analysis, 2017b). In BP Energy Outlook 2017, they expected the total amount of EVs to be 6 % of the global fleet in their base case, their probable scenario (BP, 2017). These results are summarized in *Table 4.4*.

Table 4.4: *Compilation of projections of percentage of EVs to total vehicles.*

Year	Percentage of total vehicles	Geographical area	Source
2030	3.8 % (low case)	Sweden	(Swedish Energy Agency, 2017g)
2030	17.6 % (high case)	Sweden	(Swedish Energy Agency, 2017g)
2030	19 % (5-30 %)	Sweden	(Transport Analysis, 2017b)
2035	6 %	Global	(BP, 2017)

Both UK and France have put a ban on fossil fueled (diesel and petrol) vehicles by 2040. Similar goals have also been proposed in Norway, The Netherlands, India and parts of Germany (The Guardian, 2017a, 2017b). Sweden also has a goal of fossil free vehicle transports by 2030 (The Swedish Government, 2015). Furthermore, vehicle manufacturers have an increasing interest in electric vehicles. Volvo for example, has announced that from 2019, all their *new* models will be electric or hybrid. This also includes HEVs. However, their old combustion engine models will still be produced (Volvo Cars, 2017). Some of these factors might not be included in the projections above, as the decisions are new or came at the same time as the forecasts.

4.3 Photovoltaics with batteries

A photovoltaic (PV) cell is designed to convert sunlight into electrical energy. It does so by using semiconductors, which are materials that when exposed for sunlight produces an electrical current. When it comes to power generation, silicon-based semiconductors are today the most common ones. A PV panel, sometimes referred to as a solar panel, is many PV cells connected together (Wenham, 2012). The efficiency of a single solar cell is typically around 15 %, converting solar energy into electricity (National Energy Foundation, n.d.).

Residential PV systems are dimensioned after several factors such as annual electricity consumption, house size, roof size and the roof area facing south. Today an average PV installation in Sweden will deliver approximately 5000 kWh with an installed power of 5 kW and a total solar cell area of about 30 m² (Fortum, 2018; Krafringen, 2018; Vattenfall, 2018). *Figure 4.3* presents a combined PV and battery system connected to the electricity grid. It also includes both battery and PV inverters which are necessary to control the different power flows which can occur, such as PV to load, PV to battery, PV to grid and grid to load. The power flows can shift in both size and direction, depending on size of load and amount PV production (Lorenzi & Silva, 2016). The efficiency of an inverter, for both PV and battery, is 90-97 % (Weniger, Tjaden, & Quaschnig, 2014; Reddy & Momoh, 2015; Ren, Wu, Gao, & Zhou, 2016).

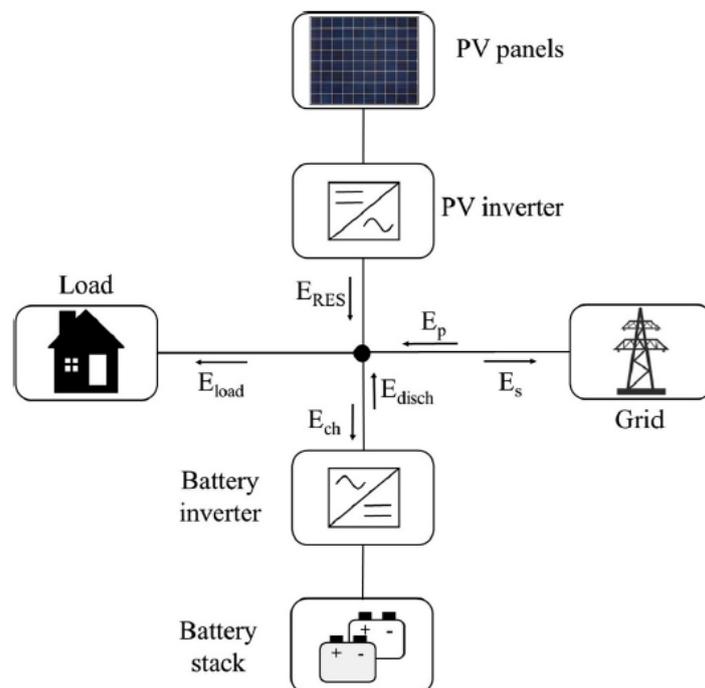


Figure 4.3: Example of a combined PV and battery system installed in a single house. Power flow directions indicated (Lorenzi & Silva, 2016).

Installing a battery energy storage system (BESS²) together with PVs has become more common. Today in Germany, 40 % of the small-scale PV installations have a BESS. The reason for this could be the German renewable energy regulation structures. The International Renewable Energy Agency (IRENA) predicts that the potential for BESS is large in the European markets. The amount of installations of BESS is also connected to the amount of *new* small-scale installations of PV since these customers tend to buy a package with PV and battery. Customers who already have a PV installation might not be interested in investing in a battery to the same extent. IRENA also states that drivers for BESS are high electricity prices, low prices for grid feed-in and a competitive cost structure for PV (International Renewable Energy Agency, 2017a).

² The words BESS and battery are used in an equivalent manner in this thesis.

From a power grid perspective, one advantage of installing batteries with PV is that most residential consumption takes place when the PVs are not producing, which is the case both on a daily- and yearly level. One part of a master thesis written by Karin Hansson and Sara Olsson investigated the grid impact of installing a large PV system in Hyllie. During summer, there was sometimes overproduction. This overproduction could however be slightly decreased when a BESS was added (Hansson & Olsson, 2014).

In the Hansson & Olsson thesis, an evaluation of eight different storage types was made with regards to technical, economical and environmental aspects. Included was four battery types, fuel cells and an additional three types of mechanical or electrical storages. The Lithium-ion battery was mentioned to be beneficial from both a technical and an environmental aspect. From an economical perspective, Li-ion was concluded to be expensive but the numbers used was from 2013 and stated to be over 2 000 dollars/kWh (Hansson & Olsson, 2014). As stated in section 4.2.2, the cost for a Li-ion battery in 2016 was 230 dollars/kWh.

Table 4.5 describes technical specifications of three BESSs that are available on the Swedish market today. The efficiency stated in the table is defined as *round trip* efficiency, η_{rt} , i.e. overall efficiency for a battery. An example is a battery with a capacity at 10 kWh and a round trip efficiency of 95 %. During a complete charge and discharge cycle, 9.5 kWh would remain usable for the customer.

Table 4.5: Examples of BESS solutions available on the Swedish market 2018. Note that the companies to the left are retailers/manufacturers. Tesla is both (E.ON, 2018c; sonnen, 2016; Krafringen, n.d.-b; Tesla, 2018).

Company	Technology	Capacity (kWh)	Power (kW)		Efficiency (%)
			Discharge	Charge	
E.ON / Fronius	Lithium Ion	3.6/9.6	3/5	5/8	95
E.ON / Sonnen	Lithium Ion	8.0		3.3	98 ³
Krafringen / Sonnen	Lithium Ion	4/6		2.5	95
Tesla	Lithium Ion	14		5	90

The battery capacity should be dimensioned after the households annual electricity use. For example, a 8 kWh battery is suitable for a consumption of 5 500 kWh (sonnen, 2016).

The state of charge, SoC, describes the current capacity in a battery relative to the full capacity (Teleke, Baran, Bhattacharya, & Huang, 2010). If the battery is charged and discharged between 0 and 100 %, the lifetime is typically shortened. Therefore, allowed SoC limits are set to retain a more sustainable battery (Xu, Oudalov, Ulbig, Andersson, & Kirschen, 2016). These values vary between different studies; 20-80 % (Weniger et al., 2014) and 10-90 % (Li, Hui, & Lai, 2013) and 30-100 % (Teleke et al., 2010).

A simulation which is a good representation of reality puts high demands on data inputs. Using input data with too low temporal resolution when simulating bidirectional flows of

³ Maximum efficiency.

power may overestimate the degree of self consumption in a residential PV system. This is because consumption and production, especially in the case of PV, shows short fluctuations on close to a second basis. These differences do however decrease in importance when a battery is used. This is due to the fact that a battery removes the need for simultaneousness, since energy can be stored as long as charging or discharging powers does not exceed inverter power. Data profiles of 1 hour gives sufficient results (Beck, Kondziella, Huard, & Bruckner, 2016).

4.3.1 DSR potential of PVs

A PV system itself can not be subject to load control as it simply is a generation source. PV can only decrease the load during hours when it is producing. A PV coupled to a battery can however maximize self consumption while also providing a decrease in peak power if energy from the battery is used instead of energy from the grid during peak hours. Energy can be stored during periods when production is higher than consumption and then be used in the opposite situation.

In order to achieve flexibility, the battery can be controlled to discharge to load during pre-determined hours. This could be done by studying the load profile and manually set the time range. It could also have inputs of current load and discharge if the load exceeds a power limit set point.

The battery could be set to charge from PV and/or from the grid. If both charging sources are used, charging from PV is prioritized. Charging of battery only takes place when the production exceeds load. Charging from grid is only realistic if the electricity price is considerably higher during peak hours compared to mid-day prices (Wu, Tazvinga, & Xia, 2015). Today, customers in Sweden can choose on either having fixed or variable electricity price. The variable price differs between months. Hourly pricing is rarely used but exist (Swedish Energy Markets Inspectorate, 2017a). Therefore, the incentives for customers to move consumption away from peak hours is low since the electricity price is typically the same during peak and non-peak hours.

In an LEC, it could be an option to have a centralized battery since the introduction of LECs emphasizes local ownership. This might not optimize the self sufficiency of an individual household but rather the total energy consumption in the community. A centralized battery can also be advantageous to efficiently handle surplus energy since the single home battery is limited by the electricity use in that specific household (Zeh, Rau, & Witzmann, 2016).

The following learnings will be used later in the simulations:

- An average PV size in Sweden is today around 5 kW and produces 5000 kWh annually.
- The battery capacity should be dimensioned after household electricity consumption.

- Batteries could be used at state of charge boundaries of 10 - 90 %, in order to retain longer lifetime while also utilizing a large part of the capacity.

4.3.2 Current market and future projections of PVs

The market for PV systems in Sweden has grown steadily since 2010, and in the last few years the annual amount of installations have grown exponentially, see *Figure 4.4*. In late 2016, the accumulated grid connected PV installations reached a total of 193 MW in Sweden. Compared to for example Germany who have made great effort to increase their PV production, today a installed power of 41 GW, this might seem as close to a negligible amount. The positive trend of PV installations in Sweden is much thanks to government subsidies (Swedish Energy Agency, 2017g; International Renewable Energy Agency, n.d.). This means that PV power could, within a few years, be an important addition to the Swedish electricity mix (Lindhahl, 2016).

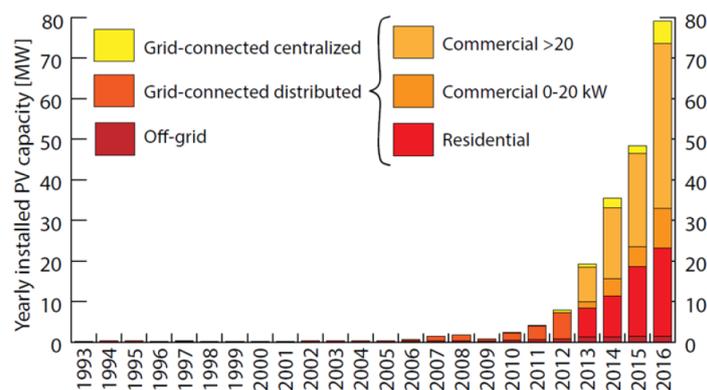


Figure 4.4: Annual installed PV power in Sweden (Lindhahl, 2016).

Today, the absolute majority of the installed PV is installed as distributed production. This means that the PVs are scattered on mainly roof tops on the low voltage grid and connected directly to a consumer. Of the distributed production, two thirds are owned by and connected to a commercial consumer such as factories, office buildings and warehouses. The rest is owned by private customers (Lindhahl, 2016).

Projections regarding PV in Sweden have been made by the Swedish Energy Agency, as for EVs in section 4.2.2. By 2030 it is predicted to be 0.07 %, or equivalent 0.1 TWh, PV using the "low electricity price" scenario. Another scenario used is the "reference EU" where the production from PV is estimated to 4.5 TWh (3.2 %) in 2030 (Swedish Energy Agency, 2017g). Another projection they have made is 5 - 10 % of the total energy use in Sweden by 2040, if the goal of 100 % renewable energy in Sweden is realized and with regards to the technical potential of such systems (Swedish Energy Agency, 2017e). The International Energy Agency have made a projection for EU of 8 % PV of the total electricity generation the year 2050 (International Energy Agency, 2014). Finally a global projection of 14 - 21%

of installed capacity have been made by IRENA where the low number is estimated based on current policies and the higher number corresponds to a scenario where the 2°C goal is achieved (International Renewable Energy Agency, 2017b). These findings are summarized in *Table 4.6*.

Table 4.6: *Compilation of projections of percentage of PVs.*

Year	Percentage	of	Geographical area	Source
2030	0.07 % (low case)	Production	Sweden	(Swedish Energy Agency, 2017g)
2030	3.2 % (high case)	Production	Sweden	(Swedish Energy Agency, 2017g)
2030	14 - 21 %	Inst. capacity	Globally	(International Renewable Energy Agency, 2017b)
2040	5 - 10 %	Energy use	Sweden	(Swedish Energy Agency, 2017e)
2050	8 %	Production	European Union	(International Energy Agency, 2014)

Simulation of units

This chapter describes the simulation method of the demand side response units; heat pumps, electric vehicles and photovoltaics with batteries. First, the management of real data of household electricity consumption is described. Secondly, the assumptions behind the low, medium and high cases for the different units are presented. Lastly, the main part of this chapter describes the simulation of units. This includes the spontaneous behaviour when units are uncontrolled, the priority order when controlling the units and all input parameters for the simulations.

5.1 Data management and fictive LEC

A fictive single house residential area with 200 houses was considered as an LEC in this thesis. It was assumed that all houses in the fictive area were of equal size; 150 m² as this is the average size of a newly built single house in Sweden (SCB, 2015). The households in the LEC were considered to have one common connection- and measuring point to the overlying grid.

A temporal resolution of one hour values was used in the simulations. The access of real data of single households with this resolution was however limited, but a large enough number of homes, built after 2007 was available. These were used as a base, here called original load, in the simulations. This group of houses was assumed to be a good representation of the homes in the fictive residential area described below.

Real hourly electricity consumption data during one year from 100 households in the range of 3000 - 7000 kWh was acquired and used as a basis for simulations. This was done in order to reflect about an average household electricity consumption of 5000 kWh, where users do not have electric heating. It was unknown what heating technique for space heating and domestic

hot water that was used in reality, but it was assumed that there was no electric heating in the original load. The data was from users in Gislaved, Sweden. The real house sizes in Gislaved was not known. Some of the houses consumption data had abnormal measurement values, such as missing data for long periods compared to the rest. Four households were dismissed due to this. Hence, data from 96 households were used in the simulation. In all household data, four days of measurements were missing. There were also additional hours missing, scattered over the year. All missing values were backfilled with measurements from the same hour the previous day. To obtain 200 household load profiles, all 96 households were doubled. For the rest, eight profiles were used again which were in the range of an average annual consumption and an average peak power.

5.2 Cases and assumptions

Three different cases were made - **low, medium and high** - in order to simulate the peak power in the LEC with several different market share developments of HPs, EVs and PVs with batteries. The cases are described below.

The **low case** was built on a "business as usual" assumption. Therefore, the assumptions for the low case were based on the projections found (in *Table 4.4* and *4.6*) that best corresponded to this. For *heat pumps*, it was assumed that 40 % of the households used a HP. This is a rounding of the current share of single houses that only uses heat pumps for space heating and DHW. For *electric vehicles*, a rounding down to 15 % of the Swedish Energy Agency high case was done. This is also the result if a mean value of the three Swedish projections in *Table 4.6* is used. For *photovoltaics*, the high projection, a PV production share of 3.2 %, made by the Swedish Energy Agency was used. This is mainly because their low projection was too low to include in the low case of this thesis. In other words, it would result in that no houses would have PV in the low case. In addition to this, the projection for the EU (for 2050) is larger, 8 % of total electricity production. It could be reasonable to assume that a large share of this PV production in EU will occur in southern Europe due to the favourable conditions with high annual solar irradiation.

The share of PV production needed to be converted into share of households that has PV. This corresponded to 15 % of the households and the calculation is presented in *Appendix A*. Further, it was assumed that batteries were included in all configurations of PV. This might not be a reasonable assumption since batteries are not standard to include when buying PV systems. But as batteries are the only contribution to flexibility, this choice was made.

The **high case** was decided to be 100 % for all three units to be able to estimate the maximum potential. The **medium case** was chosen as a number between the low and high case; 70 % for heat pumps, and 50 % respectively for EV and PV. The percentage of units in the three cases are summarized in *Table 5.1*.

Table 5.1: Assumed shares of units in the three cases.

	Low case	Medium case	High case
Heat pumps	40 %	70 %	100 %
Electric vehicles	15 %	50 %	100 %
PV + battery	15 %	50 %	100 %

5.3 Simulation of demand side response units

The simulation consisted of two parts; 1) base simulation and 2) demand side response simulation. The base simulation corresponded to the uncontrolled behaviour of the units (HP, EV and PV with batteries) when there was no demand response. In the DSR simulation, the units were controlled. The simulation was meant to illustrate the peak power differences that occurs when the units were uncontrolled (base) and controlled (DSR). The simulation process is shown in *Figure 5.1*. The identification of the priority order in the DSR simulation will be clarified in this section.

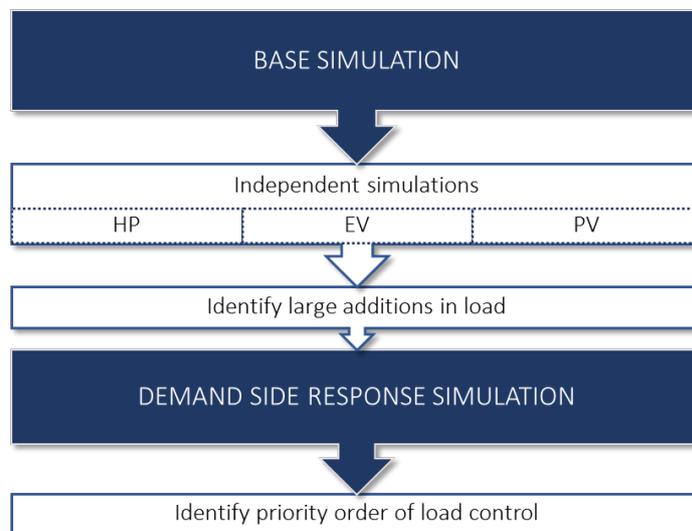


Figure 5.1: Summary of the simulation process.

For all units, Python (using Spyder development environment) and Excel was used to handle data. To differentiate between the cases, a random selection was done in Python. For example, 15 % of 200 houses had an EV in the low case. These were randomly selected. The same method was used for HPs and PVs. This means that it could be different households that got EVs and PVs in the low and medium case. In the high case, all households had all units.

5.3.1 Heat pump

In order to model the load curve of a heat pump, the simulation software VIP-Energy was used. VIP-Energy is a software used for calculating energy performance of single houses, apartment blocks or commercial buildings. It can for example perform calculations of hourly consumption data of a HP in a building over an entire year. A single house template file was used and altered in the application. Simulations of the HP performance was later conducted using this specific house as basis. See *Figure 5.2* for a visualization of the modelled house used in VIP-Energy.

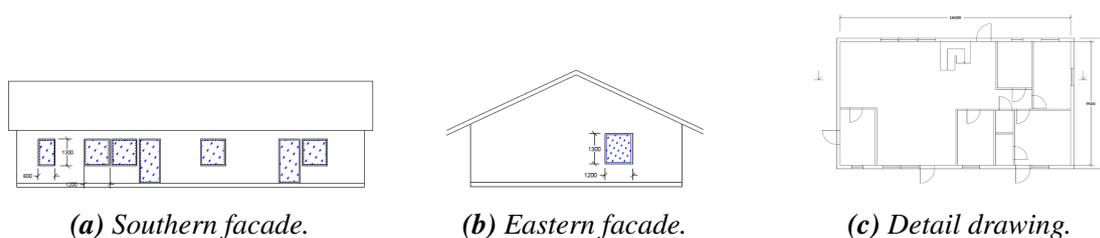


Figure 5.2: Virtual house used in VIP-Energy for HP load simulations (Strusoft, 2013).

House: The house used in the model is a single-storey house of 152 m², which represents an average size of a newly built house in Sweden as earlier mentioned. The energy performance of the building corresponds to requirements from 2013 regarding energy usage (Davidsson, 2018).

Heat pump: The energy source for space heating in the simulation was a NIBE air-to-water HP. The specific model used was F2030 7 kW, which nominally can deliver a thermal power of 7.52 kW at a corresponding electrical power of 1.48 kW and an outdoor temperature of 10°C. The heat pump has a SCOP of 3.1 in Swedish conditions (NIBE, n.d.).

Domestic hot water: VIP-Energy did not manage to simulate the DHW production in a reasonable way. Therefore, DHW load profile was added separately to those households where a HP existed, since it was assumed that every HP provided both space heating and DHW. Data for a HP producing DHW in a laboratory was obtained from NIBE. The method for adding DHW is described in *Appendix B*.

Weather data: Normalized weather data from 1981-2010 from Malmö was used in the simulations in VIP-Energy. The data was acquired by the Swedish Meteorological and Hydrological Institute on behalf of Sveby.

Demand side response simulation

The HPs were assumed to be able to be turned off during four hours without causing a decrease in indoor temperature by more than 1°C if the outdoor temperature was above

0°C. During times when the outdoor temperature was below 0°C, the HP was only allowed to be deactivated during three hours to prevent indoor temperature to decrease more than 1°C.

First, VIP-Energy was used to model the load control of HPs. This was done by during certain hours decrease the reference temperature in the house by 1°C, allowing the HPs to adapt to the new temperature by decreasing power output. However, the software proved to be insufficient as it continuously overestimated the energy loss from the house when compared to results from the literature study (*Section 4.1.1*). The initial simulations showed that the temperature dropped 1°C during only one to two hours, despite that the outdoor temperature was above 15°C. Because of this, the VIP-Energy simulated deactivation time was considered to be too short and not usable. However, the rebound effect simulated in VIP-Energy was used, as this still was considered to be a reasonable increase in power after a temperature drop of 1°C.

In order to model deactivation of a HP according to earlier mentioned studies (*Section 4.1.1*), a manual override of the results from VIP-Energy was done. The HP load curve generated in VIP, including rebound effect, was used and the HP was manually "turned off" in Excel during the hours the HP was supposed to be deactivated. The values during the time for deactivation were set to zero, i.e. three or four hours depending on outdoor temperature.

To maximize the use of DSR of HPs, all HPs could not be turned off at once as this would yield a large rebound effect. Instead, the households were divided into 12 groups. The first group was set to be turned off at 18.00 until 22.00 every night, after which next group was turned off from 19.00 until 23.00. This pattern continued until the last group of HPs was turned on again at 09.00. This created a smoother power decrease throughout the entire night. This meant that the time during which load control of HPs could be utilized well responded to the time period which the controlled charging of EVs were distributed to (described in the following section).

The domestic hot water was not regarded as flexible and was only added as a load in the DSR simulation as well.

5.3.2 Electric vehicles

For simplicity it was assumed that all EVs operate in the same way, both in the vehicle specifications and the user behaviour. This was based on the information in *Section 4.2*. To simulate the charging behaviour, assumptions in the following areas were made:

Battery: No distinction was made between BEV and PHEV. The reason was motivated in *Section 4.2*; for an average travel, the capacity of a PHEV battery is enough, hence a BEV and PHEV will be equally discharged each day. With the average travel distance, the battery

would need to charge 7 kWh each day.

Charging: The travel distance for the cars was assumed to be 34 km/day. Since some PHEVs has limited a charging power of 3.7 kW, this power was used. This resulted in a charging time of 1 h 53 min, using a charging need of 7 kWh. Since the simulation was done on hourly values, this was rounded to 2 h.

Distribution of start time: No distinction was done between weekdays and weekend. In the base simulation, the charging was assumed to start when the residents come home from work. It was assumed that most people start charging at 17.00 and that there is a normal distribution, with a standard deviation of one hour, around this time.

Electric vehicles are only operating in grid-to-vehicle. Other options are vehicle-to-grid and vehicle-to-home, but these are excluded.

In the base simulation, the above assumptions were used to build a model with Python.

Demand side response simulation

In the DSR simulation, the difference from the base simulation was the distribution of start time. It was assumed that the residents were flexible with starting time from when they got home (17.00) and the time they want the vehicle the next day (6.00 and forward). To also avoid the peak from the original load, usually at 19.00, the vehicle charging was set between 20.00 - 6.00. All vehicles still needed to charge for 2 hours with a power of 3.7 kW.

Charging vehicles during the night (rather than early evening) was prioritized. This meant that the first group of EVs was assigned to start charging at 4.00, next at 3.00 and so on until 20.00. This strategy for starting times was looped. In other words, nine batches of starting times were used. This ensured that all vehicles had met their charging need at 6.00.

This DSR charging model was also built with Python.

5.3.3 Photovoltaics with batteries

In order to simulate the production and self consumption made possible from PV, the software System Advisor Model (SAM) was used. To simulate the PV production for a single house, the following assumptions and inputs were used:

System design: The module used was JA Solar (Model: JAM6(K)(BK)-60-285/PR). The installed capacity of the PV was 5.13 kW, covering a roof area of 28.5 m². The panels were facing south with a tilt of 30°. The individual module had a power of 285 W. The inverter

used was from Fronius (Model: Primo 3.8-1 208-240).

Weather data: The weather data used in SAM was for Copenhagen. SAM uses a typical year data. In the case of Copenhagen, data exist between the years 1983-1999. The input for each month is coherent data from an actual month of measurements. This data best represent the average of all data for that specific month between 1983-1999. For example, the January weather data is from 1984 and in February it is from 1999.

In the base simulation, no battery was enabled. The output used from SAM was the amount of energy produced by the PV. The same PV production profile was used for all households. This was subtracted from the original load data to obtain a new load profiles. This new load profile included self consumption from PV. If the production was larger than the load, this was simply visualized by a negative number meaning that the electricity was exported to the grid.

Demand side response simulation

In the DSR simulation, a BESS was enabled. A model was constructed in Python to simulate the behaviour of the battery. The input load consisted of; original load, controlled EVs and controlled HPs in a combined simulation. A separate simulation was also done for only the original load.

Battery: The BESS chosen was sonnen (Model: sonnenBatterie eco 8.0) and had a capacity of 8 kWh and a charge/discharge power of 3.3 kW. This battery capacity was recommended by sonnen for a household electricity consumption of 5 500 kWh, which well corresponded to about the yearly consumption in the original load. The SoC limits were set between 10 - 90 %, i.e 6.4 kWh was utilized in the battery. The round-trip efficiency of the battery was set to 95 %.

The basics of the control strategy was:

Priority: The PV production was set to first meet the load, then charge the battery (with respect to charging power limits and the capacity of the battery). After this, any excess energy was exported to the grid. The battery did not charge from the grid.

Discharge limit: A discharge-to-load limit was used in order to not empty the battery too early. Due to this limit, the battery could meet the load arising from the electric vehicles. In the simulation of all DSR units, this limit was therefore set to 1.5 kW, i.e. if the load was smaller than 1.5 kW, the battery would not discharge. In the simulation with only original load, no such limit was used.

The full charge/discharge strategy is shown in *Appendix C*.

5.3.4 Hierarchical design of demand side response

In the base simulation the units - HP, EV and PV - were simulated independently. After this, it was possible to identify which unit that contributed with the largest addition in load. After the base simulation it was possible to determine a priority order of the load control. This process is shown in *Figure 5.3*.

In the DSR simulation, the unit with largest addition in load, EV, was therefore chosen to be simulated first. Next, the HPs were turned off during the time that had the largest peak power, i.e. during the EV charging period. Lastly, the PV battery could discharge to meet the load, after the above mentioned measures, during the peak hours until it was emptied.

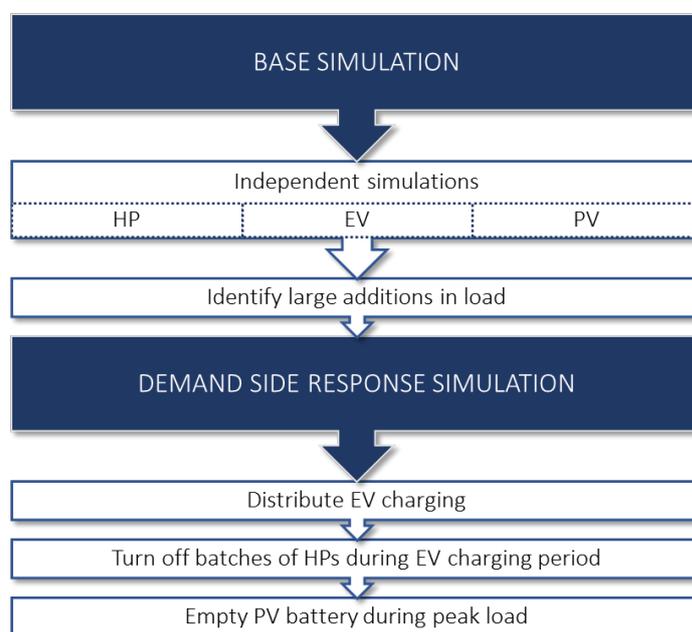


Figure 5.3: Summary of the simulation process, with load control priority identified.

It is important to emphasize that this is a manual optimization of this specific case and that no general control strategy was used. In reality, the control could be handled differently. For example, users of EV might want to start charging earlier, charge more etc. The control system could then react to actual inputs.

5.3.5 Calculations

To measure the potential for DSR to contribute to peak shaving, the following equation have been used:

$$DSR/base [\%] = \frac{DSR_{PP} - base_{PP}}{base_{PP}} \quad (5.1)$$

PP refers to the (annual or monthly) peak power for the simulation (base or DSR). *Equation 5.1* measures how flexible the unit is and how much the power can be decreased, in percent, when the unit is controlled.

In addition to this, *Equation 5.2* has been used to measure the peak power increase to a reference value:

$$Value/ref.value [\%] = \frac{Value_{PP} - Ref_{PP}}{Ref_{PP}} \quad (5.2)$$

In *Chapter 6: Result and analysis of simulation*, in the results from the base simulation, "Ref" is the original load and "Value" refers to the peak power for each case (low, medium and high). In *Chapter 7: Sensitivity analysis*, "Ref" is the result peak power value from the DSR main result and "Value" is the new peak power with DSR in the sensitivity analysis. These inputs are more clearly stated in the chapters affected.

Result and analysis of simulation

This chapter contains the results and analyses of the simulations. Results from all cases - low, medium and high - are presented. First, the results from the base simulation are presented. Second, the result from the demand side response simulation is shown (together with base simulation as reference).

6.1 Base simulation

In the base simulation, the units were added without demand side response. The original load is included in all results, in order to have a reference when the units are added. All figures and numbers shown are on aggregated level, i.e. the total LEC profile of 200 households.

For each individual unit in the base simulation, two types of results are displayed: a duration curve and a table showing total energy consumption, the annual peak power and the percentage change in peak power compared to the original load. The energy consumption refers to electricity from the grid. The duration curve for one year shows the in- or output power seen from the connection point of the LEC. The annual peak power refers to the single highest hourly power measured during one year. Then a combined result (all units and original load) of the base simulation is presented including peak powers for each month. The peak power per month refers to the single highest hourly power during each month.

Heat pumps

One individual HP, providing the house presented in *Figure 5.2* with space heating energy and domestic hot water, consumed 3750 kWh annually. During the summer, the HP is usually off due to high outdoor temperature. The load during June - August is therefore mainly

energy for DHW.

The duration curve when HPs were added to the original load is shown in *Figure 6.1*.

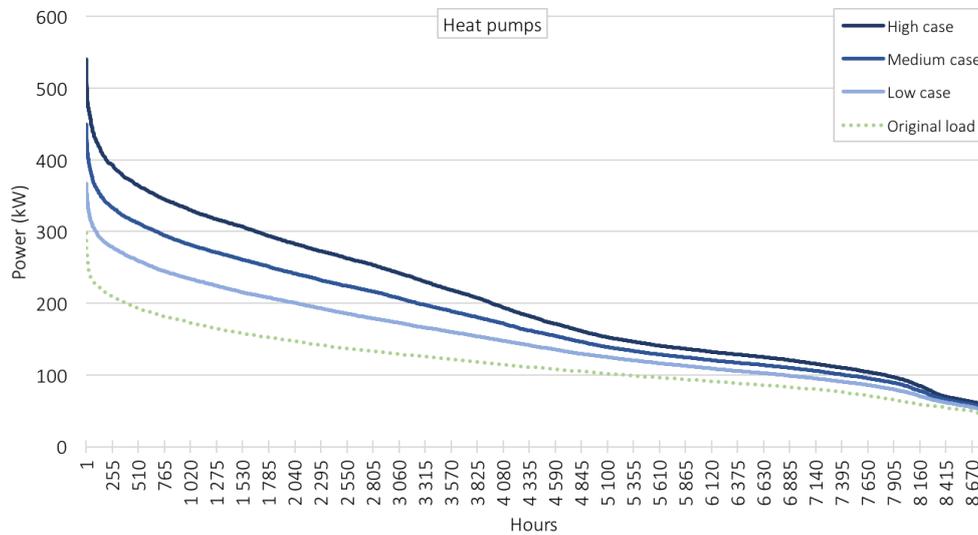


Figure 6.1: Duration curve for heat pumps in the base simulation. Original load is also included in the three cases.

The operation of HPs in an LEC was relatively constant over a day, but varied seasonally. Hence, it did not give rise to a specific peak during the day but rather a general increase in load. This is why the increase in power occurs during many hours in *Figure 6.1*. The curves merge in the end due to a generally low (often zero) HP consumption for space heating during summer.

The percentual change in annual peak power when adding HPs, compared to the original load, for all cases are shown in *Table 6.1*. For example, in the high case the peak power (544 kW) was increased by 1.72 times compared to the original load (317 kW).

Table 6.1: Total consumption and annual peak power of heat pumps. The original load serve as reference value and is included in the cases. Change in PP refers to the percentual difference in peak power between case and original load.

HP	Original load	Low case	Medium case	High case
Total consumption (MWh)	1 028	1 328	1 553	1 779
Peak power, PP (kW)	317	384	450	544
Change in PP, case/original load	-	+ 21 %	+ 42 %	+ 72 %

Electric vehicles

In the base simulation, the electric vehicle charging was added according to the assumed spontaneous behaviour of users as earlier described. *Figure 6.2* shows the duration curve when EVs were charged in the LEC, with EVs driving an average distance (≈ 34 km) every day.

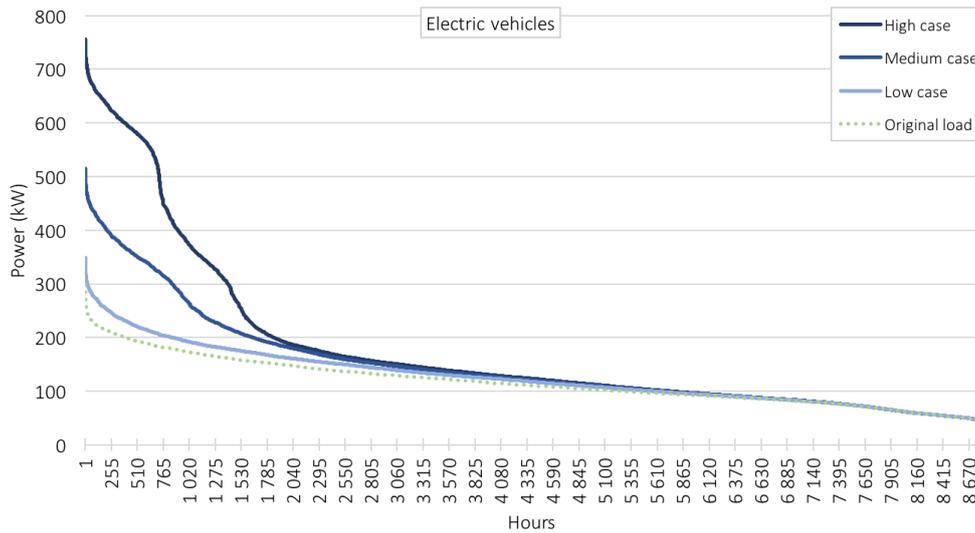


Figure 6.2: Duration curve for electric vehicles in the base simulation. Original load is also included in the three cases.

The pattern that derived from the spontaneous charging of EVs gave rise to a peak around 17.00 - 18.00 every day during the year. It was only during the charging hours that an increase in load occurred, resulting in the shape of the duration diagram, where a large part of the load was unchanged (seen as where the lines merge).

The percentual change in annual peak power and annual consumption when adding EVs both increased compared to the original load for all cases. This is shown in *Table 6.2*.

Table 6.2: Total consumption and annual peak power of electric vehicles. The original load serve as reference value and is included in the cases. Change in PP refers to the percentual difference in peak power between case and original load.

EV	Original load	Low case	Medium case	High case
Total consumption (MWh)	1 028	1 109	1 297	1 567
Peak power, PP (kW)	317	371	522	778
Change in PP, case/original load	-	+ 17 %	+ 65 %	+ 146 %

Photovoltaics

In the base simulation, no batteries were added. The duration curve when adding PVs to original load is shown in *Figure 6.3*.

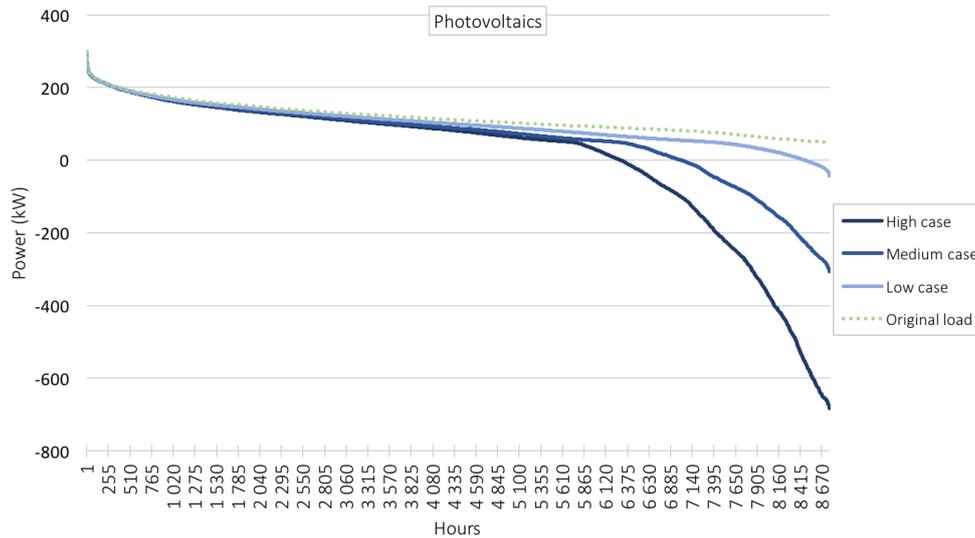


Figure 6.3: Duration curve for photovoltaics in the base simulation. Original load is also included in the three cases.

The addition led to a large amount of energy being exported to the grid in the medium and high case, and a small amount in the low case. This corresponds to the power below zero in the duration curve.

The percentual change in annual peak power when adding PVs, compared to the original load, for all cases is shown in *Table 6.3*. This change was zero in all cases. The peak powers in the original load was during the winter, where the PV is not producing as much as in the summer. Therefore, the annual peak power was unchanged. The annual consumption did however decrease with PV.

Table 6.3: Total consumption and annual peak power of photovoltaics. The original load serve as reference value and is included in the cases. Change in PP refers to the percentual difference in peak power between case and original load.

PV	Original load	Low case	Medium case	High case
Total consumption (MWh)	1 028	887	756	696
Peak power, PP (kW)	317	317	317	317
Change in PP, case/original load	-	0 %	0 %	0 %

Combined

In the combined simulation, HPs, EVs and PVs were added to the original load. The duration curve is shown in *Figure 6.4*.

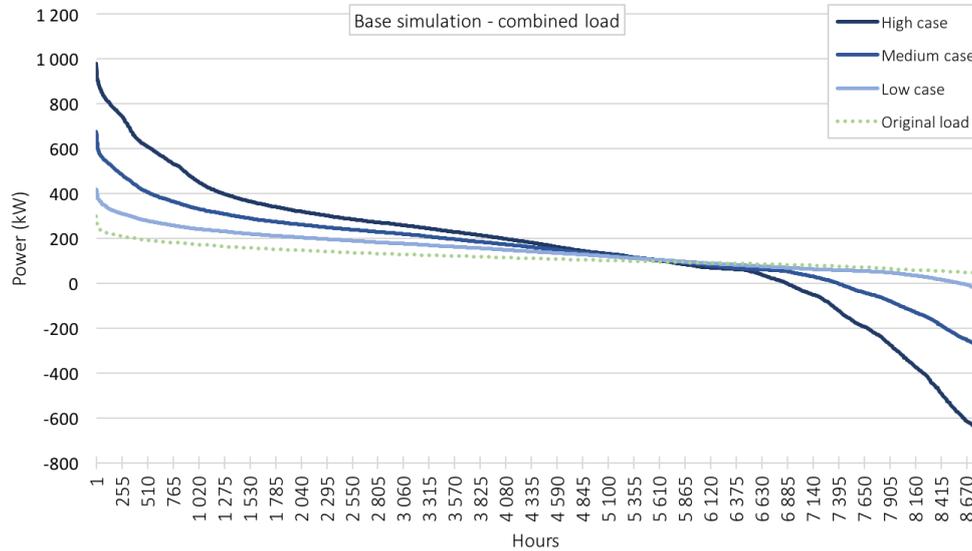


Figure 6.4: Duration curve in the base simulation for the combined load of HPs, EVs and PVs. Original load is also included in the three cases.

The increase in peak power comes from the addition of HPs and EVs and the negative load is due to PV production.

The percentual change in annual peak power when adding all units, compared to the original load, for all cases is shown in *Table 6.4*.

Table 6.4: Total consumption and annual peak powers in the base simulation. The load is combined; HP, EV and PV is included. The original load serve as reference value and is included in the cases. Change in PP refers to the percentual difference in peak power between case and original load.

	Combined	Original load	Low case	Medium case	High case
Total consumption (MWh)		1 265	1 503	1 859	1 345
Peak power, PP (kW)		317	436	683	1 018
Change in PP, case/original load		-	+ 38 %	+ 116 %	+ 221 %

The monthly peak powers are shown in *Table 6.5*. The highest monthly peak power was in January for the original load and the low case, but in February in the medium and high case. This can be explained by the fact that the weather data used for heat pumps showed that February was the coldest month. Hence, the impact in peak power from HPs (which consumed the most energy in February), was increased with a larger amount of HPs. Or equivalent; the highest peak power of the original load was in January, which had greater impact in the low case.

Table 6.5: Monthly peak powers (kW) in base simulation for low, medium and high case for all units combined. The highest peak power is marked in purple.

Month	Original load	Low case	Medium case	High case
January	317	436	634	942
February	257	420	683	1018
Mars	238	341	552	871
April	182	278	476	747
May	161	246	411	661
June	136	221	392	613
July	126	211	378	613
August	147	243	407	678
September	170	248	428	700
October	193	308	497	789
November	213	368	590	901
December	240	384	630	938

6.2 Demand side response simulation

In the DSR simulation the units were controlled as described in *Chapter 5*. The original load is still included in all results and results are shown at an aggregated level.

To illustrate how the load profile changes during a shorter time period, two sets of two days were chosen for this purpose. Hourly load profiles for 9 - 10 February are displayed for the units individually and combined. 9th of February contained the highest yearly peak and can thus be considered to be the worst case. 29-30 June are also displayed, since the highest PV production was 30th of June, and HP consumption was low during May - September.

Three types of results are displayed: a duration curve, hourly profiles for a two day period and a table with peak powers and percentual change from base simulation. The combined result is presented with peak powers and a comparison between the base and DSR simulations.

Heat pumps

The introduction of demand side response of the HPs led to a decrease in total energy use, see *Figure 6.5*. The annual consumption for 200 HPs without load control was 750 MWh and with load control the consumption was 710 MWh. This corresponds to a decrease in annual HP consumption of 5 %. This is a reasonable result when the HP has a lower average reference temperature, which is the case if the HP is turned off for several hours. However,

this might not always be the result in reality, as seen in the studies in *Table 4.1* that showed both increase and decrease in energy consumption.

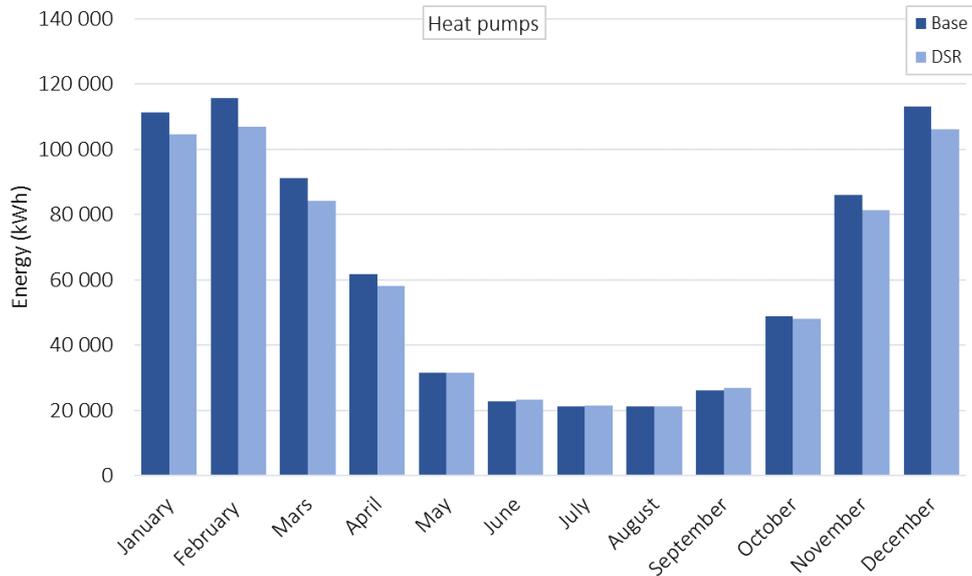


Figure 6.5: Monthly energy consumption for 200 NIBE F2030 7 kW heat pumps in 152 m² houses, in base simulation and with DSR. DHW included.

The domestic hot water was included as a load but is not regarded as flexible, which is why the summer consumption is equal between the base and DSR simulation, in *Figure 6.5*.

The duration curves for HPs, both in the base and DSR simulation, are shown in *Figure 6.6*. The curves with the same colour corresponds to the same case, whereas the solid line is the base simulation and the dashed line is the DSR simulation. The simulations resulted in a slight decrease in consumption during many hours when using DSR.

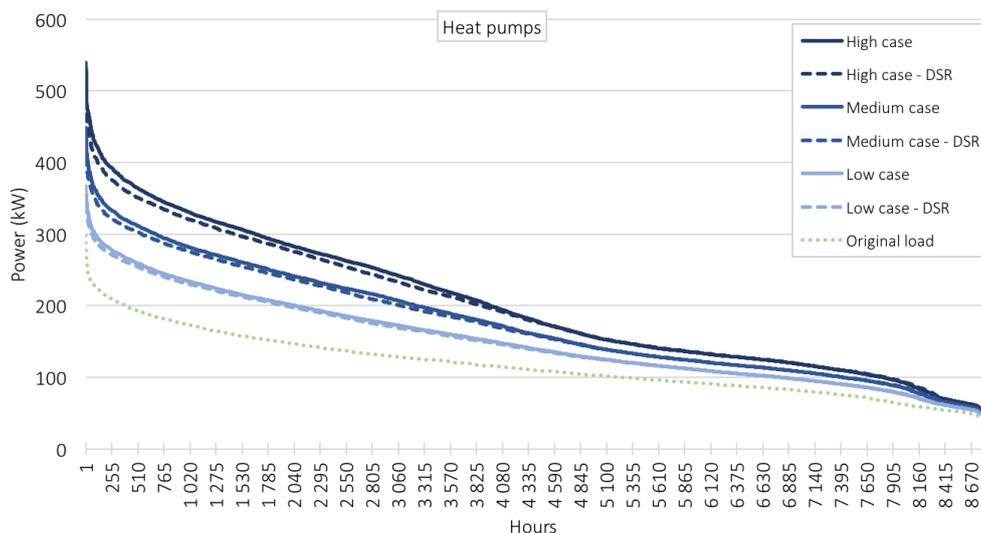


Figure 6.6: Duration curve for heat pumps in base simulation (solid lines) and with DSR (dashed lines). HPs and original load included.

Figure 6.7 shows hourly profiles for two days during winter and summer.

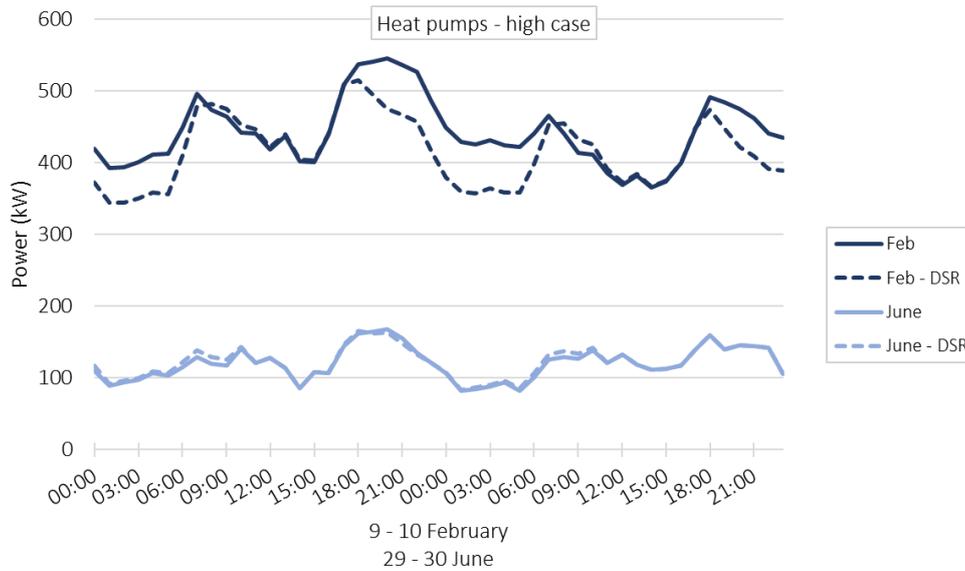


Figure 6.7: Load profiles during 9-10 February and 29-30 June for high case in base simulation (solid lines) and with DSR (dashed lines). HPs and original load included.

In February the control of HPs could achieve a power decrease during peak hours. The decrease was around 50 kW during evening and night hours. From 7.00, in Figure 6.7, there was an increase in power of the HPs due to the rebound effect when all HPs were back to regular operation. In June, the HPs delivered very little or no energy for space heating in both the DSR- and base simulation. Therefore, the power difference was small in June.

One aspect of Figure 6.7 is that the deactivation of HPs might appear to start too late. The reason is that the deactivation of HPs was decided to match the controlled EV charging (next section), and not only the original load.

The percentual change in annual peak power when adding load control of the HPs, compared to HPs without control, for all cases is shown in Table 6.6. For example, in the high case the peak power in the DSR simulation (514 kW) was decreased by 6 % compared to the base simulation (544 kW).

Table 6.6: Annual peak powers in base simulation and with DSR. HPs and original load included. Change in PP refers to the percentual difference in peak power between DSR and base simulation.

HP	Low case	Medium case	High case
Base			
Peak power, PP (kW)	384	450	544
DSR			
Peak power, PP (kW)	375	430	514
Change in PP, DSR/base	- 2 %	- 4 %	- 6 %

The change in peak power was small because all HPs were not turned off at the same time in order to decrease the impact from the rebound effect.

Electric vehicles

The added load control of EVs led to a large decrease in peak power. The duration of high powers was overall also decreased, see *Figure 6.8*.

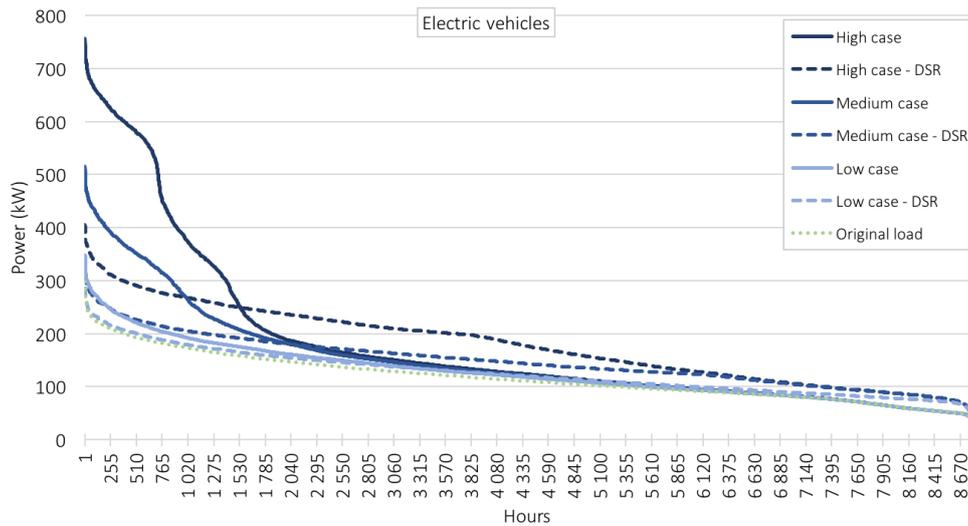


Figure 6.8: Duration curve for electric vehicles in base simulation (solid lines) and with DSR (dashed lines). EVs and original load included.

Figure 6.9 shows hourly profiles for two days during winter and summer.

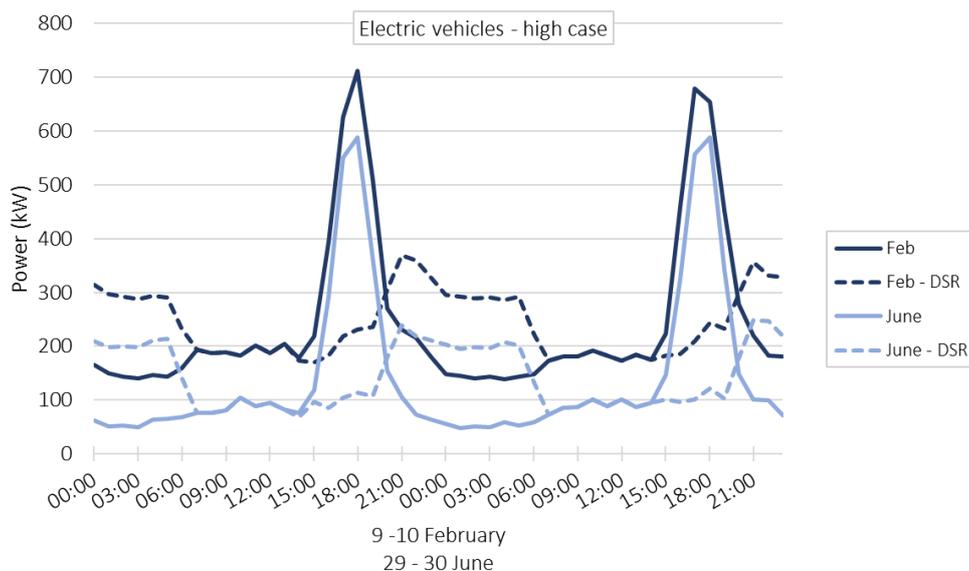


Figure 6.9: Load profiles during 9-10 February and 29-30 June for high case in base simulation (solid lines) and with DSR (dashed lines). EVs and original load included.

The difference in power between February and June only comes from the difference in energy use in the original load, as the charging behaviour was assumed to be the same every day all year around. The small peak around 21.00, seen in the DSR simulation, comes from the peak in original load.

The percentual change in annual peak power when adding load control of EVs, compared to EVs without control, for all cases is shown in *Table 6.7*.

Table 6.7: Annual peak powers in base simulation and with DSR. EVs and original load included. Change in PP refers to the percentual difference in peak power between DSR and base simulation.

EV	Low case	Medium case	High case
Base			
Peak power, PP (kW)	371	522	778
DSR			
Peak power, PP (kW)	317	366	440
Change in PP, DSR/base	- 15 %	- 30 %	- 43 %

The decrease in peak power when smoothing out the EV load was of significant size and was almost reduced by half in the high case.

Photovoltaics with batteries

In the DSR simulation, a battery was added to handle overproduction from PV and to discharge to load during high power demand. The duration curve is shown in *Figure 6.10*.

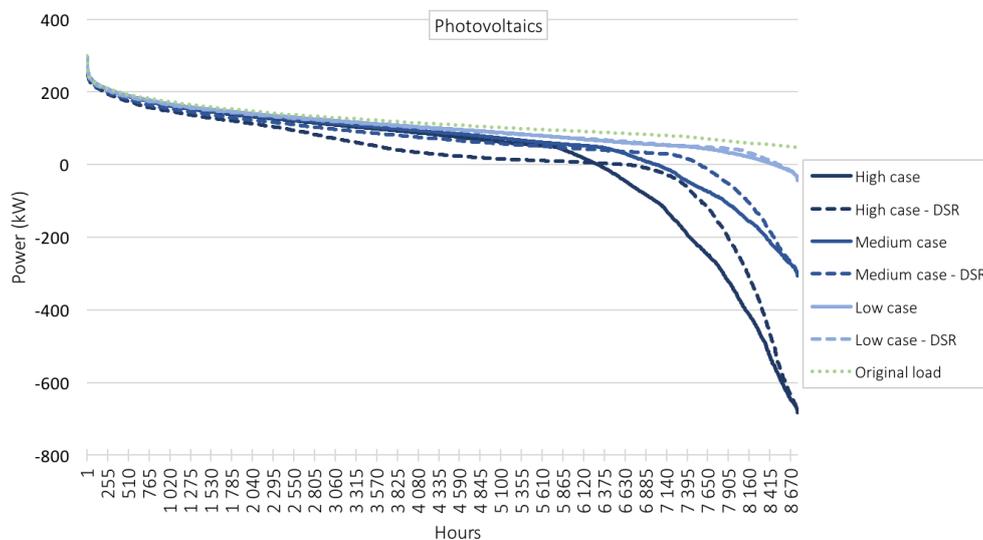


Figure 6.10: Duration curve for photovoltaics in base simulation (solid lines) and with DSR of batteries (dashed lines). PVs (with batteries) and original load included.

The negative power means that energy was exported to the grid. The dashed lines shows that less energy was exported to the grid when a battery existed, meaning that the battery was being utilized. The maximum negative power was however unchanged between base and DSR simulation.

Figure 6.11 shows hourly profiles for two days during winter and summer.

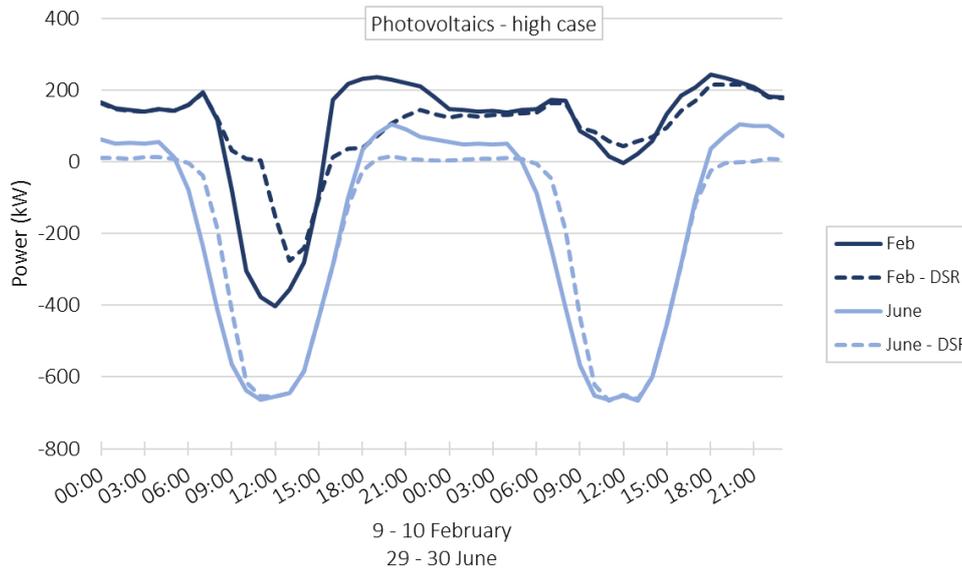


Figure 6.11: Load profiles during 9-10 February and 29-30 June for high case in base simulation (solid lines) and with DSR of batteries (dashed lines). PVs (with batteries) and original load included.

The difference between the dashed and the solid line corresponds to the charging time of the battery. During summer, the battery was not emptied during the nights, which is why it was charged faster. As seen this difference was larger in February, where the battery was empty when it started to charge between 9.00 - 12.00.

It can also be noted that 9th of February was a very sunny February day and had an unusually large PV production compared to an average winter day. Many days in the winter had no PV production and consequently an empty battery for several days. The fact that the battery was full a lot of the time in June indicates that the battery was oversized for this energy consumption (the original load).

The percentual change in annual peak power when adding load control (of batteries) to the PVs, compared to PVs without control, for all cases is shown in Table 6.8.

Table 6.8: Annual peak powers in base simulation and with DSR. PVs (with batteries) and original load included. Change in PP refers to the percentual difference in peak power between DSR and base simulation.

PV + battery	Low case	Medium case	High case
Base			
Peak power, PP (kW)	317	317	317
DSR			
Peak power, PP (kW)	309	301	285
Change in PP, DSR/base	- 2 %	- 5 %	- 10 %

The annual peak power took place during the winter, hence the decrease in peak power was small with PV and batteries since PVs produced much less during winter.

Combined

In the combined DSR simulations, all units - HPs, EVs and PVs with batteries - were added to the original load. The duration curve is shown in *Figure 6.12*.

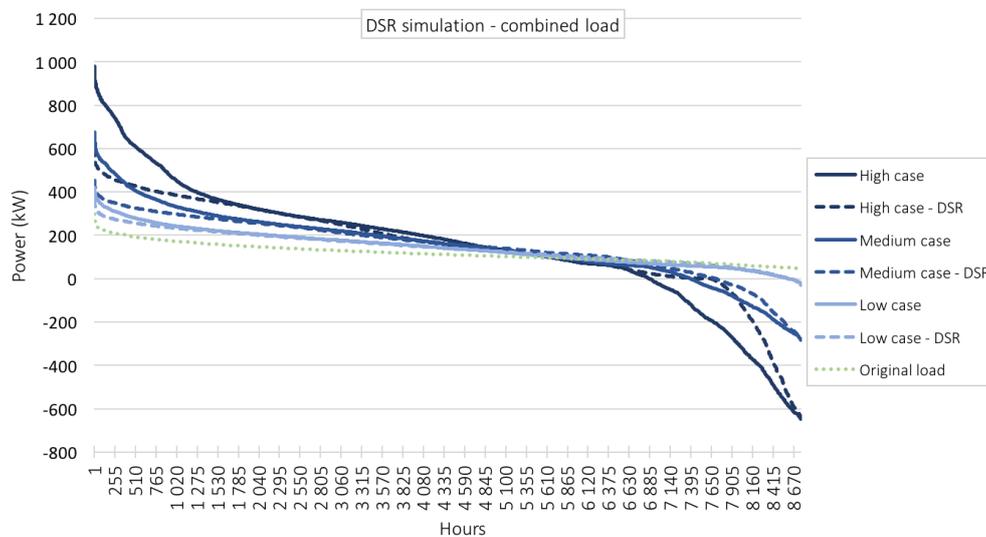


Figure 6.12: Duration curve in the base simulation (solid lines) and with DSR of the combined load of HPs, EVs and PVs (dashed lines). Original load is also included in the three cases.

The decrease in power mainly came from the distribution of EV charging, while less power was exported to the grid due to the introduction of batteries.

Figure 6.13 shows hourly profiles for two days during winter and summer.

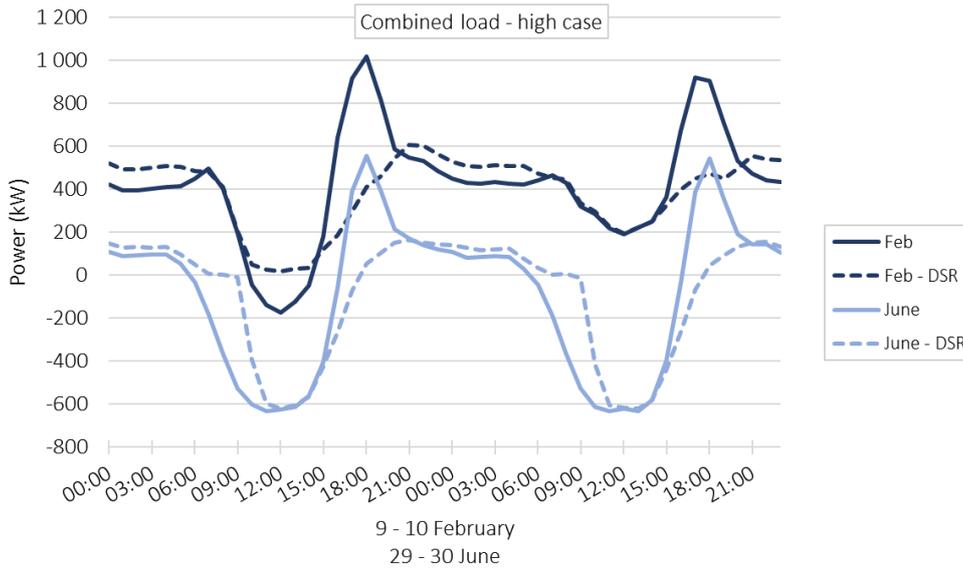


Figure 6.13: Load profiles during 9-10 February and 29-30 June for high case in base simulation (solid lines) and with DSR (dashed line). All units - HP, EV and PV with batteries - and original load are included.

The percentual change in annual peak power when adding load control of all units combined for all cases is shown in *Table 6.9*.

Table 6.9: Annual peak powers in base simulation and with DSR. All units (HP, EV, PV + batteries) and original load included. Change in PP refers to the percentual difference in peak power between DSR and base simulation.

	Combined	Low case	Medium case	High case
Base				
Peak power, PP (kW)		436	683	1018
DSR				
Peak power, PP (kW)		368	455	606
Change in PP, DSR/base		- 16 %	- 33 %	- 40 %

The monthly peak powers are shown in *Table 6.10*. The monthly peak power was highest in January for the original load, low case and medium case. For high case, the monthly peak power was highest in February.

Table 6.10: Monthly peak powers (kW) in the DSR simulation for low, medium and high case for all units (HP, EV and PV with batteries) and original load. The highest peak power is marked in purple.

Month	Original load	Low case	Medium case	High case
January	317	368	455	565
February	257	336	453	606
Mars	238	298	378	494
April	182	213	271	381
May	161	187	234	319
June	136	154	196	199
July	126	147	182	196
August	147	158	189	236
September	170	182	233	324
October	193	238	326	433
November	213	292	392	523
December	240	316	424	559

The percentual change between the base and DSR simulation is shown in *Table 6.11*. The largest power decrease was during the summer months in all cases. This can be explained by the fact that the batteries could be utilized mostly during the summer. The peak power decrease caused by distributed charging of EVs was the same each month and therefore contributed to an overall peak shaving. PV and HP are much more seasonally dependent with the assumptions made. Due to the same reason, the lowest decrease in peak power occurred during the winter; the batteries were less utilized. In absolute terms, the decrease in monthly peak power varied between 342 - 441 kW over the year, but lacks a clear seasonal trend. Another explanation for the lower relative decrease during winter is that the overall consumption was higher during winter (especially for HPs, but also in the original load). There was also a shorter control period of the HP for temperatures below zero.

Table 6.11: *Percentual change between base and DSR simulation, each month. All units (HP, EV and PV with batteries) and original load are included. The largest decrease is marked in green and the smallest decrease is marked in red for each case.*

Month	Low case	Medium case	High case
January	- 16%	- 28%	- 40%
February	- 20%	- 34%	- 40%
Mars	- 13%	- 32%	- 43%
April	- 24%	- 43%	- 49%
May	- 24%	- 43%	- 52%
June	- 30%	- 50%	- 68%
July	- 30%	- 52%	- 68%
August	- 35%	- 54%	- 65%
September	- 27%	- 46%	- 54%
October	- 23%	- 34%	- 45%
November	- 21%	- 34%	- 42%
December	- 18%	- 33%	- 40%

The discharge limit of batteries at 1.5 kW was set in order to avoid discharge of battery before peak hours, and especially before EV charging. However, some households had EV charging very late at night and a high consumption of household electricity (and HPs). This caused the battery to discharge before EV charging occurred. Note that the discharge limit was the same all year and could therefore not be lowered in order to also utilize the battery during summer when consumption was lower.

6.3 Summary of DSR potential of units

In the high case, the highest annual potential for DSR was found for the EVs and the lowest for HPs, see *Table 6.12*.

Table 6.12: *Summary of annual DSR potential in the LEC for the different units, individually and combined.*

Unit	Low case	Medium case	High case
Heat pumps	- 2 %	- 4 %	- 6 %
Electric vehicles	- 15 %	- 30 %	- 43 %
PVs with batteries	- 2 %	- 5 %	- 10 %
Combined	- 16 %	- 33 %	- 40 %

Sensitivity analysis

This chapter aims to test the sensitivity of three parameters that were considered to have high impact on the end result; charging power and charging need of electric vehicles and the capacity of the battery connected to the PV system.

Results are presented only on an aggregated level and contains all units regardless of which parameter that is altered. Results are shown on annual and monthly level. For the annual results, all cases are presented. For monthly results, only the high case is shown.

7.1 Charging power and charging need of EVs

The charging power and charging need were considered to have high impact on the results since the EVs proved to have the most peak shaving potential compared to the other units. Therefore, a change of these parameters was tested in two new simulations. The first, "larger need", had a charging need of 22 kWh. The second, "higher power", had a charging power of 7 kW, see *Table 7.1*.

Table 7.1: EV sensitivity analysis simulations.

	Power (kW)	Charging need (kWh)	Charging time (h)
Reference simulation	3.7	7	2
Sensitivity - larger need	3.7	22	6
Sensitivity - higher power	7	7	1

The reference is the simulation done in previous chapters. Note that the charging limits that may be in PHEVs are disregarded in the sensitivity analysis.

Result

With the simulation of 3.7 kW/7 kWh as reference, the sensitivity simulations showed that when the charging need was larger (22 kWh), the DSR potential was increased in the low case and decreased in the medium and high case, see *Table 7.2*. This refers to "Change in PP, DSR/base", meaning that the percentual difference in the low case between DSR- and base simulation was decreased by 15 % in the reference simulation, and 23 % in the "larger need"-simulation. This means that the potential was higher in the "larger need" simulation for the low case. In the "higher power"-simulation, the DSR potential was roughly the same as in the reference simulation for all cases.

The second percentual number, called "Change in PP, DSR/ref. DSR", compares the annual DSR peak power in the sensitivity simulation, to the annual DSR peak power in the reference simulation. For example, in the low case, the peak power was increased from 369 kW to 381 kW in the "larger need"-simulation, corresponding to a 3 % increase. In the "larger need"-simulation, the annual peak powers were increased in all cases, see *Table 7.2*. In the "higher power"-simulation, the annual peak powers were almost unchanged.

Table 7.2: Annual peak powers for different configurations of EV battery. Peak power change between base and DSR simulation. Change in peak power compared to the reference (ref) case. Red cell color marks the largest increase in peak power. Green cell color marks the simulation with largest change in PP.

	Low case	Medium case	High case
Reference: 3.7 kW, 7 kWh			
Peak power (kW), base	436	683	1 018
Peak power (kW), DSR	369	457	614
Change in PP, DSR/base	- 15 %	- 33 %	- 40 %
Change in PP, DSR/ref. DSR	-	-	-
Larger need: 3.7 kW, 22 kWh			
Peak power (kW), base	495	819	1 284
Peak power (kW), DSR	381	669	1 099
Change in PP, DSR/base	- 23 %	- 18 %	- 14 %
Change in PP, DSR/ref. DSR	+ 3 %	+ 46 %	+ 79 %
Higher power: 7 kW, 7 kWh			
Peak power (kW), base	431	674	1 087
Peak power (kW), DSR	369	457	599
Change in PP, DSR/base	- 14 %	- 32 %	- 45 %
Change in PP, DSR/ref. DSR	0 %	0 %	- 2 %

For the distribution of EVs, an important factor is the charging *time*. When the charging time is short, the overlap of EVs charging is small. In the "higher power"-simulation the charging time was one hour while in the reference simulation it was two hours and used lower power. Therefore, each hour in these two simulations had the same addition in power from EVs (\approx 7 kW), which is why the result was almost the same.

When the charging time is long, as in the "larger need"-simulation, more EVs need to charge at the same time. This resulted in less potential for power shaving from the DSR as an increased overlap was unavoidable; only 14 % in the high case, compared to the reference simulation where the peak power decrease was 40 %.

In the low case of "larger need", the percentual decrease in peak power was larger compared to the reference simulation (23 % compared to 15 %). This can be explained as follows; in the base simulation, the charging was normally distributed. The longer charging time of 6 hours in "larger need" therefore made the peak power higher (for all cases) compared to the reference simulation. In the DSR simulation of "larger need", all vehicles had one common charging hour, at 01.00, due to the charging time of 6 hours and flexibility window of 10 hours (20.00 - 06.00). Therefore, the peak power in the DSR simulation was at 01.00. In the low case these vehicles (30 EVs) did not impact the combined load of 200 households as much as in the medium and high case where the peak constituted of 100 and 200 EVs respectively. In the higher cases, the peak during DSR was therefore almost the same as in the base simulation, which made the decrease in peak power between base and DSR simulation small compared to the reference simulation.

Looking at monthly peak powers, *Figure 7.1*, the trend was the same as for annual peak power; the reference and "higher power"-simulations were almost equal, and "larger need"-simulation had a higher peak power every month. This change corresponded to between 500 - 600 kW higher power throughout the year in "larger need" compared to the reference and "higher power".

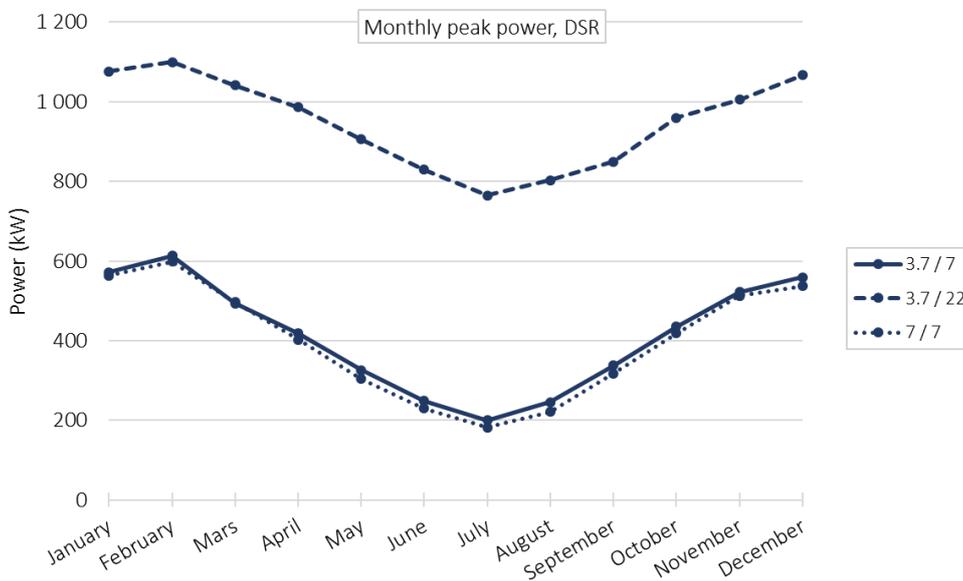


Figure 7.1: Monthly peak powers in the high case for different configurations of the EV battery. All units are included and controlled.

The peak powers were lower during summer for all configurations. This was however independent of the EV charging. It was due to the PV and battery, and the lower consumption in original load.

7.2 Size of battery

From the duration curve of photovoltaics with batteries (*Figure 6.10*), it was seen that the PV produced excess energy which was exported to the grid. In the same section it was found that the battery was often fully charged during summer. In this context, it was interesting to see how the result changed with changed battery size. The sizes tested were 0 kWh, simulation name "no battery", and 16 kWh, called "higher capacity", see *Table 7.3*.

Table 7.3: Battery sensitivity analysis simulations.

	Capacity (kWh)
Reference simulation	8
Sensitivity - no battery	0
Sensitivity - higher capacity	16

Regarding other inputs, everything else was the same as in the reference simulation; charge/discharge power of 3.3 kW and discharge-to-load limit of 1.5 kW.

Result

With the battery of 8 kWh as reference, the sensitivity analysis showed that the annual peak power decrease between base and DSR simulation was unchanged both with no battery and with a larger battery. The change in peak power compared to the reference simulation was also relatively unchanged, see *Table 7.4*.

Table 7.4: Annual peak powers with different sizes of the battery. Peak power change between base and DSR simulation. Change in peak power compared to the reference (ref) case. Red cell color marks the largest increase in peak power. Green cell color marks the simulation with largest change in PP.

	Low case	Medium case	High case
Reference: 8 kWh			
Peak power (kW), base	436	683	1 018
Peak power (kW), DSR	369	457	614
Change in PP, DSR/base	- 15 %	- 33 %	- 40 %
Change in PP, DSR/ref. DSR	-	-	-
No battery: 0 kWh			
Peak power (kW), base	436	683	1 018
Peak power (kW), DSR	375	465	614
Change in PP, DSR/base	- 14 %	- 32 %	- 40 %
Change in PP, DSR/ref. DSR	+ 2 %	+ 2 %	0 %
Higher capacity: 16 kWh			
Peak power (kW), base	436	683	1 018
Peak power (kW), DSR	368	455	606
Change in PP, DSR/base	- 16 %	- 33 %	- 40 %
Change in PP, DSR/ref. DSR	0 %	0 %	- 1 %

The annual peak powers occurred in the winter, which is why the result was unchanged with other sizes of the battery.

A larger battery does not necessarily decrease the larger power peaks that could arise from for example charging an EV at higher power (7 or 11 kW) as the charge/discharge power of the battery is limited to 3.3 kW. As EV charging of 3.7 kW was used here, this might not be an issue in these simulations. It is although worth mentioning that the outcome of combining higher EV charging powers with a larger battery is not ideal if the charge/discharge powers in the battery are not also higher.

Looking at monthly peak powers, the result was different. When there was no battery, the peak powers were higher during summer. When there was a larger battery, the peak powers were lower during summer, compared to the reference simulation, see *Figure 7.2*.

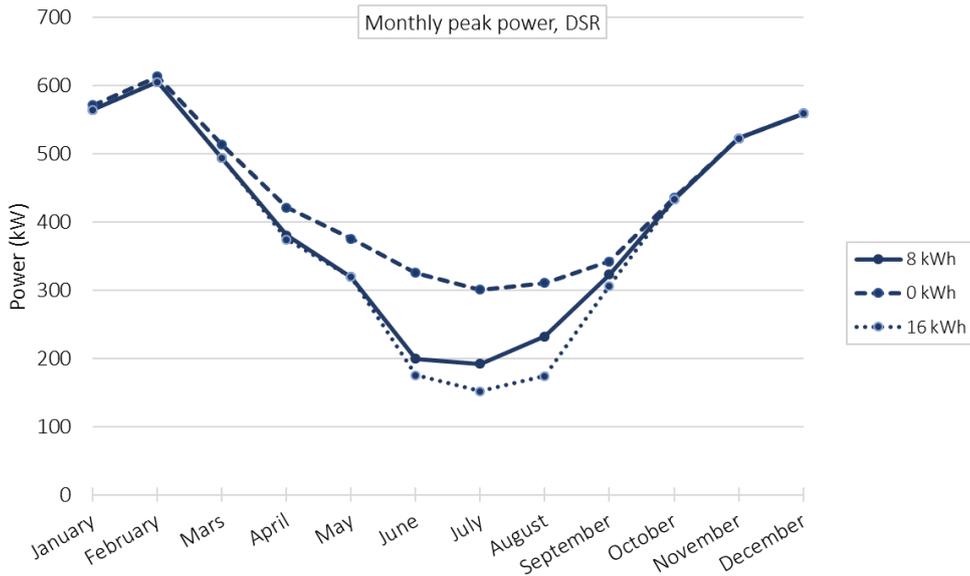


Figure 7.2: Monthly peak powers in the high case for different configurations of the PV battery. All units are included and controlled.

The difference in monthly peak powers in the summer was much larger when comparing the 0 kWh and 8 kWh battery, compared to the difference when instead doubling the size of the battery. One explanation for this was thought to be the discharge-to-load limit of 1.5 kW used, and that this had an especially large limiting impact of the battery in the 16 kWh simulation. This limit was set in order to fairly compare the simulations.

Due to this, another simulation was done where the discharge limit of the 16 kWh battery was removed. The result showed that the monthly peak powers remained or even increased some months when there was no discharge limit. The reason is that the battery had time to fully discharge its capacity in many cases before the peak load (from EVs) occurred.

This suggests that a battery of 8 kWh is preferable to 16 kWh both on annual and monthly basis, since the additional decrease in peak power during summer was small.

Chapter 8

Economic analysis

In this chapter, earlier results are analysed from an economic perspective. A comparison between the LEC in the base simulation and the LEC in the DSR simulation is made in order to find the economic potential of using DSR. As the savings potential varies between different electricity tariffs, three tariffs are applied to the results from the simulations. Two Swedish and one German tariff are examined.

First, electricity tariffs in Sweden and Germany are stated together with inputs used in the calculations. Then, the results of the calculations are presented in terms of relative savings for the customers in a DSR LEC compared to a non-DSR LEC as well as payback. An extended analysis of the investment where batteries are excluded, using the payback method, is also presented.

8.1 Electricity tariffs

Electrical energy pricing models differs between companies as well as countries. Some reasons behind these differences are legislations and varying expenses for grid owners. In this analysis, three different tariffs from three distribution system operators (DSOs) were analysed and compared. The DSOs have been anonymised. There are two Swedish, referred to as DSO-1 and DSO-2, and one German, DSO-3.

8.1.1 Swedish tariff examples

The tariff structure in Sweden is divided in two parts; electricity trading and electricity distribution fees. Electricity trading originates from, as the name suggests, electricity trading

related costs while distribution costs are paid to the DSO. The distribution company and the energy trading company are not necessarily connected to the same company. For the electricity trading, the same pricing have been used for the Swedish tariffs. This is due to the fact that electricity trading tariffs do not normally contain a capacity fee, which is of interest in this thesis.

In this section, the different parts of the tariffs are described and the economic inputs used for calculations for the two different Swedish DSOs are stated in *Tables 8.1, 8.2 and 8.3*.

Electricity trading: Electrical energy is traded on Nord Pool. This combined Nordic market sets the spot price, which is an important part of the electricity trading price. The total cost for electricity trading can, depending on the type of contract the customer has chosen, vary over time or be fixed or a mixture of the both. Here, a variable price was used. The total price consists of spot price, a supplemental charge, an annual subscription which is charged monthly and value added tax (VAT) see *Table 8.1*. The presented spot price is the average spot price during 2017. In the calculations, the average monthly spot price was used.

Table 8.1: Variable electricity trading price for companies connected to the low voltage grid in SE4 during 2017. Prices are used for DSO-1 and DSO-2.

Price element	Cost	Unit
Spot price	0.31	SEK/kWh
Supplement charge	0.025	SEK/kWh
Annual charge	336	SEK/year
VAT	25	%

Electricity distribution: The electricity distribution fee is based on the expenses of the DSO, which in its turn is regulated by the revenue cap. The revenue cap is decided on forehand by the Swedish Energy Market Inspectorate, in order for the DSO to charge reasonable and fair tariffs. In the absence of competition, in practice, only one company owns and maintains the grid in a certain area. The revenue cap decides how much money the DSOs can make during the upcoming four year period (Swedish Energy Market Inspectorate, 2016).

It was assumed that an LEC could be charged accordingly to the already existing company distribution fees. How this would actually work in the future is not known. The tariffs used in the calculations included charges for electricity usage, which is charged per consumed kWh. The second part of this tariff is capacity fees which is based on peak power. There are also subscription charges and taxes. See *Table 8.2* for detailed tariff of DSO-1 and DSO-2.

Table 8.2: Distribution tariff for a company connected to the low voltage grid with a fuse larger than 80 A, for DSO-1 and DSO-2.

Price element	Cost, DSO-1	Cost, DSO-2	Unit
Usage fee	0.064	0.075	SEK/kWh
Fixed subscription charge	600	500	SEK/month
Peak-based subscription charge	-	193	SEK/kW _{peak,year} ¹
Yearly capacity fee	-	453	SEK/kW _{peak,year} ²
Monthly capacity fee	95.20	-	SEK/kW _{peak,month}
Energy tax	0.33	0.33	SEK/kWh
VAT	25	25	%

Excess production: A customer producing electricity can sell excess production to over-laying grid. For this, the customer will be paid a variety of revenues. This includes the spot price for the sold electricity and a so called loss compensation. A customer producing its own electricity decreases losses in the grid, a service for which the customer will be compensated for. In addition to what the energy trading company pays, producers receives electricity certificates for their renewable energy production which can be sold on a market for electricity certificates. The prices of the certificates are market based and the prices will vary depending on demand and supply (Swedish Energy Agency, 2017f).³

Above described revenues will vary depending on the choice of energy trading company. The revenues for a customer selling their excess energy to DSO-1 and DSO-2 are shown in *Table 8.3*. The spot- and electricity certificate prices presented below are averages of the 2017 prices, monthly costs were however used in the calculations.

Table 8.3: Revenues for a PV producer.

Type of revenue	Earnings, DSO-1	Earnings, DSO-2	Unit
Spot price	0.31	0.31	SEK/kWh
Loss compensation	0.029	0.050	SEK/kWh
Electricity certificate	0.06025	0.06025	SEK/kWh

¹ Annual one hour power peak, paid monthly.

² Average value of two highest monthly one hour peaks during January - March and November - December.

³ The interested reader might know that there is tax reduction when selling microproduced energy and that some utility companies offer feed-in tariffs (Swedish Tax Agency, n.d.). This is however limited to microproducers, and an LEC of this size does not qualify as a microproducer. The limit of installed capacity of a microproducer is 43.5 kW (E.ON, 2018a) and this LEC exceeds that by far (roughly 75 kW in the low case).

8.1.2 German tariff example

In this section, the different parts of the German tariff are described and the economic inputs used for calculations for the German DSOs are stated in *Tables 8.4* and *8.5*.

Electricity trading: The German electricity supplier related costs includes, besides costs for procurement and sales of electricity itself, a number of different regulatory levies and taxes. Amongst these are fees for renewable energy sources, interruptible loads, offshore liability and compensation for combined heat and power plants. These fees are presented in *Table 8.4*, merged as "Regulatory levies and fees".

Table 8.4: German electricity trading prices in 2017.

Price element	Amount	Unit
Procurement and sales	0.056	EUR/kWh
Regulatory levies and fees	0.090	EUR/kWh
Electricity tax	0.021	EUR/kWh
VAT	19	%

Electricity distribution: The distribution fee of DSO-3 consists of a usage fee and a capacity fee which is based on annual peak power. The tariff differs depending on the voltage level and the amount of full load hours (FLH)⁴, see *Equation 8.1*.

$$\text{Annual full load hours (FLH)} = \frac{\text{Annual energy use [kWh/year]}}{\text{Annual peak power [kW]}} \quad (8.1)$$

Depending on the number of FLH, the usage- and capacity fees differs, see *Table 8.5*.

Table 8.5: DSO-3 electricity distribution fee when connected to the low voltage grid.

Price element	<2500 FLH	≥ 2500 FLH	Unit
Capacity fee	14.76	128.52	EUR/kW,year
Usage fee	0.066	0.021	EUR/kWh

This tariff ensures that a customer pays more both when increasing peak power and increasing energy consumption in a reasonable way. This is visually displayed in *Appendix D*.

Excess production: Since early 2018, there are no feed in-tariffs available for customers investing in new PV installations in Germany. This means that the only revenue paid for

⁴ Annual full load hours is a theoretical number describing the amount of hours it would take to consume the given annual consumption if using its given maximum power at all times.

excess production is the spot from the European Power Exchange (EPEX) market, where electricity is traded in Germany (European Power Exchange, 2018). The average price during 2017 was 0.032 EUR/kWh. However, monthly averages were used in the calculations.

8.2 Equipment for demand side response

In order to control the units - HP, EV and PV with batteries - additional equipment is needed. This is the investment necessary for load control. For HPs, an Ngenic Tune was used. For EVs, a charging box was needed (Garo Wallbox). To control the battery connected to the PV system, the battery (sonnenBatterie) itself was enough. In order to coordinate these, a central control system is also needed. The costs for these equipments are listed in *Table 8.6* together with their respective subsidy, when existing. Additional information about the equipment is stated below.

Table 8.6: Fixed unit investments for DSR (E.ON, 2018b; Ngenic, n.d.-a; Solcellspatrollen, 2018). The central control system has a one time investment and an annual cost.

Unit	Cost (SEK)	Subsidy (SEK)	Net cost (SEK)
Ngenic Tune	4 995	-	4 995
Garo Wallbox	14 995	7 497	7 498
sonnenBatterie	90 640	50 000	40 640
Central control	514 000 SEK + 1 542 000 SEK/year		

The costs in *Table 8.6* constitutes the total investment for an LEC to be able to participate in DSR. Other costs in reality could arise; all residents may not have PV systems for example. This is however not regarded as an investment needed for DSR, as it has been assumed that PVs exist both in the base and DSR simulation.

Garo Wallbox: The Garo Wallbox is an EV charger which allows a secure and fast charging. Further, the box is "smart grid ready", i.e. includes software necessary for DSR activities (E.ON, 2018b; Garo, n.d.). EV home chargers are subject for subsidies. Since February 2018, they are granted 50 % of the charging device itself and 50 % of the installation costs, up to a total of 10 000 SEK per real estate (Swedish Environmental Protection Agency, 2018). Installation costs are included in the number in *Table 8.6*.

Ngenic Tune: An Ngenic Tune enables DSR from a HP by manipulating its regular control function when desirable (Ngenic, n.d.-b). The principle of control is to "trick" the HP that it no longer needs to heat the house, in order to deactivate the HP. The device is not currently granted any subsidies.

sonnenBatterie: The battery considered in this thesis was a 8 kWh sonnenBatterie. A pri-

vate customer can apply for subsidies when investing in a battery, if it increases the self consumption and if the battery is coupled to a PV system. The subsidy can cover costs up to 60 % of the total investment, however not more than 50 000 SEK (Swedish Energy Agency, 2017h).

Central control: In order to allow synchronized control of the above described units, a central control IT platform is necessary. The central control has a fixed investment of 50 000 EUR. In addition to this, there there is an annual charge of 150 000 EUR for the investment. This price has been used regardless of the amount of units in the LEC. There are no subsidies.

8.3 Calculations

To perform a final cost analysis of the different tariffs, the total electricity cost (both trading and distribution fees) was calculated month by month in the different cases. *Equation 8.2* describes how the monthly costs for the different cases were calculated.

$$Total\ cost = (Consumption \cdot Variable\ costs + Fixed\ costs) \cdot VAT \quad (8.2)$$

Income from excess PV production was also calculated for the different cases. This export to the overlaying grid yields incomes, depending on contracted energy trading company and was calculated according to *Equation 8.3* below.

$$Income = Excess\ production \cdot Price\ of\ excess\ production \quad (8.3)$$

Finally, a simple payback was calculated in order to analyse and compare how introduction of DSR affected the LEC with the different tariffs. The calculation excluded the cost of capital. This payback was calculated according to *Equation 8.4*, where "DSR investments" were the investments presented in *Table 8.6*. "Annual LEC savings" is defined as the decreased costs of electricity of the LEC when DSR is introduced, i.e. $Costs_{No\ DSR} - Costs_{DSR}$.

$$Payback = \frac{DSR\ investments}{Annual\ LEC\ savings} \quad (8.4)$$

8.4 Result and analysis of economic aspects

In these results, only the combined loads were used from the base and DSR simulation.

Relative expense differences

In *Table 8.7*, the relative expense differences in high case for each tariff are presented. This relative change corresponds to a percentual saving in the combination of trading and distribution costs when the LEC has DSR compared to when it does not. For example, in January, the LEC decreased their costs by 15 % when using DSR, and having the price tariff of DSO-1. It can be seen that the profitability of DSR varied with different tariffs, as the annual percentual decrease varied from 24 % using the DSO-1 tariff, while when using the DSO-3 tariff the corresponding number was limited to 14 %.

Table 8.7: *Monthly power and usage decrease. Relative expense differences for the different tariffs in high case when DSR is implemented in the local energy community. Red color marks the lowest expense difference and green color marks the highest, for each case.*

Month	Power decrease (kW)	Usage decrease (kWh)	DSO-1	DSO-2	DSO-3
January	377	8 620	- 15 %	- 11 %	- 13 %
February	411	15 671	- 18 %	- 13 %	- 14 %
March	377	24 539	- 22 %	- 17 %	- 17 %
April	366	27 384	- 28 %	- 21 %	- 17 %
May	342	28 093	- 33 %	- 26 %	- 15 %
June	414	28 695	- 46 %	- 30 %	- 15 %
July	417	29 792	- 46 %	- 30 %	- 15 %
August	441	30 108	- 43 %	- 28 %	- 16 %
September	376	23 038	- 31 %	- 23 %	- 12 %
October	356	17 554	- 22 %	- 17 %	- 12 %
November	378	7 469	- 17 %	- 12 %	- 11 %
December	379	6 369	- 14 %	- 10 %	- 13 %
Year	-	247 331	- 24 %	- 18 %	- 14 %

The expense differences of the low and medium case are not presented here. They were however following the same trend as in the high case, only difference being that the percentual decrease in expenses for energy in the LEC was lower.

In the medium and high case, calculating with the DSO-3 tariff, the full load hours (FLH) of the LEC was less than 2500 hours in the base simulation, and more than 2500 hours in the DSR simulation. The low case had more than 2500 FLH in both base and DSR simulation.

A general pattern for the DSO-1 and DSO-2 tariffs can be seen; DSR led to larger cost savings during summer compared to the winter months. This can be explained by the fact that both the PV and battery contributes to increased self consumption, which leads to lowered

energy consumption from the grid and therefore lower electricity trading costs. When using DSR, there was a decrease in income from sold PV production due to the battery. This decrease in income was however smaller than what a customer saves on energy expenses thanks to an increased self consumption. This led to an overall expense decrease.

The relative cost saving for a customer of DSO-1 was higher than that of DSO-2 especially during summer. This is due to the monthly based capacity fee where the customers benefited from peak shaving also during summer, where the potential for peak shaving was highest. For the DSO-3 tariff, a trend was harder to identify.

For DSO-2 and DSO-3, the capacity fee was based on annual peak, while DSO-1 charged the customer based on monthly peaks. This gives DSO-1 customers incentives to decrease the peaks throughout the year, while the other tariffs only encourage decrease of the annual peak power. It should also be mentioned that the annual peak power is in general harder to decrease. This is due to the colder weather and darker days during winter months which leads to generally higher loads but also high peak loads, which are harder to decrease without affecting customer comfort.

In the case of DSO-3, the FLH of the LEC was less than 2500 in the base simulation and greater than 2500 in the DSR simulation. This complicated the analysis. This difference in FLH between base and DSR simulation was the reason the monthly savings were about the same each month. In the base simulation (FHL <2500), the energy price had a larger share of the total price, while the opposite was true for DSR simulation. In the base simulation, the annual peak power was larger, but less was paid per kW compared to the DSR simulation. Therefore, customers of DSO-3 have less incentives to decrease their peak powers compared to customers of the analysed Swedish tariffs.

The fact that the distribution fee altered if $FLH < 2500$ or if $FLH > 2500$ led to an extended analysis of this tariff, where the calculations were done without changing tariff when decreasing annual peak power. This is presented in *Appendix D*. The main result was that the monthly distribution followed approximately the same pattern as it did for customers of DSO-2, i.e higher savings during summer.

Savings breakdown

In *Figure 8.1* the absolute and relative changes in electricity costs for the simulated LEC are presented. The costs for the DSO-3 tariff have been converted from EUR to SEK.

When using tariffs of DSO-1 and DSO-2, the main savings came from decreasing peak power. This means that out of the annual savings at 24 % (shown in *Table 8.7*) using a DSO-1 tariff, 83 % of the savings came from decreasing power and 17 % came from decreasing energy consumption from the grid.

For the tariff of DSO-3, there was in total savings, but they only came from a decreased usage fee. The power decrease resulted in an increased cost of power since the tariff changed, meaning that the customers paid more per kW in the DSR simulation. For the simulated LEC with DSO-3 tariff, there were incentives to introduce DSR, but only because the energy became cheaper when increasing the full load hours (as when decreasing peak power).

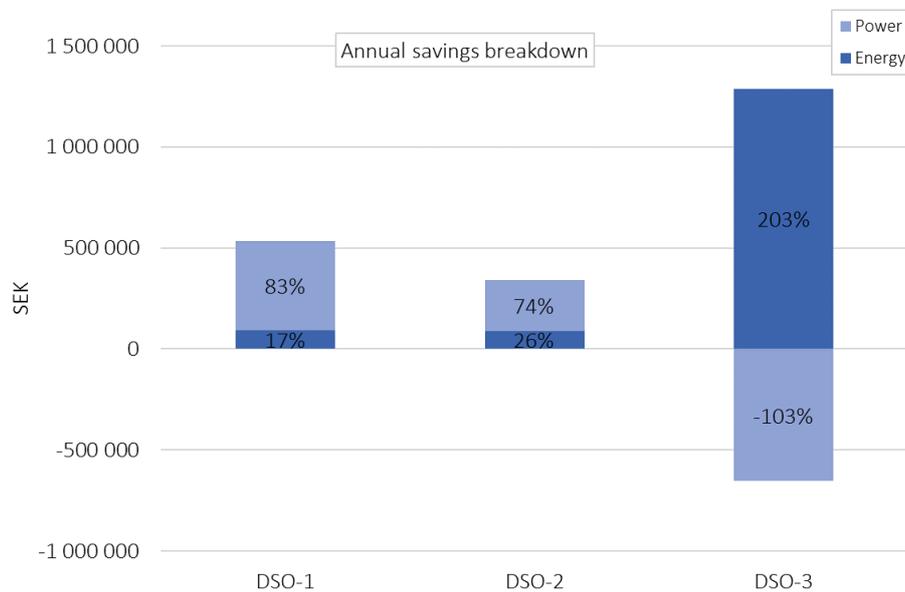


Figure 8.1: Distribution of annual savings between base and DSR simulation in high case for customers of DSO-1, DSO-2 and DSO-3. 1 EUR = 10.39 SEK (2018-04-12).

It is clear that the tariff of DSO-1 gives larger incentives for user flexibility compared to the tariff of DSO-2 (and DSO-3). This can be explained by the differences in how the two DSOs charge for capacity.

Payback time

A payback time was calculated with the investments necessary to enable DSR of the LEC. The result of this was an infinite payback time, which means that *the investment is not profitable in any case, with any tariff*. As the main issue of this was the investment and licence cost of the central control system, a payback time excluding this also was calculated. The following payback time result is therefore only including the remaining investments; Ngenic Tune (for HPs), Garo Wallbox (for EVs) and sonnenBatterie (for PVs).

The payback time, when excluding central control, for each tariff and case was under 25 years, see *Figure 8.2*. In the case of DSO-1 and DSO-3 it was around 15 years, while it was higher in the case of DSO-2.

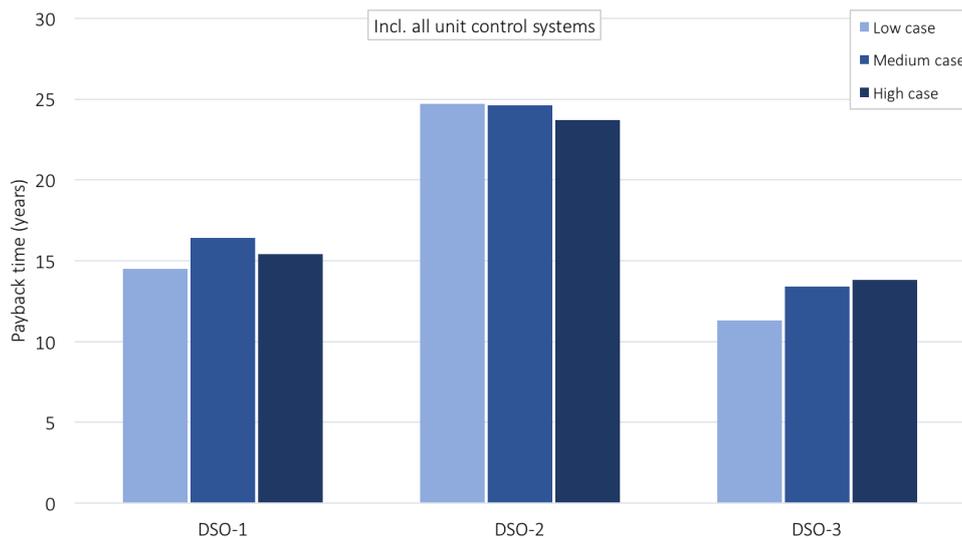


Figure 8.2: Payback time when using tariff structures from DSO-1, DSO-2 and DSO-3. Investments included: Ngenic Tune, Garo Wallbox and sonnenBatterie.

The payback time was shorter with a DSO-3 tariff, despite that this tariff showed the smallest relative decrease. This is due to the higher absolute electricity costs in Germany compared to Sweden. As an example, a 10 % cost decrease with the DSO-3 tariff contributes to better payback as it corresponds to a larger amount of saved money in absolute terms, compared to the two Swedish DSOs where the price of electricity is lower.

The difference between DSO-1 and DSO-2 comes from the fact that the DSO-2 tariff charges only annual peak and resulted in less annual savings compared to the DSO-1 tariff (see Figure 8.1).

No battery

Since batteries are a large investment cost and not that common today in Sweden, it was interesting to see how the payback time were affected when the batteries were removed from the PV system. Note that the central control also was excluded.

Excluding household batteries from simulation and investments, the payback time decreased with all tariffs and in all cases (see Figure 8.3) compared to the previous result (in Figure 8.2). For the DSO-3 tariff, in the medium and high case, the FLH of the LEC was less than 2500 hours in the base simulation, and more than 2500 hours in the DSR simulation. The low case had more than 2500 FLH in both base and DSR simulation.

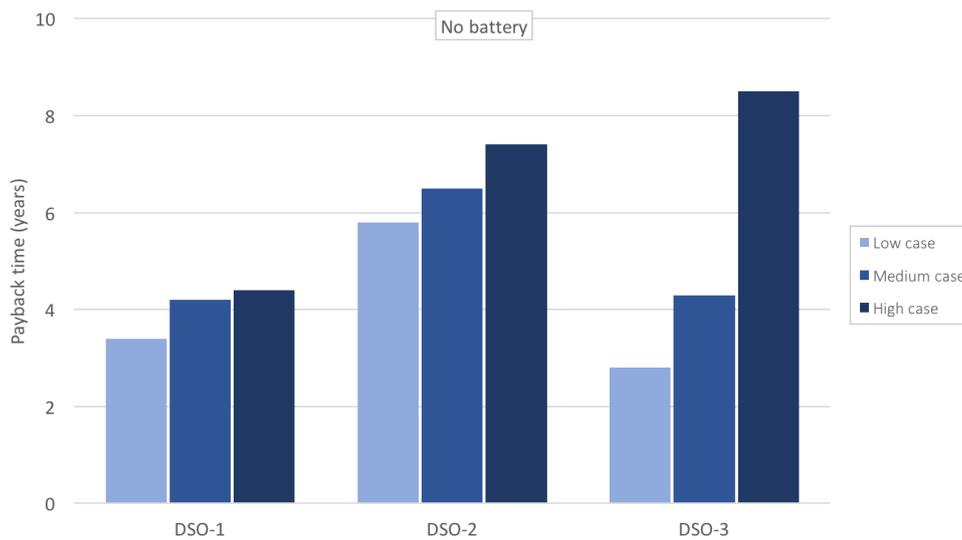


Figure 8.3: Payback time when using tariff structures from DSO-1, DSO-2 and DSO-3. Investments included: Ngenic Tune and Garo Wallbox.

The payback time decreased most in the low case. This trend was shown for all three tariffs. The reason was that the savings, which came from using more units with DSR, did not compensate for the increased investment costs. In other words, when increasing the amount of units between for example the low and medium case, the investment cost was higher relative to the savings made possible by the units.

The decreased payback times using DSO-1 and DSO-2 tariffs were due to the fact that household batteries contributed with low cost savings in terms of peak shaving or an increased self consumption relative to the investment cost. With low energy prices, it is cheaper to import electricity from the grid instead of storing excess production in a battery. However, with higher electricity prices it would become more interesting to be self-sufficient.

With the DSO-3 tariff, payback times decreased in all cases when the batteries were excluded. It is however notable that in the high case, the payback decreases substantially less compared to low and medium case. This was due to the relatively small annual savings in the high case which in turn were due to relatively equal amount of energy use between base and DSR simulations. In the base simulation, some PV production can be used during summer to meet EV charging load. This decreased the energy use in the base simulation of high case. In the medium and low case, households may not necessarily have both EV and PV, and therefore did not have this decrease in energy use in the base simulation. This made the difference in energy use between base and DSR simulations relatively smaller in the high case, which resulted in longer payback time.

Of the investment costs, the batteries were the most expensive equipment. Excluding this cost decreased the payback time. The resulting payback time is short and it would be beneficial for private customers in an LEC with any tariff - if they do not need to invest in central control.

Chapter 9

Discussion

In this chapter, the choice of method for each unit is discussed first. Then, the peak shaving potential for the units individually and combined is discussed. This also includes the usefulness of DSR and LECs outside the scope of this thesis. Finally, the economic aspects are discussed.

9.1 Choice of method

This section discusses the assumptions done and methods used in the thesis as well as other considered, and discarded, methods. First, the method when using original load is discussed. Then, the units are discussed individually in the order HP, EV and PV with batteries.

In the original load, it was assumed that only household electricity was included, i.e. no electricity for heating. This assumption was based on the annual electricity demand of the houses. The initial plan was to use consumption data from an existing area where the houses were connected to district heating to ensure that heating was not included in the electricity consumption. However, this required hourly data, which is rare, and that E.ON also owned the electricity grid in that area.

In the simulations of the heat pumps (HPs), there were difficulties in gaining realistic results. The available simulating tool, VIP-Energy, showed that the temperature in the house dropped surprisingly fast when the HPs were subject to load control. One explanation for the fast temperature drop could be that the house in VIP-Energy did not contain any furnitures, residents or electrical appliances. This would have increased the thermal inertia of the house in reality. Why the simulation tool might have overestimated the decrease in energy consumption could be that it is primarily a building energy simulation tool, not designed for simulation control behaviour of a HP. In addition to this, customers might be able to han-

dle a larger temperature drop than 1°C which would also point to an underestimation of the potential found in this thesis.

Another method considered for DSR simulation was to preheat the house, which would allow a slower temperature drop. This was however discarded as the available simulation tool could not, to a satisfactory level, simulate such behaviour. To acquire more accurate results from VIP-Energy, one idea was to increase the insulation of the template house more in the software to counteract the fast temperature drop simulated. As VIP-Energy proved to be a complex tool, this was considered to be a difficult method to carry out within the available time.

The reason for the interference with the results from VIP-Energy was to adjust the simulation results in accordance with findings in the literature study. As the availability of software able to simulate desired behaviour of HPs was limited, the manual override of the simulated results in VIP-Energy was considered the most accurate method with the alternatives on hand. It is however obvious that this is not an optimal solution, but with the limited impact of the HP simulation on the final result, it was considered to be sufficient.

Initially, a water heater was a part of the DSR units. This was later dismissed and the DHW was considered to be produced by the HP, as this is a common choice in newly built houses that buys a HP. However, it could be possible to include demand response of DHW also in a HP. This would require a more advanced method than the one used in this thesis. The HP alters between producing heat for space heating and DHW. This would be needed to take into account in the control strategy of the HP. In this thesis it was assumed that the production of DHW was never restricted, which simplified the control.

To increase the reliability of the simulation of electric vehicles, more variation of input parameters could be used. For example, different driving behaviour during weekdays and weekends. This would however contribute to more complexity. It is also reasonable to consider the inputs used as an average, but this method could result in missing possible sudden large peaks that can occur in reality. The method chosen also assumes that all customers are flexible with their charging between 20.00 - 06.00, which is an optimistic assumption. This could have overestimated the potential of DSR for EVs. In reality, customers might have the option to override the controlled charging when necessary.

For the photovoltaics, it was assumed that all PVs were optimally and equally placed on every house. In reality, some houses would probably have less favourable conditions for PV production such as different roof angle or that the roof would face east/west. The chosen method could therefore have overestimated the PV production of the LEC. Initially, the battery would be simulated in SAM, but this proved to be far too time-consuming in order to simulate the LEC in a reasonable way. Therefore, a battery model was created in Python instead. In this model, efficiencies of the inverter and other system components connected to the battery was however not included, which slightly overestimates useful energy in the battery. This was however assumed to have a negligible effect on the final results, why the

simplifications could be made.

Generally, the three cases (low, medium and high) can be seen as covering minor differences between houses. For example, the medium case can be considered to correspond to a situation where some PV systems have less favourable placements.

It was initially planned that the investment cost of the PV system should have been included in the economic analysis, as this is a large investment (twice the battery cost). It was unlikely to assume that this is something customers would buy either way, which could be assumed for EVs and HPs. PV investment cost was however not possible to include in the payback analysis since it was assumed that PV existed in both the base and DSR simulation. Therefore, the cost for a PV system could be added in reality.

9.2 Peak shaving potential of units

For all units, the simulations showed that there was technical potential in using DSR to decrease peak powers. In this section, the potential is discussed for each unit individually (in the order HP, EV and PV with batteries) and then the potential of the combined units is discussed.

The thermal inertia of buildings allows deactivation of HPs over time. The potential of DSR proved to be larger during winter than summer, even though the outdoor temperature is lower in the winter. This was because the HPs are generally much less active during summer months since the outdoor temperature is high. Despite this, the annual decrease in peak power on aggregated level was only 2 - 4 % in the different cases. This is due to the rebound effect, which decreased the peak shaving potential of HPs on an aggregated level. The rebound effect of one HP, in these simulations, occurred at the same time as another HP was deactivated. Seen from an individual household perspective, the HPs could be turned off during the house peak load and turned back on when consumption is low and the impact from the rebound effect is less of a problem.

The HPs could have been used for peak shaving differently if they were the only controllable devices in the LEC. This could have given an increased peak shaving from HPs compared to the results presented in this thesis. The decrease in annual peak of 2 - 4 % can possibly be an underestimation of the potential of HPs. This is due to the control strategy used, where the deactivation of HPs should match the EV charging. When looking at only HPs (as seen in *Figure 6.7*), one can see that the decrease of the highest peak could be decreased even more if the HPs were deactivated earlier. It should however be noted that when including EVs, the peak shaving potential from HPs is still small.

As HPs are becoming more efficient and newly built houses demand less energy, the potential of HPs for DSR is possibly decreasing. Although, the result of this could also be that HPs

could be turned off for a longer time, but with lower power decrease. It is hard to say whether or not the potential in this future case is lower, higher or the same as today.

Electric vehicles were a large addition in load even when charging at a relatively low power (3.7 kW). This can be compared to the average household power in the original load, which was 0.6 kW. Especially in a case with high penetration of EVs, the addition in peak power is remarkably increased under the assumptions used in this thesis. The assumptions also led to the possibility of large annual peak power decrease, which was reduced by 15 - 43 % in the different cases. This points to the necessity of controlling such high loads on an aggregated level. The sensitivity analysis showed that with a high charging need, it was harder to decrease the peak power using demand response of EVs during night as it is difficult to distribute over time.

The DSR of EVs differs from the DSR of HPs and PVs when it comes to the need of customer involvement. The use of HPs and PVs with batteries fulfills more indirect purposes for the customer. HPs should achieve sufficient indoor temperature and PVs with batteries should for example result in increased self consumption. When the DSR of these units occurs is not relevant for the customer, as long as the unit fulfills its purpose. For EVs it is different as the time aspect is of importance to the customer. Customers may have different charging requests and consequently can not be flexible during the times assumed in this thesis, which is needed to take into account in reality.

The photovoltaics mainly decreased the load during daytime where there was no daily peak. The batteries were however useful in decreasing monthly peak powers mainly during April - September. The PV with batteries also decreased annual peak power by 2 - 10 % in the different cases. Thereby the batteries had better technical potential for peak shaving compared to HPs, but less potential compared to EVs.

In the sensitivity analysis, it was noted that a larger battery contributed to only slightly decreased monthly peak power during June - August. The overall usefulness of the battery can be questioned, depending on what type of peak that is desired to decrease. If it is equally important to decrease the peak every month, a battery is suitable when the PV is producing. If it is more important to decrease peaks during winter months, the battery has less of a purpose. Further, the charging conditions of the battery also matters. It could be an option to charge the battery from the grid in the middle of the day during winter to store it until the evening peak. The yield from such a charging depends on electricity price differences between day and night. It could also have negative effects on the lifetime of the battery as it would be charged/discharged more annually.

Combining all of the loads when using DSR, the peak power was decreased throughout the year. The percentual decrease was however higher during summer. This is due to the overall lower consumption of both household electricity (original load) and HPs. Therefore, the impact of distributing EVs, in combination with PV with batteries which is better during summer, was larger.

Seen from the connection point of the LEC, as the aggregated simulations are, DSR of the units contributed to peak shaving on both annual and monthly basis. However, an important aspect of DSR in an LEC is what type of other loads that surrounds the area. If an LEC is connected to the same local grid as for example office buildings, which are mainly active during the day, it would not be appropriate to distribute the LEC peak loads to office hours. In this context, central control is needed both within the LEC and in coordination with other LECs or loads.

Another aspect of the use of DSR potential is what peaks that are actually most interesting to decrease. In this thesis, the aim has been to decrease peaks all year which is interesting today for a customer that has a tariff based on monthly peaks. Seen from an energy utility perspective, that has both production and owns a grid, the objective could be different. Decreasing the annual or winter peaks can be more important since these peaks usually consist of more expensive electricity production peak facilities. For a grid owner, decreasing the highest peaks during the year is important since the grid needs to be dimensioned after these peaks. This results in a grid with high capacity that is unused most of the year.

9.3 Economic savings potential

The various tariff structures of DSO-1, DSO-2 and DSO-3 had different impacts on the savings of the LEC as well as payback time on investments made to enable DSR. The capacity fee of DSO-1 charges customers based on monthly peaks, which led to the highest annual percentual savings. DSO-2 and DSO-3 charges capacity based on annual peak which led to slightly less percentual savings compared to DSO-1. It is however important to keep in mind that the investigated tariffs are developed on the basis on current electricity consumption. In the coming years, as peak power will increase in importance for grid owners, it is possible that the tariff structures will adapt to new legislations in order to enable a renewable energy system with continued high demands on reliability. This is likely to increase the importance for customers to decrease peak powers throughout the year, a behaviour which can be incentivised by the DSO tariff.

The DSO-3 tariff increased the complexity of the economic analysis. The main issue was that the distribution fee structure changed between base and DSR simulation as it is based on annual FLH. When decreasing the annual peak power, the amount FLH increases. Customers that lowered their annual peak, in this case uses DSR, may pay more per peak kW compared to what they did in the base simulation. This meant that the comparison which was made for the DSO-1 and DSO-2 was harder to perform for DSO-3 with the same clear conclusions.

The savings breakdown of DSO-1 and DSO-2 tariffs showed that the power savings were larger in not only relative but also absolute terms for DSO-1. The reason behind this is again the difference in how the DSOs differ in the way they charge for capacity. It is noteworthy

that the decrease in usage costs represents 17 % and 26 % for DSO-1 and DSO-2 respectively. These savings in usage costs came mainly from an increased self consumption enabled by batteries, but also due to the fact the HPs decreased their energy demand slightly in the DSR simulation. Savings due to self consumption will however increase in the future if there is a rise in the electricity price and the absolute difference between bought and sold electricity increases. This will, in combination with decreasing prices for storage, increase the profitability of investing in a PV and battery.

An important result is that there was no profitability when investment and annual costs for a central control was included. With the current prices of DSR equipment, it would be irrational to make the necessary investments. However, with the cost for a central control system disregarded, the payback were in the range of 11 - 25 years. With also batteries excluded from simulations and calculations, the payback time for all DSOs decreased even more. Despite that batteries enable an increased self consumption, the investment cost is still high and as long as prices for batteries remain so, it will be more economically viable to purchase electricity from the grid instead of investing in a battery.

The simulations made in this thesis, together with the results of relative cost savings, showed that there is great technical potential for peak shaving using demand side response. The economic calculations did however not give full justice to this fact, as investment costs were high. The central control system is an example of this - the annual cost was three times the amount of the annual savings with the tariff of DSO-1. The technical potential exists, but the cost of investments must decrease. If the current CEP proposal is implemented, the energy market could change to benefit solutions which enables a more flexible power system. With continued interest from utilities, authorities and private customers alike, it is only a question of when LECs becomes an alternative in practice.

Conclusions

This chapter concludes the thesis and states suggestions for future work.

10.1 Conclusions

The aim of this thesis was to investigate if the use of demand side response in a local energy community could contribute to peak shaving on an aggregated level. The results showed that it was possible to decrease the power peaks on both monthly and annual basis when using DSR of heat pumps, electric vehicles and photovoltaics with batteries. More specific conclusions found in the simulations are presented below.

- The thermal inertia of houses and the outdoor temperature determines the possible deactivation time of a HP. It can be deactivated for several hours, but this comes with a rebound effect, which increases power after deactivation. On an aggregated level, the rebound effect is too large to achieve a substantial peak shaving.
- EV charging can be moved over time. Distributing the charging of EVs in an LEC has high potential to decrease peak powers. This potential is higher when the charging time is short.
- A battery connected to a PV system can store energy produced by the PV during the day and discharge during peak load. When combined with PV, a battery has largest potential for peak shaving during summer as the PV produces a vast majority of its annual production in summer. A larger battery than 8 kWh does not necessarily decrease peak power more.
- Combined, these units can achieve peak shaving on an aggregated level throughout the year, with higher relative potential during summer.
- An LEC have potential to reduce its annual electricity costs with 14 - 24 %, depending

on which of the three different tariffs that were evaluated in this thesis that is used. The savings are achieved by introducing DSR of HPs, EVs and PVs with batteries in the LEC.

- Calculating with an investment cost including all control systems and the battery, the investment is not profitable with current prices. This is mainly due to the central control system which is the most expensive investment.
- When excluding the cost for central control, the payback time for necessary DSR investments is estimated to 11 - 25 years, depending on tariff.
- A battery is a large cost and, in relation to this, does not contribute with corresponding savings when reducing peak powers and increasing self consumption. When excluding the battery (and central control) from the simulation and investment, the payback time is estimated to 3 - 9 years.

10.2 Future work

In this section, suggestions for future work are presented.

- **Business case for the LEC aggregator**
The focus of this thesis was to investigate LECs from an aggregated customer perspective. For LECs to become a reality, there must be a business case for the aggregator.
- **Centralised control of DSR in one LEC**
The control strategy in this thesis was manually optimized for these specific simulations. A general control strategy on higher level, i.e. the central control, within the LEC could be made in order to get a more accurate evaluation of load control and how it might be used in a real LEC.
- **Centralised control of several LECs**
This thesis has achieved peak shaving in a single LEC. In order for LECs to have technical potential to peak shave on larger scales, in the distribution or transmission power grid, many LECs need to be coordinated with respect to surrounding loads.
- **Financial customer model of an LEC**
In this thesis, only the aggregated economic aspects were considered. These costs and incomes do however need to be distributed in a fair manner within the LEC in order for customers to be willing to join.
- **LECs on balancing markets**
In the future, it is possible that aggregated household customers could offer their flexibility and excess production on the balancing markets. This potential could be investigated in order to find if and how this could be done. Such a study could prove incentives for aggregators as well as introducing new actors on the balancing markets.

References

- ABB. (n.d.). *Peak shaving*. Retrieved 2018-01-25, from <http://new.abb.com/substations/energy-storage-applications/peak-shaving>
- Ahmed, K., Pylsy, P., & Kurnitski, J. (2016). Hourly consumption profiles of domestic hot water for different occupant groups in dwellings. *Solar Energy*, *137*, 516-530.
- Alimohammadisagvand, B., Jokisalo, J., Kilpeläinen, S., Ali, M., & Sirén, K. (2016). Cost-optimal thermal energy storage system for a residential building with heat pump heating and demand response control. *Applied Energy*, *174*, 275-287.
- Alvehag, K., Werther Öhling, L., Östman, K., Broström, E., Strömbäck, E., Klasman, B., ... Morén, G. (2016). *Åtgärder för ökad efterfrågefleksibilitet i det svenska elsystemet*. Eskilstuna: Swedish Energy Markets Inspectorate. (Ei R2018:15)
- Arteconi, A., Hewitt, N. J., & Polonara, F. (2013). Domestic demand-side management (dsm): Role of heat pumps and thermal energy storage (tes) systems. *Applied thermal engineering*, *51*(1-2), 155-165.
- Beck, T., Kondziella, H., Huard, G., & Bruckner, T. (2016). Assessing the influence of the temporal resolution of electrical load and pv generation profiles on self-consumption and sizing of pv-battery systems. *Applied energy*, *173*, 331-342.
- Birgersson, A. (2017). *Vilket värmesystem passar bäst i ett nybyggt hus?* Retrieved 2018-02-05, from <https://blogg.ivt.se/energipararen/vilket-varmesystem-passar-bast-i-ett-nybyggt-hus>
- Bloomberg New Energy Finance. (2017). *Why battery cost could put the brakes on electric car sales*. Retrieved 2018-02-06, from <https://www.bloomberg.com/news/articles/2017-11-28/electric-cars-need-cheaper-batteries-before-taking-over-the-road>
- Boverket. (2015). *Bostadsbeståndet 2015*. Retrieved 2018-03-14, from https://www.scb.se/sv_/Hitta-statistik/Statistik-efter-amne/Boende-byggande-och-bebyggelse/Bostadsbyggande-och-ombyggnad/Bostadsbestand/87469/87476/Behallare-for-Press/402441/
- BP. (2017). *Bp energy outlook 2017*.
- Broberg, T., Brännlund, R., Kazukauskas, A., Persson, L., & Vesterberg, M. (2014). *An electricity market in transition - is consumer flexibility for sale, or even for real?* Umeå: Centre for Environmental and Resource Economics, School of Business and Economics, Umeå University. (Swedish Energy Markets Inspectorate report)
- BUILD UP. (2017). *Ecodesign and energy labelling of electrical heat pumps*. Retrieved

- 2018-03-19, from <http://www.buildup.eu/en/news/overview-ecodesign-and-energy-labelling-electrical-heat-pumps-0>
- Davidsson, K. (2018). *Technical sales & support - vip-energy*. (Interview 2018-03-13)
- Elsäkerhetsverket. (2017). *Laddstationer*. Retrieved 2018-02-01, from <https://www.elsakerhetsverket.se/privatpersoner/sakra-elprodukter/laddstationer/>
- Energinet, Fingrid, Statnett, & Svenska Kraftnät. (2017). *Unlocking flexibility, nordic tso discussion paper on third-party aggregators*.
- Energy Saving Trust. (2008). *Measurement of domestic hot water consumption in dwellings*. UK Department for Environment, Food and Rural Affairs.
- E.ON. (2017). *Normalförbrukning*. Retrieved 2018-02-02, from <https://www.eon.se/privat/for-hemmet/energiradgivning/normalfoerbrukning.html>
- E.ON. (2018a). *Ersättning och avgifter*.
- E.ON. (2018b). *Laddbox till hemmet*. Retrieved 2018-04-03, from <https://www.eon.se/privat/for-bilen/koera-pa-el/bestaell-vara-laddloesningar.html>
- E.ON. (2018c). *Solcellsbatteri från fronius*. Retrieved 2018-02-15, from <https://www.eon.se/privat/for-hemmet/solceller/solcellspaket/fronius-solcellsbatteri.html>
- European Commission. (n.d.-a). *2030 energy strategy*. Retrieved 2018-01-25, from <https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2030-energy-strategy>
- European Commission. (n.d.-b). *Clean energy for all europeans*. Retrieved 2018-02-07, from <https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans>
- European Commission. (2017). Proposal for a directive of the european parliament and of the council on common rules for the internal market in electricity. , 2-6 and 67-69. (2016/0380 (COD))
- European Power Exchange. (2018). *About us*. Retrieved 2018-04-27, from http://www.epexspot.com/en/company-info/about_epex_spot
- Fischer, D., Wolf, T., Scherer, J., & Wille-Haussmann, B. (2016). A stochastic bottom-up model for space heating and domestic hot water load profiles for german households. *Energy and Buildings*, 124, 120-128.
- Fortum. (2018). *Solpaket från fortum*. Retrieved 2018-02-06, from <https://www.fortum.se/privat/smarta-hem/solceller>
- Frankel, D., & Wagner, A. (2017). *Battery storage: The next disruptive technology in the power sector*. (Statistics 2015:10)
- Fransson, V. (2017, 04). *Investigating dwellings' response to heating power cuts: Simulations and field tests*. (Licentiate Thesis)
- Fuentes, E., Arce, L., & Salom, J. (2018). A review of domestic hot water consumption profiles for application in systems and buildings energy performance analysis. *Renewable and Sustainable Energy Reviews*, 81, 1530-1547.
- Garö. (n.d.). *Garö wallbox*. Retrieved 2018-04-04, from <http://www.garö.se/en/ev-charger/ev-chargers/garö-wallbox>
- Georges, E., Cornélusse, B., Ernst, D., Lemort, V., & Mathieu, S. (2017). Residential

- heat pump as flexible load for direct control service with parametrized duration and rebound effect. *Applied Energy*, 187, 140–153.
- Grahn, P. (2013). *Electric vehicle charging impact on load profile*. (Licentiate Thesis)
- Habib, S., Kamran, M., & Rashid, U. (2015). Impact analysis of vehicle-to-grid technology and charging strategies of electric vehicles on distribution networks – a review. *Journal of Power Sources*, 277, 205 - 214.
- Hansson, K., & Olsson, S. (2014). *Micro-generation in local power grids - balancing intermittency with energy storage and demand response*.
- Holmström, A., & Wiklund, M. (2015). *Rvu sverige 2011-2014, den nationella resvaneundersökningen*. (Statistics 2015:10)
- Ingelson Wendell, J., & Rydberg, A. (2017). *Economic incentive model for demand side response in a local energy system*.
- Intergovernmental Panel on Climate Change. (2015). *Summary for policymakers*. Cambridge University Press.
- International Energy Agency. (2014). *Technology roadmap, solar photovoltaic energy*.
- International Energy Agency. (2017a). *Average ev price and range*. Retrieved 2018-03-19, from <https://www.iea.org/newsroom/energysnapshots/average-ev-price-and-range.html>
- International Energy Agency. (2017b). *Renewables 2017 - analysis and forecasts to 2022*. (Executive Summary)
- International Renewable Energy Agency. (n.d.). *Solar energy data*. Retrieved 2018-02-13, from <https://www.irena.org/en/solar>
- International Renewable Energy Agency. (2017a). *Electricity storage and renewables: Costs and markets to 2030*. Abu Dhabi.
- International Renewable Energy Agency. (2017b). *Perspectives for the energy transition, investment needs for a low-carbon energy system, chapter 3*.
- Kjellén, P., & Sjölander, S. (2018). *Engineers, e.on*. (Interview 2018-05-07)
- Kraftringen. (n.d.-a). *Elbilsladdning - frågor och svar*. Retrieved 2018-05-09, from <https://www.kraftringen.se/Foretag/laddstationer/elbilsladdning-for-brf/fragor-och-svar/>
- Kraftringen. (n.d.-b). *Solcellsbatteri*. Retrieved 2018-03-14, from <https://www.kraftringen.se/Privat/solceller/solcellsbatteri/>
- Kraftringen. (2018). *Vad kostar solceller?* Retrieved 2018-02-06, from <https://www.kraftringen.se/Privat/solceller/vad-kostar-solceller/>
- Kroon, D. (2018). *Development engineer in energy and heat pumps, nibe ab*. (Interview 2018-03-26 and 2018-03-27)
- Leisse, I. (2018). *Power engineer, e.on*. (Interview 2018-03-16)
- Li, X., Hui, D., & Lai, X. (2013). Battery energy storage station (bess)-based smoothing control of photovoltaic (pv) and wind power generation fluctuations. *IEEE Transactions on Sustainable Energy*, 4(2), 464-473.
- Lindahl, J. (2016). *National survey report of pv power applications in sweden*. Uppsala: Uppsala University and International Energy Agency.
- Lindmark, S. (2018). *Project leader at the swedish energy agency*. (E-mail contact 2018-02-06)

- Lorenzi, G., & Silva, C. A. S. (2016). Comparing demand response and battery storage to optimize self-consumption in pv systems. *Applied Energy*, 180, 524-535.
- Ma, Z., Callaway, D. S., & Hiskens, I. A. (2013). Decentralized charging control of large populations of plug-in electric vehicles. *IEEE Transactions on Control Systems Technology*, 21(1), 67-78.
- Mathieu, J., Dyson, M., & Callaway, D. (2012). Using residential electric loads for fast demand response: The potential resource and revenues, the costs, and policy recommendations. *ACEEE Summer Study on Energy Efficiency in Buildings*, 189-203.
- Miljöfordon. (2017). *Elhybrid*. Retrieved 2018-03-08, from <https://www.miljofordon.se/bilar/elhybrid/>
- Mitsubishi. (n.d.). *Outlander plug-in faq*. Retrieved 2018-02-20, from <http://mitsubishimotors.se/kopa-aga/faq#faq-outlander-plug-in-hybrid>
- Montin, S., Björck, A., Adsten, M., & Haegermark, H. (2013). *Översiktlig bedömning av teknikutveckling och tillämpning inom nyckelområden som ställer nya krav på att elnäten utvecklas - elfordon, vindkraft, solceller och energilagring*. North European Power Perspectives.
- National Energy Foundation. (n.d.). *Types of photovoltaic (pv) cells*. Retrieved 2018-03-19, from <http://www.nef.org.uk/knowledge-hub/solar-energy/types-of-photovoltaic-pv-cells>
- Ngenic. (n.d.-a). *Ngenic tune*. Retrieved 2018-04-03, from <https://ngenic.se/>
- Ngenic. (n.d.-b). *Styrning*. Retrieved 2018-04-04, from <https://ngenic.se/faq/#styrning>
- NIBE. (n.d.). *Nibe f2030*. Retrieved 2018-03-14, from <http://svenskvillavarme.cmsehandel.se/wp-content/uploads/sites/75/Nibe-F2030.pdf>
- Nissan. (n.d.). *Räckvidd och laddning*. Retrieved 2018-02-20, from <https://www.nissan.se/fordon/fordon-utbud/leaf/rackvidd-laddning.html>
- Nordsyn. (2015). *Stategic nordic products - heat pumps*. Retrieved 2018-02-08, from <https://www.energimyndigheten.se/globalassets/energieffektivisering/produkter-med-krav/pannor-och-varmepumpar/nordsyn-rapport-om-marknadskontroll-av-varmepumpar.pdf>
- Persson, S., & Forsström, E. (2017). *Nätteknisk och affärsmässig utvärdering av vehicle-to-home*.
- Philipson, A., & Lavin, H. (2017). *Future network loading and tariffs with electric vehicles - exploiting data from 1 million customers*.
- Polarpumpen. (n.d.). *Värmepumpens cop och scop värde*. Retrieved 2018-02-11, from <https://www.polarpumpen.se/varmepumpar/guide/cop-scop>
- Polarpumpen. (2015). *Fördelar med inverterteknik*. Retrieved 2018-03-09, from <https://www.polarpumpen.se/blogg/fordelar-med-inverterteknik/>
- Power Circle. (n.d.-a). *Elbilsstatistik*. Retrieved 2018-02-01, from <https://www.elbilsstatistik.se/elbilsstatistik>
- Power Circle. (n.d.-b). *e-mobility, grunderna i laddning / laststyrning*. Retrieved 2018-02-01, from <http://emobility.se/startside/laddinfrastruktur/elbilsladdning/>
- Power Circle. (n.d.-c). *e-mobility, snabbladdning*. Retrieved 2018-02-01, from

- <http://emobility.se/startside/laddstationsguiden/forberedelser/1-2-snabbladdning-eller-normalladdning/>
- Ranstorp, T. (2018). *Automation and smart grids, ivago ab*. (Interview 2018-03-27)
- Reddy, S. S., & Momoh, J. A. (2015). Realistic and transparent optimum scheduling strategy for hybrid power system. *IEEE Transactions on Smart Grid*, 6(6), 3114-3125.
- Ren, H., Wu, Q., Gao, W., & Zhou, W. (2016). Optimal operation of a grid-connected hybrid pv/fuel cell/battery energy system for residential applications. *Energy*, 113, 702 - 712.
- Renault. (n.d.-a). *Batteri och laddning*. Retrieved 2018-02-20, from <https://www.renault.se/bilar/personbilar/nya-zoe/batteri-och-laddning.html>
- Renault. (n.d.-b). *Metoder för att ladda hemma*. Retrieved 2018-02-20, from <https://www.renault.se/bilar/personbilar/nya-zoe/batteri-och-laddning/laddning-i-detalj.html#ladda-var-som-helst>
- Rouleau, J., Ramallo-González, A., & Gosselin, L. (2017). Towards a comprehensive tool to model occupant behaviour for dwellings that combines domestic hot water use with active occupancy. *Proceedings of the 15th IBPSA Conference*, 635-643.
- Rydén, B., Sköldberg, H., Unger, T., Göransson, A., Linnarsson, J., Badano, A., & Montin, S. (2015). Elanvändningen i sverige 2030 och 2050.
- Saele, H., & Grande, O. S. (2011). Demand response from household customers: Experiences from a pilot study in norway. *IEEE Transactions on Smart Grid*, 2(1), 102-109.
- SCB. (2015). *Byggande. nybyggnad: Färdigställda bostadshus 2014*. Stockholm: Statistiska Centralbyrån. (Statistiska meddelanden, BO 20 SM 1501)
- SCB. (2017). *El-, gas- och fjärrvärmeförsörjningen 2016*. Stockholm: Statistiska Centralbyrån. (Statistiska meddelanden, EN 11 SM 1701)
- Schwaegerl, C., & Tao, L. (2014). *Microgrids: Architectures and control*. West Sussex, United Kingdom: John Wiley and Sons Ltd.
- Sernhed, K. (2004). *Effekten av effekten, elanvändning och laststyrning i elvärmda småhus ur kund-och företagsperspektiv. fallstudier*. (Tech. Rep.). Lunds Tekniska Högskola.
- Shao, S., Pipattanasomporn, M., & Rahman, S. (2012). Grid integration of electric vehicles and demand response with customer choice. *IEEE Transactions on Smart Grid*, 3(1), 543-550.
- Soares, J., Morais, H., Sousa, T., Vale, Z., & Faria, P. (2013). Day-ahead resource scheduling including demand response for electric vehicles. *IEEE Transactions on Smart Grid*, 4(1), 596-605.
- Solcellspatrullen. (2018). *E.on customer service*. (Interview 2018-04-03)
- sonnen. (2016). *Technical data sonnenbatterie*. Retrieved 2018-03-13, from https://sonnenbatterie.de/sites/default/files/161018_datasheet_sonnenbatterie.pdf
- Stadler, I. (2008). Power grid balancing of energy systems with high renewable energy penetration by demand response. *Utilities Policy*, 16(2), 90-98.
- Strusoft. (2013). *Beräkningsexempel 3 småhus ritningar*.
- Sveby. (2012). *Brukarindata bostäder*. (Version 1.0)
- Svensk Energi. (2014). *Laddinfrastruktur för elfordon, vägledning för att sätta upp laddstation eller laddstolpe - tredje versionen*.
- Svenska Kraftnät. (2017a). *Kraftbalansen på den svenska elmarknaden vintrarna 2016/2017*

- och 2017/2018, en rapport till miljö- och energidepartementet.* (Case number 2017/1015)
- Svenska Kraftnät. (2017b). *Systemutvecklingsplan 2018 - 2027, mot ett flexibelt kraftsystem i en föränderlig omvärld.* Sundbyberg: Svenska Kraftnät.
- Swedish Energy Agency. (2014). *Frånluftsvärmepumpar.* Retrieved 2018-03-19, from <http://www.energimyndigheten.se/tester/tester-a-o/franluftsvarmepumpar/>
- Swedish Energy Agency. (2017a). *Ekodesigndirektivet.* Retrieved 2018-02-08, from <http://www.energimyndigheten.se/energieffektivisering/lag-och-ratt/ekodesign1/>
- Swedish Energy Agency. (2017b). *Elfordon och laddning.* Retrieved 2018-02-01, from <http://www.energimyndigheten.se/klimat--miljo/fossilfria-transporter/elfordon-och-laddning/>
- Swedish Energy Agency. (2017c). *Energistatistik för småhus 2016.* Eskilstuna: Swedish Energy Agency. (ES 2017:3)
- Swedish Energy Agency. (2017d). *Energy statistics from one- and two-dwelling buildings in 2016.* Eskilstuna: Swedish Energy Agency. (ES 2017:03)
- Swedish Energy Agency. (2017e). *Förslag till strategi för ökad användning av solel.* Eskilstuna: Swedish Energy Agency.
- Swedish Energy Agency. (2017f). *Om elcertifikatsystemet.* Retrieved 2018-04-05, from <http://www.energimyndigheten.se/fornybart/elcertifikatsystemet/om-elcertifikatsystemet/>
- Swedish Energy Agency. (2017g). *Scenarier över sveriges energisystem 2016.* (ER 2017:06)
- Swedish Energy Agency. (2017h). *Stöd och bidrag.* Retrieved 2018-04-04, from <http://www.energimyndigheten.se/fornybart/stod-och-bidrag-pa-fornybartområdet/>
- Swedish Energy Market Inspectorate. (2016). *Elnät och reglering av elnätsavgifter.* Retrieved 2018-04-04, from <https://www.ei.se/sv/for-energiforetag/el/Elnat-och-natprisreglering/#hanchor2g>
- Swedish Energy Markets Inspectorate. (2017a). *De vanligaste elavtalstyperna.* Retrieved 2018-03-19, from <https://www.ei.se/sv/for-energikonsument/el/ditt-elavtal/vanligaste-elavtalstyperna/>
- Swedish Energy Markets Inspectorate. (2017b). *Sveriges el- och naturgasmarknad 2016.* Eskilstuna: Swedish Energy Markets Inspectorate. (Ei R2017:04)
- Swedish Environmental Protection Agency. (2018). *Laddstation för elfordon.* Retrieved 2018-04-04, from <https://www.naturvardsverket.se/Stod-i-miljoarbetet/Bidrag/laddstation-elfordon/#>
- Swedish Tax Agency. (n.d.). *Skattereduktion för mikroproduktion av förnybar el.* Retrieved 2018-04-05, from <https://www.skatteverket.se/privat/fastigheterochbostad/mikroproduktionavfornybarel/skattereduktionformikroproduktionavfornybarel.4.12815e4f14a62bc048f4220.html>
- Tan, Z., Yang, P., & Nehorai, A. (2014). An optimal and distributed demand response

- strategy with electric vehicles in the smart grid. *IEEE Transactions on Smart Grid*, 5(2), 861-869.
- Teknikens Värld. (2017). *Så långt kommer tio laddhybrider på el*. Retrieved 2018-02-20, from <http://teknikensvarld.se/sa-langt-kommer-tio-laddhybrider-pa-el-542984/>
- Teleke, S., Baran, M. E., Bhattacharya, S., & Huang, A. Q. (2010). Rule-based control of battery energy storage for dispatching intermittent renewable sources. *IEEE Transactions on Sustainable Energy*, 1(3), 117-124.
- Tesla. (n.d.-a). *Beställ en tesla model s*. Retrieved 2018-02-20, from https://www.tesla.com/sv_SE/models/design
- Tesla. (n.d.-b). *Home charging installation*. Retrieved 2018-02-20, from https://www.tesla.com/sv_SE/support/home-charging-installation
- Tesla. (2018). *Powerwall*. Retrieved 2018-02-15, from https://www.tesla.com/sites/default/files/pdfs/powerwall/Powerwall%20AC_Datasheet_en_northamerica.pdf
- The Guardian. (2017a). *Britain to ban sale of all diesel and petrol cars and vans from 2040*. Retrieved 2018-03-28, from <https://www.theguardian.com/politics/2017/jul/25/britain-to-ban-sale-of-all-diesel-and-petrol-cars-and-vans-from-2040>
- The Guardian. (2017b). *France to ban petrol and diesel cars by 2040*. Retrieved 2018-03-28, from <https://www.theguardian.com/business/2017/jul/06/france-ban-petrol-diesel-cars-2040-emmanuel-macron-volvo>
- The Swedish Government. (2015). *Faktablad fossilfritt sverige*. Retrieved 2018-03-28, from http://www.regeringen.se/4add1a/contentassets/790b8b0d7c164279a39c9718ae54c025/faktablad_fossilfritt_sverige_webb.pdf
- The Swedish Government. (2016a, jun). *Ramöverenskommelse mellan socialdemokraterna, moderaterna, miljöpartiet de gröna, centerpartiet och kristdemokraterna*. Press release.
- The Swedish Government. (2016b). *Överenskommelse om sveriges mål för energieffektivisering*. Retrieved 2018-01-25, from <http://www.regeringen.se/pressmeddelanden/2016/11/overenskommelse-om-sveriges-mal-for-energieffektivisering/>
- Transport Analysis. (2017a). *Körsträckor*. Retrieved 2018-02-20, from <https://www.trafa.se/vagtrafik/korstrackor/>
- Transport Analysis. (2017b). *Prognoser för fordonsflottans utveckling i sverige*.
- Vanhoudt, D., Geysen, D., Claessens, B., Leemans, F., Jaspers, L., & Van Bael, J. (2014). An actively controlled residential heat pump: Potential on peak shaving and maximization of self-consumption of renewable energy. *Renewable Energy*, 63, 531–543.
- Vattenfall. (n.d.). *Laddportalen*. Retrieved 2018-05-09, from <https://www.vattenfall.se/foretag/energilosningar/ladda-elbil/laddportalen/>
- Vattenfall. (2017). *Framtiden för r1 och r2*. Retrieved 2018-01-25, from <https://corporate.vattenfall.se/om-oss/var-verksamhet/var-elproduktion/ringhals/produktion-och-driftlage/framtiden-for-r1-och-r2/>

- Vattenfall. (2018). *Solcellspaket och priser*. Retrieved 2018-02-06, from <https://www.vattenfall.se/solceller/solcellspaket/>
- Volkswagen. (n.d.). *Hur gör jag för att installera en laddbox?* Retrieved 2018-02-20, from <https://www.volkswagen.se/sv/modeller/passat-gte.html#c64c0f3fab7408f896561fb3c8dd2fb3&powerLayer=modeller/gte-fragor-och-svar.display>
- Volvo Cars. (2017). *Volvo cars to go all electric*. Retrieved 2018-03-28, from <https://www.volvocars.com/uk/about/our-company/news#!/id:470535/volvo-cars-to-go-all/>
- Värmepump.se. (n.d.). *Olika typer av värmepumpar*. Retrieved 2018-03-09, from <https://xn--vrmpump-0za.se/artiklar/olika-typer-av-v%C3%A4rmepumpar>
- Wang, D., Parkinson, S., Miao, W., Jia, H., Crawford, C., & Djilali, N. (2013). Hierarchical market integration of responsive loads as spinning reserve. *Applied energy*, 104, 229–238.
- Wenham, S. R. (2012). *Applied photovoltaics*. Routledge.
- Weniger, J., Tjaden, T., & Quaschnig, V. (2014). Sizing of residential pv battery systems. *Energy Procedia*, 46, 78 - 87. (8th International Renewable Energy Storage Conference and Exhibition (IRES 2013))
- Wu, Z., Tazvinga, H., & Xia, X. (2015). Demand side management of photovoltaic-battery hybrid system. *Applied Energy*, 148, 294 - 304.
- Xu, B., Oudalov, A., Ulbig, A., Andersson, G., & Kirschen, D. S. (2016). Modeling of lithium-ion battery degradation for cell life assessment. *IEEE Transactions on Smart Grid*, 9(2), 1131-1140.
- Zeh, A., Rau, M., & Witzmann, R. (2016). Comparison of decentralised and centralised grid-compatible battery storage systems in distribution grids with high pv penetration. *Progress in Photovoltaics: Research and Applications*, 24(4), 496-506.

Appendix A

Share of houses with PV

As stated in *Section 4.3.2*, 30 % of the installed PV production in 2015 was installed by private customers and the average PV system delivers 5000 kWh annually. It was assumed that private customers in the fictive LEC consists of single houses only. In 2015, the number of single houses in Sweden was 2 018 064 (Boverket, 2015). The Swedish Energy Agency estimated a total PV production of 4.5 TWh (see section 4.3.2).

Using these inputs, the calculation for estimating the number of houses having PV installed was as followed:

$$\begin{aligned} PV_{prod,tot} &= 4.5 \cdot 10^{12} Wh \\ Share_{prod,private} &= 0.30 \\ PV_{prod,1\ house} &= 5 \cdot 10^6 Wh \\ Nr_{houses} &= 2\ 018\ 064 \\ Nr_{houses\ with\ PV} &= \frac{Share_{prod,private} \cdot PV_{prod,tot}}{PV_{prod,1\ house}} = \frac{0.30 \cdot 4.5 \cdot 10^{12}}{5 \cdot 10^6} = 270\ 000 \\ Share_{houses} &= \frac{Nr_{houses\ with\ PV}}{Nr_{houses}} = \frac{270\ 000}{2\ 018\ 064} \approx 13.4\% \end{aligned}$$

This percentage was rounded up to 15 % to harmonize with the other percentages of HPs and EVs.

Appendix B

Domestic hot water profiles

As VIP-Energy was limited in its ability to simulate DHW load curve, this was done manually. A load curve from a laboratory tested HP, acquired from NIBE, was used as a starting point. This HP only produced DHW. The laboratory test was performed on a ground-source HP which, according to NIBE, provides similar results as the NIBE F2030 7 air-to-water HP, used in the VIP-Energy simulations. The HP was tested at an outdoor temperature of 7 °C, a standard testing environment (Kroon, 2018). This yields a COP of 3.5 (NIBE, n.d.). The COP variation over the year was in this case however ignored due to the increased complexity this would add.

The DHW load profile was later scaled to fit an average single household DHW annual consumption according to Sveby, a Swedish energy industry standardisation organisation (Sveby, 2012). This profile was in Excel added to the VIP-Energy acquired space heating load curve, as the HP in the fictive are LEC provides for both space heating and DHW.

Further, it was assumed that the HP during every hour of the year could produce energy for both space heating and DHW at the same time. In reality, the HP alternates between the two demands, normally providing DHW at a higher priority. It will produce energy for each purpose during a maximum of 20 minutes, before switching to the second if both require energy at the same time (Kroon, 2018). However, as the DSR simulation was performed in intervals of one hour, it is not possible to see this alternation. It was therefore necessary that the manually added load profiles from space heating and DHW did not exceed the actual maximum power output of the HP. This would disprove above mentioned assumption. During the analysis of the HP simulation, it was however concluded that the simulated HP providing for both space heating and DHW maximum power output never exceeded, 2.05 kW which is below its maximum output.

Since only a one day profile had been obtained from NIBE, this was used for every day of the year. The look of the profile was also compared to the literature findings below. *Table B.1* shows results from several studies investigating the tap water usage behaviour.

Table B.1: Summary of peak behaviour of tap water

Morning peak	Evening peak	Source
8-9	19-20	(Energy Saving Trust, 2008)
8-9	20-22	(Ahmed, Pylsy, & Kurnitski, 2016)
8-12	19-21 (main peak)	(Rouleau, Ramallo-González, & Gosselin, 2017)
7- 10	18-20	(Fuentes, Arce, & Salom, 2018)

An example of a heat pump for DHW in a single family house in Germany is shown in *Figure B.1*. In this study, the tap profile follows the HP consumption well, meaning that the tap behaviour studies in *Table B.1* can be used as reference when comparing the NIBE curve to literature.

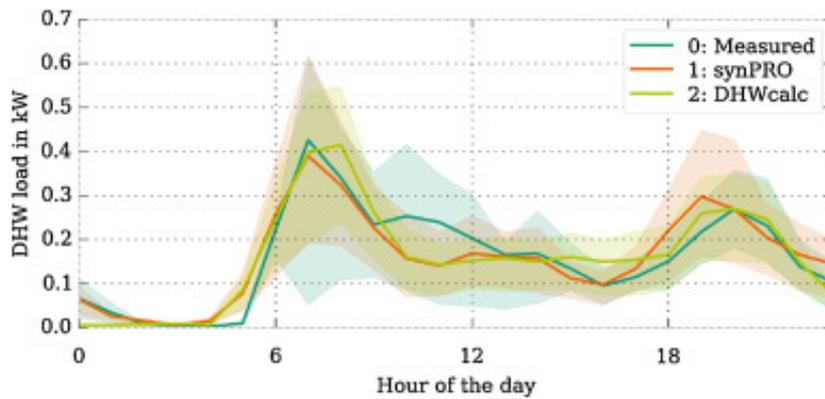


Figure B.1: Example of a heat pump profile producing domestic hot water (Fischer et al., 2016).

The HP consumption for producing DHW was spread out between households in eight batches, in order to obtain a more reasonable look for the total area, seen in *Figure B.2*.

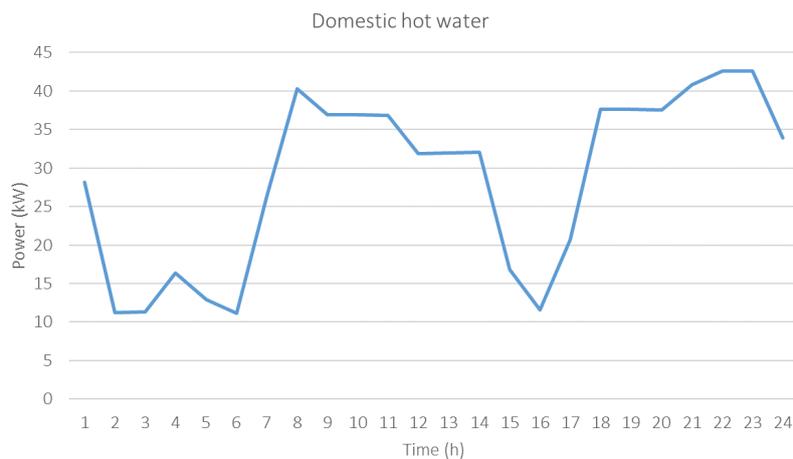


Figure B.2: Aggregated load profile for DHW in the LEC.

Charge/discharge strategy for PV battery

Figure C.1 shows the charge and discharge strategy of the household battery connected to the PV system. A list of the abbreviations used in the figure is shown below the figure. The circles represents actions and the squares represents questions with conditions.

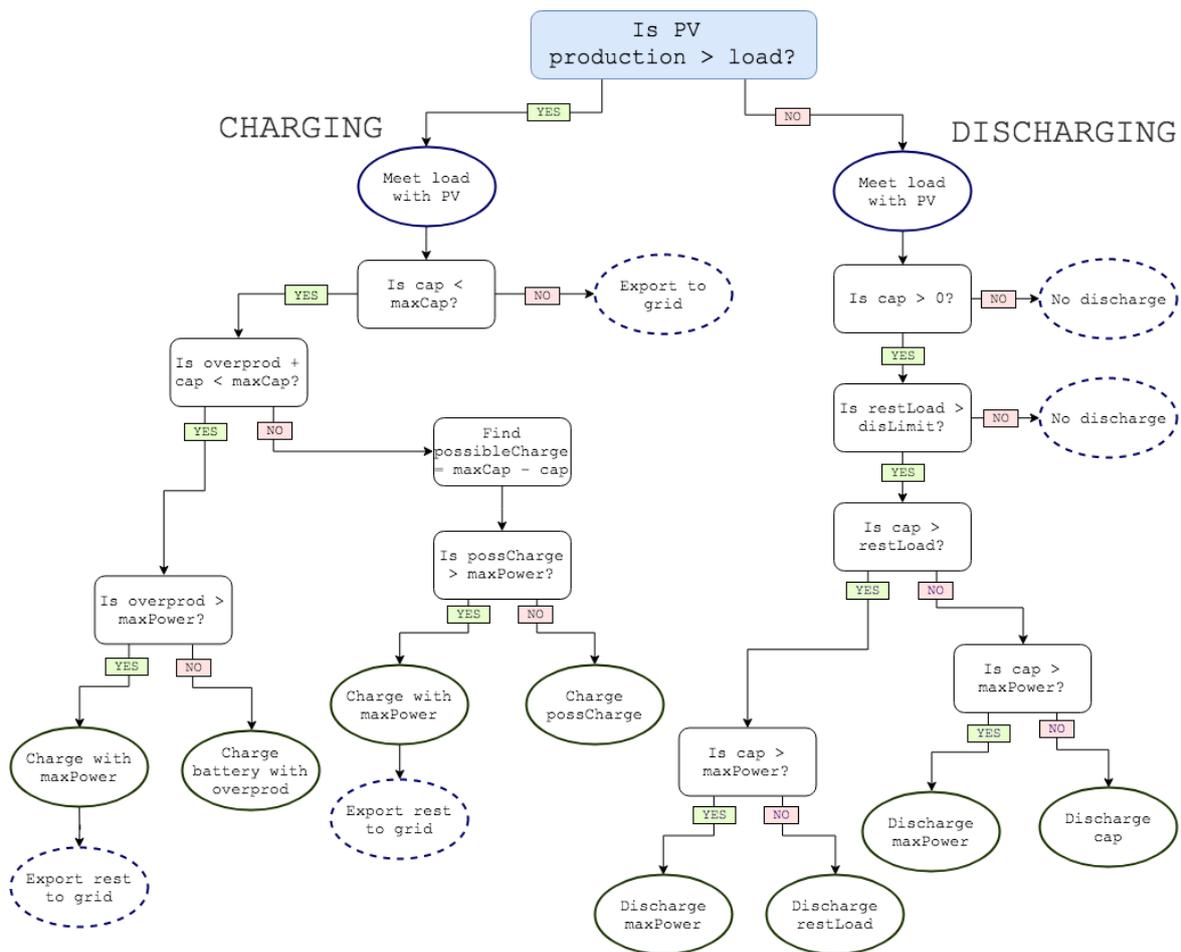


Figure C.1: Charging strategy of the battery connected to the PV system.

Explanation of abbreviations used in *Figure C.1*:

cap = current energy content in the battery.

maxCap = max capacity of the battery, 6.4 kWh (8 kWh battery with SoC limits of 10-90%).

overprod = the difference between PV production and load when PV production > load.

restLoad = the difference between PV production and load when PV production < load.

disLimit = discharge-to-load limit, the minimum power of load needed to discharge battery. A 1.5 kW limit was used.

DSO-3 tariff structure

Visual representation of tariff

Figure D.1 shows how the costs increase with increased energy consumption and peak power using the tariff structure of DSO-3. *Figure D.2* shows the cost if only the "FLH < 2500" tariff was used. *Figure D.3* shows the cost if only the "FLH \geq 2500" tariff was used.

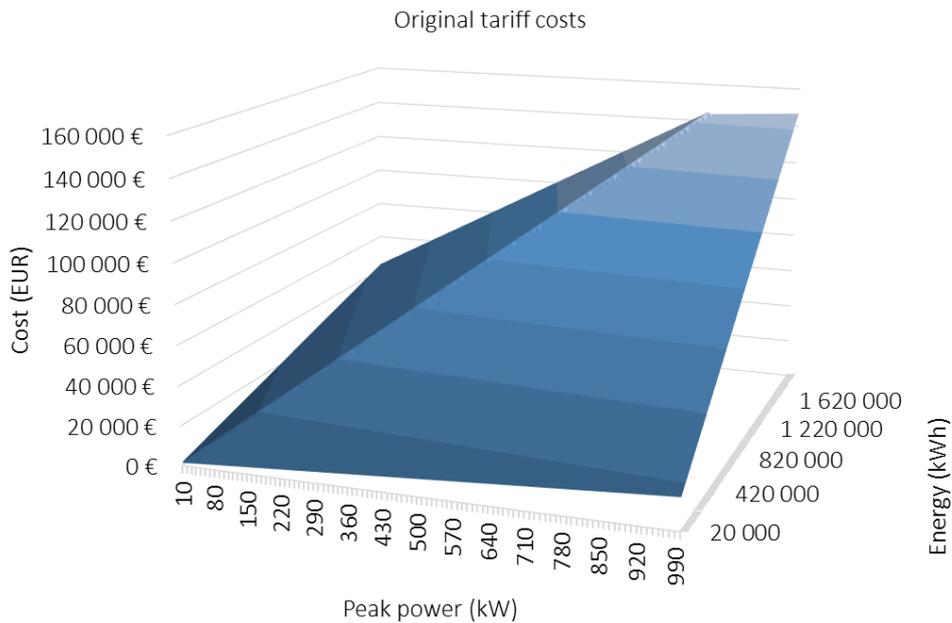


Figure D.1: Costs with the original tariff.

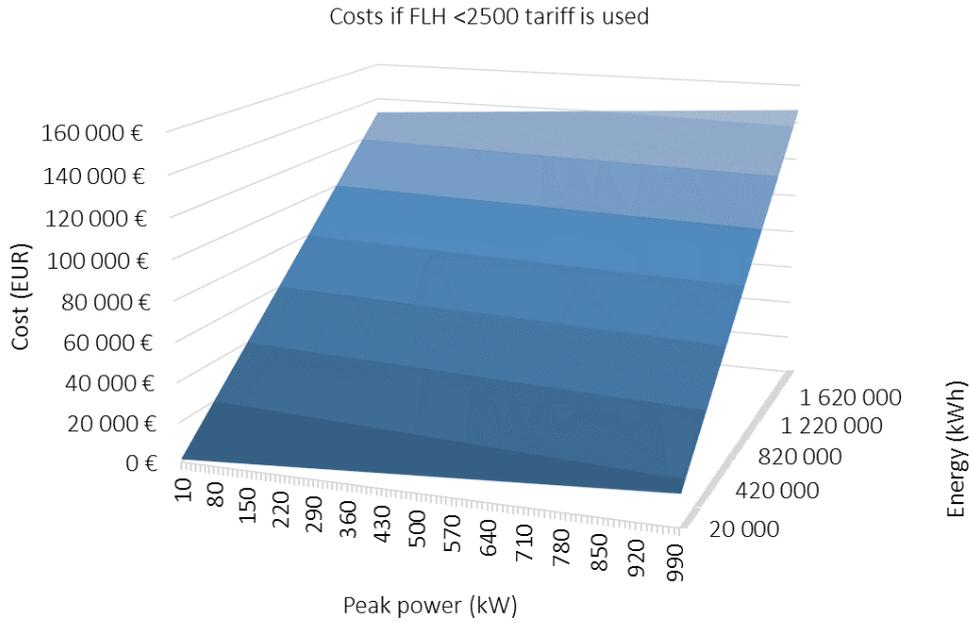


Figure D.2: Costs with the "FLH <2500" tariff.

Using the tariff in *Figure D.2*, a customer could increase their *peak power* considerably without a substantial cost increase.

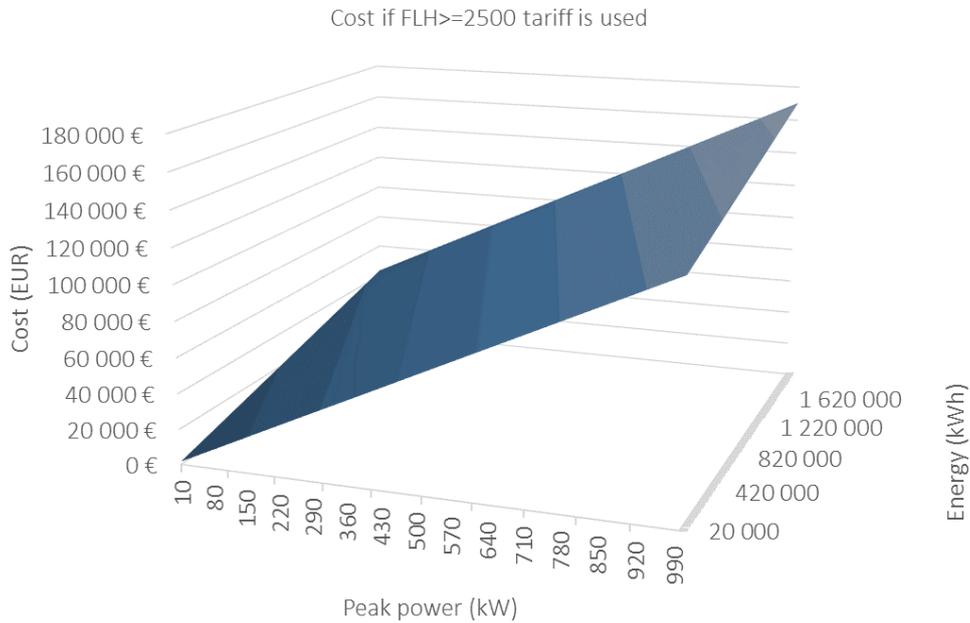


Figure D.3: Costs with the "FLH \geq 2500" tariff.

Using the tariff in *Figure D.3*, a customer could increase their *energy consumption* considerably without a substantial cost increase.

Extended results

In *Table D.1* the tariff for DSO- 3 used in calculations is shown. In *Chapter 8, Table 8.7*, the relative expense difference calculated with the two different FLH was presented. This section presents the results if a customer only had one part of the FLH tariff, i.e. $FLH < 2500$ or $FLH \geq 2500$.

Table D.1: German electricity distribution fee when connected to the low voltage grid.

Price element	<2500 FLH	≥ 2500 FLH	Unit
Capacity fee	14.76	128.52	EUR/kW,year
Usage fee	0.066	0.021	EUR/kWh

The expense differences, when using only the tariff of $FLH \geq 2500$ is used in both base and DSR simulation, is shown in *Figure D.2*.

Table D.2: Relative energy expense differences when $FLH \geq 2500$, i.e the capacity fee is expensive.

Month	Low case	Medium case	High case
January	- 3 %	- 7 %	- 10 %
February	- 4 %	- 9 %	- 14 %
March	- 4 %	- 11 %	- 19 %
April	- 5 %	- 14 %	- 25 %
May	- 4 %	- 16 %	- 32 %
June	- 5 %	- 20 %	- 36 %
July	- 5 %	- 20 %	- 37 %
August	- 5 %	- 19 %	- 35 %
September	- 4 %	- 15 %	- 27 %
October	- 4 %	- 11 %	- 19 %
November	- 4 %	- 8 %	- 12 %
December	- 4 %	- 7 %	- 10 %
Year	- 4 %	- 12 %	- 20 %

This type of tariff follows the same patterns as the DSO-1 and DSO-2 does; larger relative savings during summer.

The expense differences, when using only the tariff of $FLH < 2500$ is used in both base and DSR simulation, is shown in *Figure D.3*.

Table D.3: Relative energy expense differences when $FLH < 2500$, i.e. the usage fee is expensive.

Month	Low case	Medium case	High case
January	- 2 %	- 3 %	- 4 %
February	- 2 %	- 4 %	- 7 %
March	- 2 %	- 6 %	- 12 %
April	- 2 %	- 8 %	- 19 %
May	0 %	- 8 %	- 27 %
June	0 %	- 11 %	- 35 %
July	- 1 %	- 12 %	- 36 %
August	- 1 %	- 11 %	- 32 %
September	0 %	- 6 %	- 21 %
October	- 1 %	- 4 %	- 12 %
November	- 2 %	- 3 %	- 4 %
December	- 2 %	- 3 %	- 3 %
Year	- 1 %	- 5 %	- 13 %

A tariff where the capacity fee is higher will naturally benefit from DSR. This can be clearly seen when comparing *Table D.2* and *Table D.3*. The annual savings are larger when using the tariff with an expensive capacity fee.