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Techno-economic analysis of PV and energy storage systems for Swedish households

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Abstract

As more countries progress towards renewable energy, intermittency in the power system is causing an unreliable power supply. Flexibility solutions from prosumers, which both consume and produce electricity, is one solution to provide stability to the power system. Households with both PV and energy storage are studied for this purpose in this thesis where the following flexibility services for both a household and the electricity grid of Sweden are studied: Increasing PV self-consumption, peak shaving, energy arbitrage at the day-ahead electricity market and providing the frequency regulation reserves FCR-N, FCR-D, aFRR and mFRR. Each house is assumed to have a 10 kW PV capacity and a battery capacity of 7.68 kWh. The services are studied in the software HOMER Grid and are modelled in different scales to see how the load in different aggregated levels affect the services. The case studies are a single family house, an overloaded transformer, an energy community and on a national scale. For the aggregated case studies, the potential capacity for PV will be based on the existing Swedish policies and the number of energy storages will be inspired by one the leading countries in Europe in energy storage installations, Germany.

The results showed that for a single household the self-consumption and self-sufficiency increased the most with an addition of a battery. The battery was most efficient in peak shaving and reducing the overall electricity cost when the electricity fee targeted both the electricity consumption during peak hours and the monthly peaks. With this price scheme, the payback time of the battery and PV system is around 14 years. However, when the electricity fee is only targeting the electricity consumption during peak hours, the results showed that the monthly electricity demand peaks actually increase with an addition of a battery.

For the aggregated case studies, it showed that decentralized batteries are not as effective in decreasing the electricity demand peaks if the peak lasts more than a few hours. On a national scale the results show that 20% of the aggregated batteries capacity is sufficient to provide around 70-100% of each of the frequency reserves individually. The highest savings are gained for the households when both the primary frequency reserves, FCR-N and FCR-D, are provided by the aggregated batteries together with increasing the PV self-consumption, peak shaving and energy arbitrage. The battery payback time is then reduced to 11 years. Based on a sensitivity analysis, the costs that affects the battery payback the most are the investment cost and the power fee.

Sammanfattning

I takt med att fler länder använder sig mer av förnybar energi, ökar opålitligheten i kraftsystemet på grund av förnybar energis intermittenta natur. Flexibilitetslösningar från konsumenter som kan både producera och konsumera el är en lösning för att förse stabilitet till kraftsystemet. Hushåll med både PV och batteri studeras för detta ändamål i detta examensarbetet där följande flexibilitetstjänster för både hushållet och elnätet studeras: Öka egenkonsumtionen av solel, kapning av effekttoppar, energiarbitrage samt tillhandahålla frekvensregleringens reserver FCR-N, FCR-D, aFRR och mFRR. Varje hus antas ha en 10 kW installerad kapacitet för PV och 7.68 kWh för batteriet. Tjänsterna studeras i programmet HOMER Grid och modelleras i olika skalor för att undersöka hur elkonsumtionen i aggregerade nivåer påverkar dessa tjänster. Fallstudierna är ett enskilt hus, en överbelastad transformator, en samling av hus samt i nationell skala. För de aggregerade fallstudierna kommer den potentiella kapaciteten för PV baseras på Energimyndighetens målbild för produktion av solel och antalet batterier är inspirerade av ett av de ledande länderna i Europa inom energiinstallationer, Tyskland.

Resultaten visar att för ett enskilt hushåll ökar egenförbrukningen och självförsörjningen som mest med både batteri och PV. Batteriet var mest effektiv med att minska effekttopparna och den totala elkostnaden när eltariffen innehöll både effekttariffen och tidstariffen. PV systemet med batteriet hade då en återbetalningstid på 14 år. Med endast tidstariffer visar resultatet att de månatliga effekttopparna ökar med tilläggen av batteriet.

För de aggregerade fallstudierna visar resultatet att decentraliserade batterier inte är lika effektiva att minska effekttopparna om de varar mer än några timmar. På nationell skala visar resultaten att 20% av den sammanlagda batterikapaciteten är tillräcklig för att förse cirka 70–100% av varje frekvensreserv. Den högsta besparingen för hushållen för den nationella fallstudien fås när både av de primära frekvensreserverna, FCR-N och FCR-D tillhandahålls av de aggregerade batterierna, tillsammans med tjänsterna för att öka PV-konsumtionen, kapning av effekttopparna och energiarbitrage. Batteriets återbetalningstid reduceras då till 11 år. Känslighetsanalysen visar att de kostnader som påverkar batteriets återbetalning mest är investeringskostnaden och effekttariffen.

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Amber Ahmed

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Abbreviations

AC – Alternating current

aFRR – automatic frequency restoration reserve

BESS – Battery energy storage systems

CEP – Clean energy package

DC – Direct current

DER – Decentralized energy resource

DSO – Distribution system operator

EV – Electric vehicle

EU – European Union

FiT – Feed in tariff

FCR-D – Frequency containment reserve - disturbed

FCR-N – Frequency containment reserve - normal

HOMER – Hybrid optimization of multiple energy resources

IE –

IEP -

IRENA – International renewable energy agency

mFRR – manual frequency restoration reserve

NPC – Net present cost

NREL – National renewable energy laboratory

PV – Photovoltaic

SDG – Sustainable development goals

SvK – Svenska kraftnät

TSO – Transmission system operator

VRE – Variable renewable energy

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1 Introduction

Energy enables a prosperous world, permitting social welfare, economic growth and development. However, there are many challenges facing the current energy system. Countries are utilizing unsustainable energy sources such as fossil fuels which leaves a negative impact on the environment, with higher pollution levels emitting from the energy sector and contributing to global warming than ever before. Also, many countries energy consumption is increasing, straining the already finite fossil fuels resources further.

Several efforts have been made where the majority of countries have vowed to minimize their impact on the environment through united goals such as the Paris Agreement. 195 countries collectively set the goal to limit the global warming to below 2℃, but aim at an increase of at most 1.5℃ to minimize the effects of climate change and contribute to a more sustainable world (United Nations, 2015). Sweden has a goal of having net-zero greenhouse gas emissions by 2045 and by 2040 have an energy system consisting solely of renewable energy (Regeringskansliet, 2016).

Countries are committing to limiting their climate change and fostering sustainable growth by decarbonizing their fossilized power sector and resort to other sources. Electricity consumption is expected to increase from various sectors as they are becoming progressively electrified, the transportation sector is expected to increase the most because of the implementation of electric vehicles (EV). All this points at an increase of electricity demand in the future (IRENA, 2019).

The International Renewable Energy Agency (IRENA) proposes a pathway on how to meet the increased electricity demand while cohering to the objectives of the Paris Agreement, and highlights that the main enabler would be to increase renewable energy generation and to increase the energy efficiency of the power sector. IRENA forecasts that around 86% of the future electricity demand can be derived from renewable sources by 2050 due to its declining costs, high energy efficiency and other enablers such as smart technologies and electrification solutions (IRENA, 2019). However, around 60% of this renewable energy will derive from sources such as solar and wind power, which are considered variable renewable energy (VRE). VRE sources are non-controllable due to their variable nature, it is not possible to control when it is sunny and windy.

Private consumers have also gained an interest in renewable energy and are beginning to invest in local production, such as rooftop photovoltaics (PV) and energy storage, becoming so called prosumers who both consume and produce electricity. In Germany, around a third of the renewable energy capacity derives from citizens through rooftop PV or by private people forming energy cooperatives with other citizens whom together invest in a larger scale renewable energy, such as wind turbines or solar parks (Clean Energy Wire, 2018a, 2018b).

For the power sector, the increase in electricity demand and local electricity generation will mean a huge transition. The current power system, created with the intention to handle non-variable generation, will be under a new strain to balance the electricity supply and demand without causing disruptions with VRE. As a portion of the electricity generation will come from the end-users, this will disrupt the uniform manner the power generation and transmission work today where the electricity generation was typically produced at one end and the consumption at the other. With a higher electricity demand, the grid will also need to expand and strengthen which is a slow and costly process (IRENA, 2018).

In order to tackle these new challenges, the power system will have to transform to become more flexible, meaning being able to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales (IRENA, 2018). In order to handle this flexibility, measures have to be taken in all sectors of the energy system, such as the transmission and distribution systems, storage and through demand-side management, as seen in Figure 1.

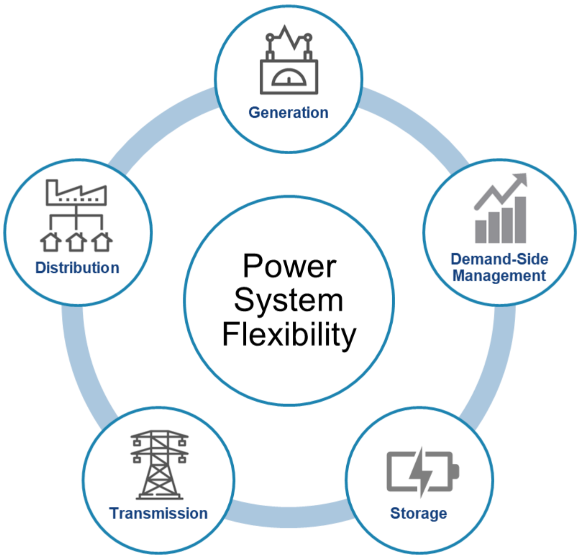

Figure 1: Power system flexibility (IRENA, 2018)

Energy storage system is a mean to provide flexibility in a power system, especially by stabilizing VRE's electricity generation. Moreover, energy storage can provide a variety of services from power quality support, frequency regulation to peak shaving and reduce a household's electricity bill, making them an attractive option for both consumers and larger actors such as the distribution system operators (DSO) and the transmission system operators (TSO).

A study done by SolarPower Europe, an association with the aim of promoting solar energy in Europe, concludes that it is possible to create an energy system that is climate neutral and meet the Paris Agreement by 2050 or earlier. It is most cost-effective if the energy system consists of 100% renewable energy where wind and solar are the two main energy sources of the future, where flexibility with energy storage is key (SolarPower Europe and LUT University, 2020).

Promoting decentralized energy resources (DER) for flexibility, such as PV and batteries, is something the European policymakers are advocating in their regulations and initiatives as well. The EU's clean energy package (CEP) states to utilize recourses optimally, implying even the small-scale resources should be used to their utmost potential. Another objective set by the CEP is to facilitate the market development for providing grid services and the electricity market, where DER also is included (Lind and Ávila, 2019). Sweden has been slow in utilizing DER for flexibility means, with very few decentralized energy storage systems existing in the country.

In order to gain an understanding of what services decentralized PV and energy storage systems can provide in Sweden this thesis will analyze this for the different scales: a single family household, a transformer, a distribution grid of an energy community and on national scale. The potential capacity for PV in Sweden will be based on existing Swedish policies and for energy storage will be inspired by one the leading countries in Europe in energy storage installations, Germany.

1.1 Previous work

A summary of studies performed for decentralized energy storage and PV providing various services are explained here.

Several studies have been performed of the usage of large-scale batteries providing grid stability amongst other services. A paper studies how energy storage can provide grid stability through participating in the regulation market, arbitrage and minimizing grid outage for the US power system (Tian et al., 2018). It concludes that mitigating outages is very valuable for grid stability and customer satisfaction, but the highest revenue is from the regulation market.

Another study (Fong et al., 2017) analyzes how a storage of 4 MW/4 MWh can provide energy arbitrage, frequency regulation and voltage support. Consequently (Asghari et al., 2015) performed an economic analysis of providing energy arbitrage, frequency regulation, investment upgrade deferral and as a reserve for the power supply from a large scale battery for the UK market. The results show that frequency regulation provides the largest revenue, however the general consensus from these studies is that the profit increases when the battery provides multiple services simultaneously.

The authors of (Parra and Patel, 2019) analyzed behind-the-meter services for energy storages with PV for around 100 different households in the UK, such as increasing the self-consumption of PV, peak shaving combined with load shifting. The results showed that individually these services were not profitable, but a combination of peak shaving and energy arbitrage proved most profitable and that the results varied significantly depending on the household's load.

A case study (Sardi et al., 2017) analyzed how aggregating individual households PV and batteries can provide a value for the whole community through energy arbitrage, system upgrade deferral, voltage support, peak shaving, emission and energy loss. (Rodrigues et al., 2017) modelled a community of 100 households under UK conditions, where half of these have PV and battery system. Two case studies are created, the first analyzing integrating PV to increase the self-consumption of the community and the second in-house energy management to provide frequency regulation and as reserves for the power system. It concludes that flexibility revenue is the highest for providing the balancing services by coordinating the decentralized energy sources.

In summation, there is a lot of research done on the services energy storages can provide, however, there was a lack of studies which focused on these services on multiple scales. Where energy arbitrage in the day-ahead market, peak shaving and increasing the self-consumption for the household together with reduction of the overall load and frequency regulation on a larger, aggregated scale are combined.

1.2 Research purpose

To investigate the economical and flexible value that decentralized PV and energy storage systems can potentially provide for a household and the electricity grid in Sweden. This is analyzed for four cases: a single house, a transformer, a distribution grid of an energy community and on a national level.

1.3 Research questions

For the different case studies the following questions will be answered to meet the research purpose:

Single family household case:

- What savings and energy benefits can be made by installing a PV system with and without energy storage?

Transformer overload case:

- Are aggregated batteries a good source for reducing the peak load on a transformer?

Energy community case:

- How much of the total load on a distributed grid for an energy community can be reduced by having aggregated batteries and PV systems?

National case:

- What proportion of Sweden's frequency regulation can the decentralized energy storage systems provide on a national scale?
- How much savings and energy benefits can be made from providing both household services and frequency regulation for an PV and energy storage system?

1.4 Scope of study

The potential of grid services will be defined as the proportion of frequency regulation and load reduction that can be fulfilled by the home energy storage systems. The frequency regulation that will be studied are the four reserves, frequency containment reserve – normal (FCR-N), Frequency containment reserve – Disturbance, automatic frequency restoration reserve (aFRR) and manual frequency restoration reserve (mFRR).

The value for household from battery usage and provision of grid services will be defined by how it affects their utility bill with the present electricity prices subsidies and taxation in Sweden, Increased PV self-consumption and self-sufficiency is handled as an additional value for homeowners, independent of economic gain.

The focus of the study is on a single family household, an actual transformer under overload for a period during a year and an actual island where a hypothetical energy community is created. Finally, the national scale is also studied for household services and grid services. What service is covered for which respective case study is shown in Table 1.

Table 1: Analyzed services and case studies for this thesis

Service	Case studies			
	Single family house	Transformer overload	Energy community	National
Energy arbitrage	X		X	X
Peak shaving	X	X	X	X
Increase PV self-consumption	X		X	X
Load reduction			X	X
Frequency regulation (primary FCR-N and FCR-D, secondary aFRR and tertiary reserves mFRR)				X

The PV system and battery sizing are common for all the case studies where the battery's capacity is set to 6 kW/7.6 kWh and PV to 10 kWp per house. However, the quantity assumed for the case studies varies based on the specific conditions for each case. The losses accounted for in the model are the conversion of electricity for both the inverter and rectifier. The losses in the PV panels are also taken into account but no losses have been modelled for the energy stored in the battery.

The loads for each case study are taken from actual sites for interpretation of how such services could benefit real life cases.

1.5 Work process

To meet the objective of this study the following work process plan shown in Figure 2 was chosen and is explained below.

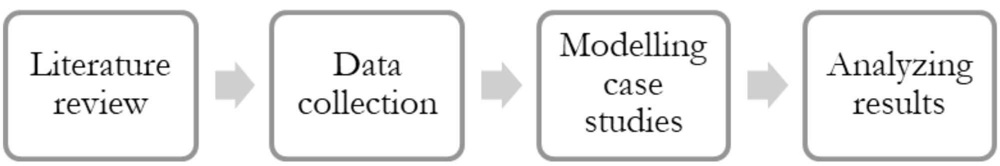

Figure 2: Workflow for the thesis

The initial step of this thesis was to conduct a literature review and gather knowledge about decentralized household PV and battery outlook in Sweden and internationally. Also, the current electricity market will be explored to gain an understanding on what drive forces and factors can allow for the increase of DER. The balancing reserves, FCR-N, FCR-D, aFRR and mFRR, are also studied with what volumes the reserves are used today and what specifications they have. The services of increase PV self-consumption, energy arbitrage peak shaving, load reduction and frequency regulation that decentralized energy storages can provide are also studied in particular in the literature review. In order to gain an understanding of what value these services can provide in different scales from an individual household to national level, the case studies of a single family house, an overloaded transformer, an energy community and the national scale are defined. These case studies are then modelled in order to quantify the value of the DER in the modelling tool HOMER Grid.

The second process is to collect data on the case studies chosen, such as the PV production and load profiles and gather data on the frequency reserves. Following, getting acquainted with the modelling tool and modelling the four case studies is done.

Finally, the results for each case study are presented and analyzed, followed by a sensitivity analysis and a general discussion.

2 Background

2.1 Photovoltaics and Energy storage

2.1.1 Photovoltaics

Photovoltaics usage can be divided in two categories, off-grid and grid-connected. In Sweden, the primary use of PV till the year 2006 was for off-grid purposes far from any grid connections. However, the share of grid-connected PV installations increased from that year due to the growing interest from the public, the utilities as well as the government which eased the investment for micro-producers with support programs that began in 2005. The national installed capacity has been growing in an exponential rate since then, as can be seen from Figure 3, the grid connected PV capacity amounted to nearly 412 MWp in the year 2018 where around 156 MWp was installed the same year. The majority of the installed PV capacity are distributed systems where the cumulative distributed capacity was around 392 MWp in 2018. This trend is also shown in previous years where the largest share of new installations are within the residential and commercial sector, seen in Figure 3 (Lindahl et al., 2019).

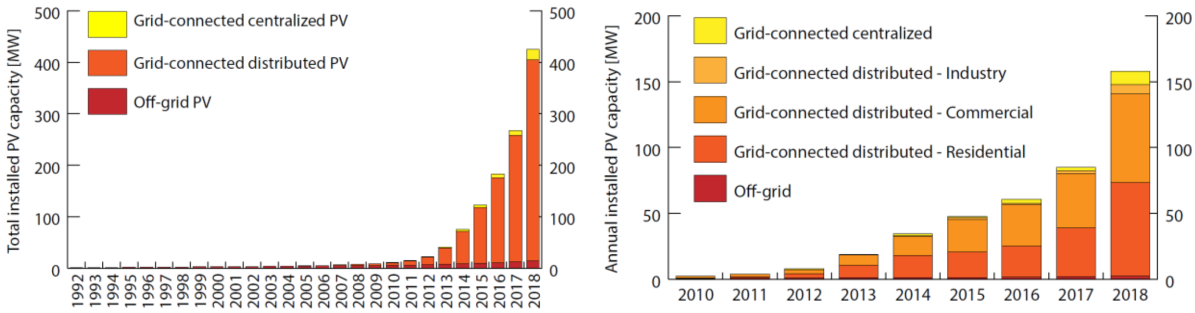

Figure 3: Total installed PV capacity (left) and annually installed PV capacity (right) for Sweden (Lindahl et al., 2019)

The Swedish Energy Agency analyzed the share of installed capacity for each segment of the sectors and found that single-family houses in the residential sector has the largest share and the commercial sector was the second largest. The various segments share can be seen in Figure 4 below which shows the share annual installed PV capacity for the different sectors (Lindahl et al., 2019).

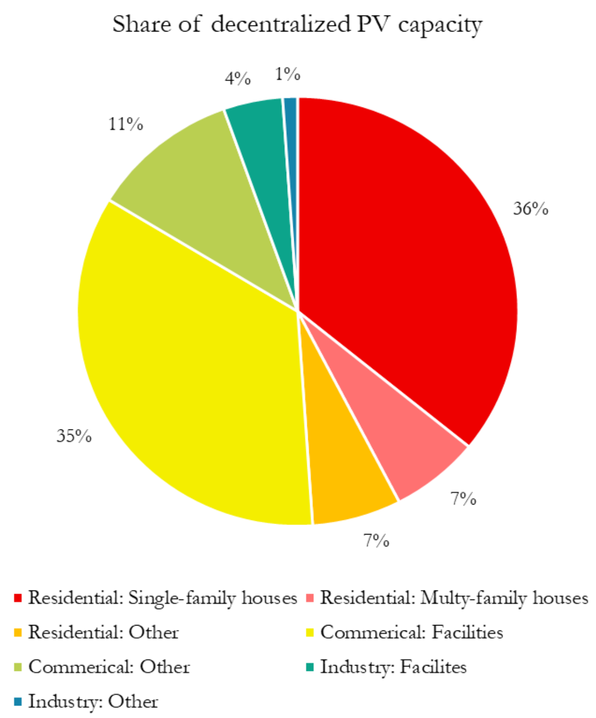

Figure 4: Sector share of annual decentralized installed PV in 2018 (Lindahl et al., 2019)

2.1.2 Battery

The basic components of a battery are an electrolyte together with a positive and negative electrode. When used, the electrodes are connected to each other via an external circuit, and the electrochemical potential between the electrodes creates a current in the circuit. The structure of the battery energy storage system (BESS) typically consists of a battery pack, a conversion system, a control system and other components such as coolers (Das et al., 2018).

BESS can be made of different elements; the type that has historically been most used are lead acid batteries, although these have low energy ratio compared to its volume and its weight (May et al., 2018). Another compound that is becoming popular since the 90's are lithium-ion batteries. They have a much higher energy density compared to lead batteries and therefore are more common in portable electric devices. Li-ion batteries are also becoming more widely used due to its longer cycle life, high roundtrip efficiency, withstanding higher temperature ranges and high efficiency in charge and discharge of the battery (Zubi et al., 2018). Due to the favorable technical capabilities of Li-ion batteries, its decreasing investment costs and improvement in its performance there are many large-scale batteries with lithium-ion batteries used as a complement to intermittent renewable energy sources, such as the 100 MW Tesla Powerpack in Australia (Tesla, 2017). The battery technology therefore used in this thesis is also the Lithium-ion battery.

The annual energy storage capacity nearly doubled internationally in 2018 from the previous year where around 3 GW was installed compared to 1.7 GW in 2017. Small scale battery installations were record-high due to the countries policy measures for behind-the-meter batteries starting to come into effect (IEA, 2019). However, the small scale battery market is mainly limited to certain countries where their incentives has accelerated the DER market such as in South Korea, Australia, Japan, Germany and the United States based on the deployment and policy trends from IEA (IEA, 2019). The annual installation rate for both large scale and small scale are shown in Figure 5. In Sweden, the installation rate for batteries has been slow, a total of 400 private people had applied for the energy storage subsidy granted by the government for installing a decentralized battery, explained further in Section 2.3.3, from 2016 to the beginning of 2018 (Energivärlden, 2018). There may have been installations done without applying for this subsidy, but this value can be considered negligible.

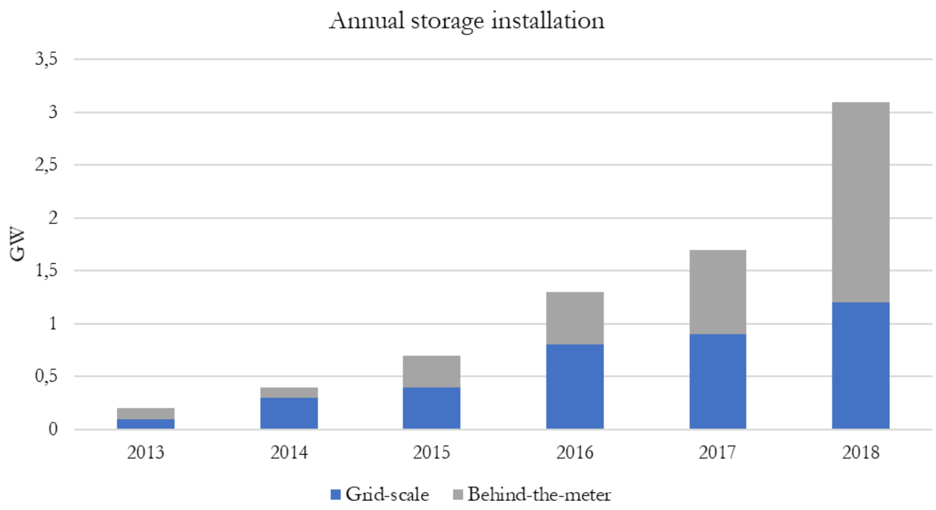

Figure 5: Annual storage installation internationally (IEA, 2019)

2.2 Policy outlook for Household PV systems and Energy storage in Sweden

In the year 2016 five of the eight political parties in the Swedish government came to an agreement called the "Energiöverenskommelsen" with a goal of producing 100% renewable electricity by the year 2040 (Regeringskansliet, 2016). However, no specific goal was made for how large share of this should originate from solar energy. Instead, the Swedish Energy Agency was given the task to propose a strategy for how to increase the share of solar energy in Sweden and analyze the necessary capacity amount of solar energy in order to meet the goal set by the Swedish government. The Swedish Energy Agency concludes that based on the technical, economical and geographical potential of solar energy in Sweden, it can provide around 5-10% of the renewable electricity share of 2040, which is around 7-14 TWh of electricity (Energimyndigheten, 2016).

The study shows that households and other facades are the most beneficial locations for producing solar energy and the total electricity generated solely from these building types amounts to 40 TWh (Energimyndigheten, 2016). Another study which performed a techno-economic analysis for solar cells in Sweden found that small houses and summer houses have the most favorable roof space for solar panels amongst building types. Industry and multi-family houses are also promising for PV (Blomqvist and Unger, 2018).

The International Energy Agency (IEA) forecasts that in order to achieve the sustainability development goal (SDG) and the Paris Agreement, an energy storage capacity of around 200 GW would be needed globally till the year 2030. The trends of recent years show that this could be achieved if the installation rate continues, as shown in Figure 5 above where decentralized batteries, such as the behind-the-meter batteries used in residents, are expanding the most. The increase of the batteries are heavily dependent on the support policies that are in effect in the different countries, resulting in different levels on exposition for each country (IEA, 2019). Sweden has at the time of writing no target for how large the share of decentralized storages should be.

2.3 Direct support policies for PV and Battery installations in Sweden

There are several support policies in place to endorse prosumers to generate their own renewable electricity through PV, and to store and feed the excess electricity to the grid. These will be described in more detail below.

2.3.1 Capital subsidy for PV installations

The capital subsidy program for homeowners started in 2009 by the government where it covered 20% of the installation cost for installing a PV system for the year 2018. The subsidy originally covered 60% of the installation cost but has since decreased at the same rate as the price decreased and the PV market grew. All private consumer types are allowed to apply for this grant as it is not limited to decentralized systems (Lindahl et al., 2019).

2.3.2 ROT tax reduction

Another option to the capital subsidy program is the ROT-program, where a service is bought to renovate and upgrade buildings. The tax reduction using the ROT-program was 30% of the labor cost in 2018, which amounts to 9% of the total investment cost of the PV system. The requirements for getting this tax reduction is that house is older than five years and that the capital subsidy is not used (Lindahl et al., 2019).

2.3.3 Capital subsidy for storage for micro-producers

To endorse increasing the self-consumption of renewable electricity, the Swedish government created a capital subsidy for batteries where up to 60% of the investment cost or a maximum of 50 000 SEK is granted for the purchase of a storage. The subsidy is provided if it can store the renewable electricity and if it can increase the self-consumption of the household. This grant began in 2016 with 25 million SEK with an additional 50 million SEK every year from 2017 to 2019 (Lindahl et al., 2019).

2.3.4 Green electricity certificate system

The green certificates scheme has existed since 2003 as a way for the government to create an incentive to increase the renewable electricity production. A renewable producer receives one certificate for each MWh renewable electricity generated, which can then be sold on an open market where the pricing is dependent on the supply and demand price. The buyers are electricity stakeholders which are obliged to purchase a certain percentage of the electricity they sell to their consumers, called the quota obligation. The percentage is decided by the government. The cost for purchasing the certificate is in turn added to the consumers bill meaning it is the consumers that pay for the certificate in the end as a way to increase the renewable electricity generation (Konsumenternas Energimarknadsbyrå, 2020a; Lindahl et al., 2019). The average weekly price for the certificate was around 0.15 SEK/kWh for the year 2018 (SKM, 2020).

2.3.5 Guarantees of origin

This electronic document is as a testimony for the origin of the electricity produced and was introduced in 2010. For every MWh the producer can apply for the guarantee of origin from the Government which can be sold, similar to the green electricity certificate. The buyers of this document are utility companies that may want to provide electricity from a specific resource to its users (Swedish Energy Agency, 2017b). The average value for guarantees of origin in Sweden for the year 2018 was only 0.01 SEK/kWh (Svensk Solenergi, 2018).

2.3.6 Tax credit for micro-producers of renewable electricity

Micro-producers of renewable electricity are valid for tax credit of 0.6 SEK/kWh that is fed to the grid, based on the Income Tax Act (Sveriges Riksdag, 1999). In order to be accounted as a micro-producer the fuse level of the building cannot exceed 100 A, the electricity is fed from the same connection as it is drawn and the grid owner is notified of the electricity generated. The amount of kWh electricity generated is also not allowed to be higher than the electricity drawn annually to be granted the tax credit and a maximum tax credit can be given to 30 000 kWh per year.

2.3.7 Grid benefit compensation

A prosumer also gains an added reimbursement from the grid owner. The grid owner compensates the energy loss reduction that the micro-producers provide by feeding its excess electricity to another consumer and use the electricity locally rather than transporting electricity from another area with the losses that entails. Depending on the grid owner, the compensation can vary between 0.02-0.1 SEK/kWh (Lindahl et al., 2019). For Vattenfall the compensation is 0.078 SEK/kWh for the southern part of the Swedish network (Vattenfall, 2018).

2.3.8 VAT exemption

VAT exemption for the electricity sold back to the grid is valid if the total renumeration made from the PV system is below 30 000 SEK per year, according to calculations made by Lindahl, such renumeration in mainly exceeded with a PV system sizing of 100-200 kWp, which is well above the average capacity of a residential PV system (Lindahl et al., 2019).

VAT is non-deductible for PV systems investment cost if part of the generated electricity meets the household load (Lindahl et al., 2019).

2.3.9 Tax redemption

On self-consumed electricity there is no tax for the PV system if the capacity is below 225 kWp, which is well above the average capacity size of a residential PV system (Lindahl et al., 2019).

2.4 Economics for both PV and Energy storage

2.4.1 The cost of PV

The cost for PV technology has consistently kept decreasing over years since 2008 where the PV market began to grow in Sweden, this was simultaneously as the international prices for the modules also decreased. However, due to the import duties set by the European Commission in 2013 the decline became more stagnant, where the import prices could not be lower than around 5.2 SEK/W_p, this limitation was however removed in late 2018. This termination decreased the module prices with 14% in the year 2018 (Lindahl et al., 2019).

The declination in prices is also mirrored in the whole PV system cost, which in addition to the cost of the PV module also includes the costs of the inverter, control components needed for the module and the installation cost. Also, as the market for PV increases the installation firms can lower their prices due to the constant stream of orders and economy of scale. For single-family houses with an installed capacity of 5-10 kW the cost has decreased between the year 2010 to 2018 from 15-23 SEK/W_p to 12-18 SEK/W_p. The cost of a PV system in 2018, taken as an average of the costs found from both the installation companies estimates and the Swedish direct capital subsidy program, is 14.6 SEK/W_p excluding VAT (Lindahl et al., 2019).

2.4.2 The cost of battery

Li-ion energy storage like many maturing technologies is experiencing a decrease in costs owing to many factors, such as a higher production volume, material and performance improvements and competition in the supply chain. But, compared to other energy storage technologies, Li-ion battery has gained a much higher interest mainly due to the market growth of EV and other flexibility uses it can provide in stationary applications. This technology is also suitable as a complement to other technological developments such as variable renewable power generation from wind or solar energy (IRENA, 2017).

Li-ion battery costs around 6 000 to 38 000 SEK/kWh internationally depending on application and size (Das et al., 2018). In Sweden the cost are closer to the lower range of that price but can vary from size, manufacturer and application (Vattenfall R&D, 2019).

2.5 PV and Battery outlook in Germany

Germany has amongst the highest installation rate for decentralized PV systems and batteries in the world, which is why it was chosen as an inspiration for Sweden as to how another European country succeeded in installing such high volume of solar panels and decentralized batteries. To gain an understanding of how Germany managed to transform its energy sector, a study on such energy systems in the country was done. In 2018, around 3 GW of PV capacity was installed with a total installed capacity at 45.5 GW by the end of the same year. This amounts to around 1.2 million distributed PV systems in the country.

The reason for the PV boom in Germany can be directed to many factors, such as the long-term support schemes from the government, support from investors and an interest to install solar panels from the residential, commercial and industrial sectors (Masson and Kaizuka, 2019). The German energy policies aim to be completely nuclear free by 2022 and move towards a more diversified energy system (IEA, 2020). One incentive to reach this goal was the Feed-in Tariff (FiT) introduced in the year 2000 for PV systems smaller than 10 kW. This tariff is given for the excess electricity which is fed to the grid and created an incentive to install decentralized PV systems. The tariff value changes annually depending on the market development such as the declining PV prices and increasing rate of PV system installments (Masson and Kaizuka, 2019). The trend of the previous year's show the FiT has been steadily decreasing and went below the retail electricity price in 2012. This also mirrors the annual PV installation rate, where the peak year was at 2012, as can be seen in Figure 6 (Kairies et al., 2019).

The reason for the decreases was for the overloading the solar production was causing to the grid. The majority of the PV systems were installed by households or farmers, which resulted in a large share of the installed capacity being located at the distribution side of the grid. During particularly sunny periods with low consumption, the distribution grid would become overloaded by the PV systems.

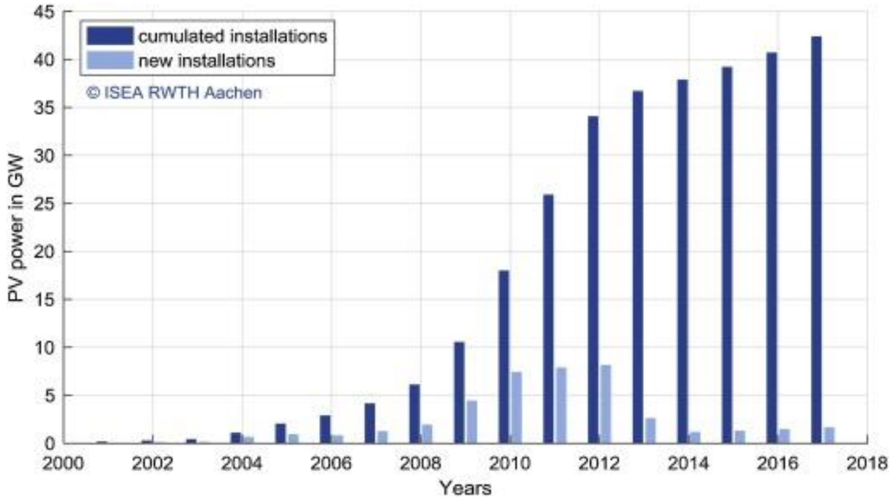

Figure 6: Cumulative and annual installation of PV in Germany (Kairies et al., 2019)

Decentralized energy storage (DES) became therefore an attractive option for both the households and the grid owners where the households could store their excess electricity and use it at another time as to not overload the grid. Germany had an incentive program for decentralized batteries which was active between 2013 to 2018 with the aim of increasing the self-consumption of small PV systems less than 30 kWp and to grow the battery market in the country. The annual installation volume of batteries and amount funded is shown in Figure 7. During this time period more than 32 000 decentralized batteries were funded with around 2 000 in the year 2018. The amount of batteries funded decreased with time, as shown in Figure 7, where 50% of all the battery installations in 2013 to 2015 were funded and during the last year, 2018, only 5% of the annual installations were funded. This showed how the incentive was successful in stimulating the decentralized energy storage market in Germany, around every other decentralized PV installation done in 2018 had also installed a battery. In total, around 40 000 batteries were installed in 2018 and the total number of energy storages installed is estimated to be 120 000 that year (Masson and Kaizuka, 2019).

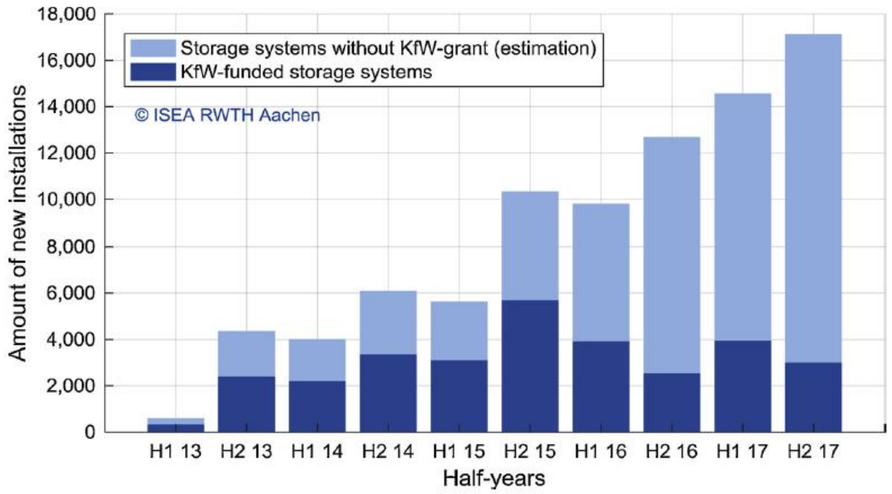

Figure 7: Battery installation in Germany with and without incentive for each half year from 2013 (Kairies et al., 2019)

2.6 Swedish electric power system

The Swedish electricity grid is today majorly uniform, where generation is produced at one end and the consumers, such as households and industries, are at the other. The grid is divided into three parts, the transmission grid, the regional or distribution grid and the local grid as shown in Figure 8. The transmission grid transports the bulk of the electricity throughout the country and has a voltage of 400 kV in order to have as little losses as possible (Jämtkraft, 2019). The regional grid and local grid are the transporter to the consumers with the local grid being connected to the end-users. The regional grid usually has a voltage between 40-130 kV but can also have less, whereas the local grid has a voltage of 230 V-20 kV (Svenska Kraftnät and Svensk Energi, 2014).

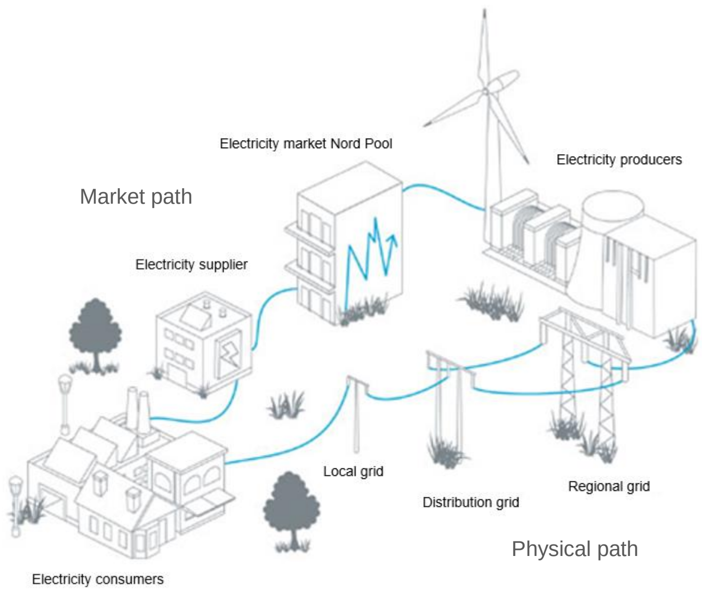

Figure 8: The physical and market pathways of electricity (Bjärke Energi, 2020)

The transmission system operator (TSO) is a government authority named Svenska Kraftnät (SvK) which has the role of maintaining and developing the transmission grid. The regional and local grid owners, also called the distribution system operators (DSO), are owned by around 160 electric companies, where the three largest are Vattenfall Eldistribution, Fortum Distribution and E.ON Elnät Sverige (Svenska Kraftnät and Svensk Energi, 2014).

2.6.1 Electricity market

The electricity can be said to be divided into two pathways, the physical path and the market path, as shown in Figure 8 above.

The Swedish electricity market is quite complex with several actors and marketplaces. The long-term electricity market is done at Nasdaq, where electricity can be purchased on yearly terms. The main electricity market in Sweden is usually through the wholesale market Nord Pool, where electricity producers sell their electricity to the electricity suppliers, which in turn sell it to the end-consumers, as shown in the market path in Figure 8 (Svenska Kraftnät, 2020a). There are two physical markets within the Nord Pool, the day-ahead market (Elspot) and intraday market (Elbas). The trading in the day-ahead market is done per hour and closes one day beforehand (Svenska Kraftnät, 2020b). With the intraday market, trading is done continuously during the day and closes an hour before delivery. The timespan for each of these markets is shown in Figure 9, the market for the frequency regulation reserves, FCR-N, FCR-D, aFRR and mFRR are explained further below. The actors buy or sell electricity so to adjust to the consumers electricity load closer to the delivery time. With VRE increasing, the intraday market is becoming more widely used for balancing the system during the day (Svenska Kraftnät, 2020c).

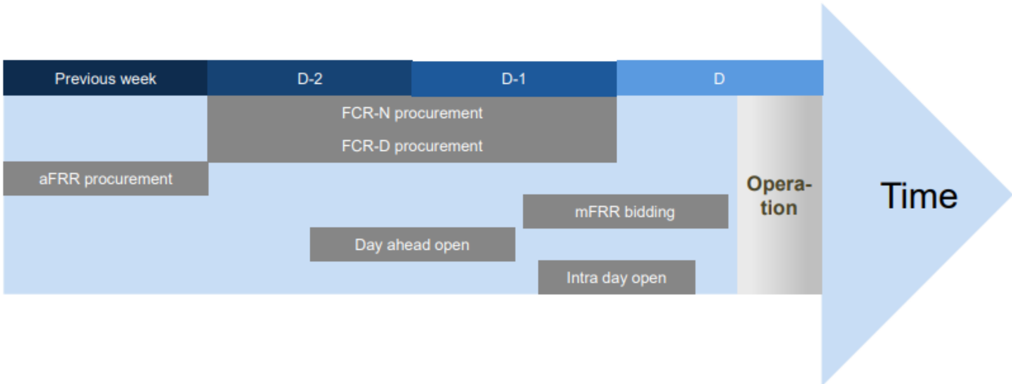

Figure 9: Timespan for the bidding and procurement of the different balancing markets in Sweden (Svenska Kraftnät, 2019a)

In addition, there are also the frequency regulating markets, which are procured to handle the momentaneous irregulates in the grid's frequency. The trading is done at latest 45 minutes before delivery time between SvK and the balancing responsibility parties which is explained further in Section 2.6.2 (Svenska Kraftnät, 2019b).

2.6.2 Balancing and frequency regulation

The electricity grid has to constantly uphold a balance between the consumption and production of electricity, with a perfect balance the frequency is at 50 Hz for the system. However, deviations between 49.9-50.1 Hz are within the acceptable levels, if these values are exceeded it could potentially damage the grid components.

The Electricity suppliers have to deliver the same amount of electricity as its consumer use according to the Electricity Act (Riksdagsförvaltningen, 2020). However, there are often irregularities between the supply and the demand, therefore, the electricity suppliers also have the balancing responsibility to fulfill this obligation.

The system responsibility to ensure that there is a constant balance in the grid system lies on Svk and was decided by the Swedish government. Svk does not balance the irregularities by its own production or load units, rather, they buy regulating power as ancillary services from the balance responsibles which SvK then activates. The energy producers that misjudged their consumption or production and caused the imbalance has to pay SvK the cost of restoring it, called the balance settlement.

The regulating reserves can either be up regulating or down regulating. If the frequency goes below 50 Hz the up regulating reserves are activated which is done either by increasing the electricity production or by decreasing the consumption. If the frequency goes above 50 Hz, down regulating reserves are activated, which means that either the electricity production is decreased, or the consumption is increased.

2.6.3 Frequency reserves

The regulating frequency reserves are divided into three levels, primary, secondary and tertiary reserves and vary with endurance and speed.

The reserves are bid by the balancing parties on the capacity they can deliver for each hour, the bid is then activated chronologically from the lowest bid, with the renumeration for the balancing parties to be "pay-as-bid" (Svenska Kraftnät, 2016). The bids value is meant to reflect the operational cost of providing the reserves with some additional costs for the risk and margins for providing the reserve. Other than the capacity renumeration, the reserves FCR-N and aFRR are also remunerated when their bid is activated. The amount of renumeration depends on the volume activated needed to restore the frequency.

The minimum bid size for the different reserves are shown in Table 2. The reserves bidding timespan is the longest for mFRR which can be procured 14 days before being activated and can be altered to 45 minutes before activation. The aFRR is bid once a week for the upcoming week and FCR is procured one to two days before being activated (Svenska Kraftnät, 2019b). The timespan for the frequency reserves are shown in Figure 9. More information on typically procured volumes can be found in Table 15 of Section 8.1.1.

The automatic reserves are today only regulated by hydropower and so the requirements are also catered for conditions suitable for that technology. Svenska Kraftnät does, however, acknowledge the need to restructure the balancing markets and conditions to include other technologies such as DER in order to follow the regulations given by the European Commission (Svenska Kraftnät, 2017). How the frequency deviates and is regulated by the reserves is shown in Figure 10.

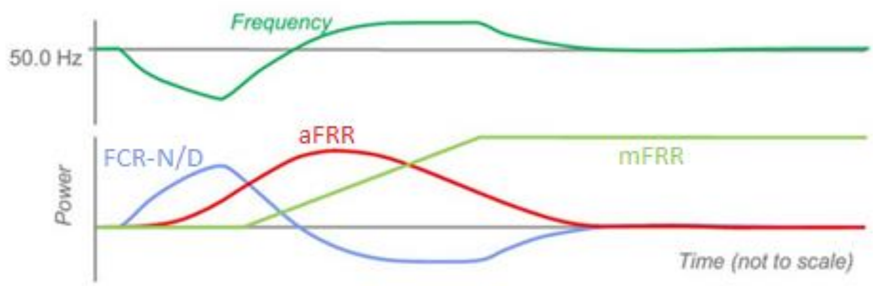

Figure 10: Timespan for the different activation and usages of frequency control (Eng et al., 2014)

The automatically activated reserves are divided into the primary and the secondary reserves. The primary reserves consist of FCR-N and FCR-D, and are first to activate during an imbalance, to make sure the frequency stays within the acceptable limit. These have the most rapid response and are activated automatically when the frequency deviates to the reserve's activation levels shown in Table 2. FCR-D is only activated during major imbalances of production losses. The primary reserves stabilize the frequency, but not necessarily to 50 Hz, the secondary reserve, aFRR is then activated to bring the frequency back to the nominal value. The final, manual reserve and also the tertiary reserve is called mFRR, and is activated to unload the aFRR and maintain the frequency at 50 Hz (Eng et al., 2014). The manual reserves are the slowest to activate and is used to bring the frequency back to the nominal value and to restore the automatic reserves. The timespan of when the reserves are activated, and the frequency deviation is shown in figure 4 and the actual response times are shown in Table 2.

Table 2: Frequency reserves overview (Svenska Kraftnät, 2019c, 2019d, 2019a, 2019e, 2019b)

	FCR-N	**FCR-D**	**aFRR**	**mFRR**
Activation upon [Hz]	Frequency Deviation within 49.9-50.1	Frequency below 49.9 to 49.5	Deviation from 50 Hz remaining from FCR-N and/or FCR-D	Deviation from 49.90 – 50.1 Hz
Response time	63% within 60s + 100% within 3 min	50% within 5s and 100% within 30s	100% within 120s	100% within 15 min (longer time is allowed)
Time frame for bidding their capacity	One or two days prior to operation	One or two days prior to operation	Once weekly for the following week	From 14 days to 45 min prior to operating hour
Min required active time	1 hour	1 hour	1 hour (max 3 hours)	Deactivated end of hour or until notified by SvK
Activates	Automatic	Automatic	Automatic	Manually by SvK
Symmetric production (Up and/or Down)	Yes	No (only Up)	Yes (one direction at a time)	Yes
Min Bid size [MW]	0.1	0.1	5	10 (5 in SE4)
Required national capacity [MW]	227	427	150	Unlimited
Remuneration	Capacity: Pay as bid Energy: In accordance to price of upward and downward regulation	Capacity: Pay as bid	Capacity: Pay as bid. Energy: In accordance to price of upward and downward regulation	Energy: In accordance to price of upward and downward regulation

Primary frequency reserves

The primary reserves are called the Frequency Containment Reserves and is separated in Normal and Disturbed (FCR-N and FCR-D), FCR-D is only activated when the frequency deviates more than the acceptable frequency limits. The FCR are automatic reserves which are the first to be activated and prevent the frequency change further. They are activated automatically by the grid frequency, but at different deviations, shown in Table 2. FCR-N is activated during minor changes in frequency from the range 49.9-50.1 Hz and is symmetric meaning it can regulate both up and down. FCR-D is only regulating up and is activated during larger frequency deviations where there are operational disturbances, between 49.9-49.5 Hz. The primary reserves have the shortest response time to an imbalance, this is due to them being the first reserves to be activated (Svenska Kraftnät, 2019d). FCR-N should be activated to 63% in 60 seconds and 100% within three minutes. FCR-D is even faster as it is used when the production units are disturbed with 50% activated in five seconds and fully activated within 30 seconds. The national required capacity procured for each hour is 227 for FCR-N and 427 for FCR-D in 2018.

2.6.4 Secondary reserve

The automatic Frequency Restoration Reserve (aFRR) is the second reserve to activate and therefore the response time is also longer than the primary reserves, it needs to be activated within 120 seconds. aFRR unloads the FCR so that they be ready for the next frequency deviation and also bring the frequency back to the nominal value.

aFRR was only procured for certain hours in 2018, weekdays between the times 04-07 and 16-19, but is expected to be procured for all hours of the week from 2021 (Svenska Kraftnät, 2019f).

2.6.5 Tertiary reserve

The final reserve is the manual Frequency Restoration Reserve (mFRR), the purpose of this reserve is to unload the automatic reserves, so they are ready for the next disturbance and keep the frequency at the nominal value. It is activated manually by SvK and should be fully activated within 15 minutes but can take longer (Svenska Kraftnät, 2019d).

2.7 Energy storage characteristics and applications

Energy storage systems can be of various technologies, such as chemical, electrical, mechanical and thermal. This thesis focuses on Li-ion batteries as they are the most widely used technology within the DES for households as explained in Section 2.1.2. Li-ion batteries are categorized within the chemical energy storage.

2.7.1 Energy storage applications

What services BESS can provide is heavily dependent on how the power system is built, the legislation that applies to it and the power system market. These factors are constantly changing which means that the services provided also alter with time. Also, since all the services are essentially based on the act of the storage charging and discharging over a period of time, there are oftentimes no standard naming for the exact service between research papers and so different names can have the same meaning (Günter and Marinopoulos, 2016).

Some energy storage technologies are more suitable than others to provide grid services depending on their unique characteristics, such as the power it can discharge with. The Figure 11 below gives an indication on which technology is better suited for which scale and service, but according to the report from Sandia National Laboratories, it should be noted that these can change with time as each technology evolves and its prices decrease. It should therefore be noted that the figure is only meant to give a general idea of the technology's capacity (Sandia National Laboratories, 2015).

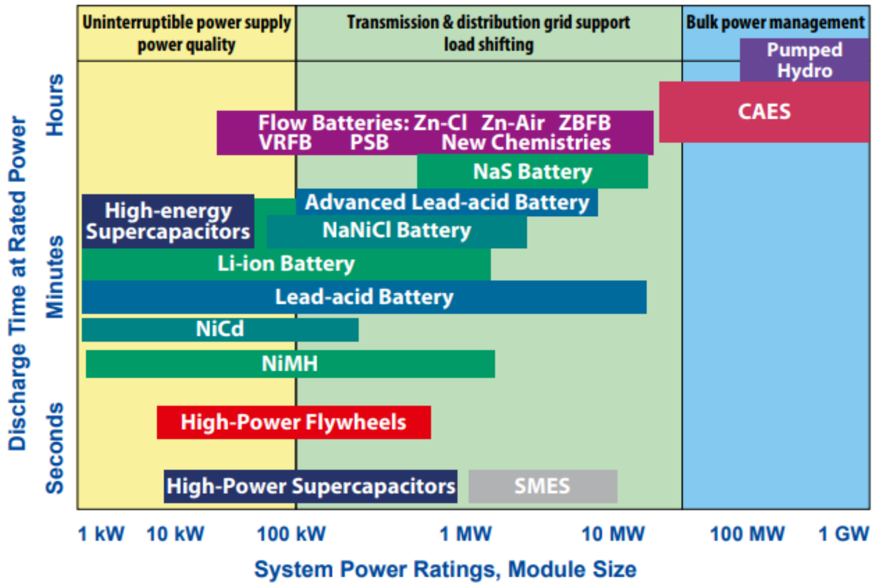

Figure 11: Energy storage technologies based on their power rating and discharge times at rated power (Sandia National Laboratories, 2015)

Figure 11 shows that storage technologies such as pumped hydro and compressed air energy density (CAES) are able to discharge high amount of power for a long duration of time and therefore are suitable for large power management services. High-power flywheels and high-power supercapacitors on the other hand have smaller discharge times with less power; and are more suitable for power supply and quality services or grid support. As seen from Figure 11, Li-ion batteries are suited for services where the discharging duration is from minutes to hours. This should however not be confused with the battery's response time which are in the time interval of milliseconds to seconds. Another advantage of Li-ion batteries is the high power and energy density combined with high efficiency (Das et al., 2018).

2.7.2 Key definitions of ESS

In order to understand the characteristics batteries some definitions are necessary to explain done below (IRENA, 2017).

- Energy: The capacity of the storage system, can also be considered to be the energy charged or discharged from the battery.
- Power: The rate of energy charges or discharged from the battery.
- Usable capacity: The amount of energy that can actually be discharged from the battery and be used.
- Installed capacity: The total amount of energy within the battery, batteries are often oversized as to not degrade the battery too much when discharging. Therefore, the usable capacity is larger than the usable capacity.
- State of Charge: The ratio of actual stored energy within the battery to the usable capacity of the battery.

3 Analysis method

To evaluate the mentioned case studies and answer the research questions, the following parameters self-consumption, self-sufficiency, total net present cost (NPC) and system payback time both discounted and simple.

3.1 Self-consumption

Self-consumption is defined as the solar electricity generated (E_{PV}) and consumed locally to the total electricity generated by the PV system (E_{Tot}) (Beck et al., 2016). Having a battery (E_{Batt}) in the system will increase the self-consumption as more of the PV generated electricity will be stored during excess generation and consumed locally during less generation. This parameter shows how much of the PV production is consumed locally and how having a battery can affect the system.

$$SC = \frac{E_{PV} + E_{Batt}}{E_{Tot}}$$

3.2 Self-sufficiency

The solar-sufficiency parameter shows the proportion of the load that is met by solar electricity (E_{PV} and E_{Batt}) divided by the total electrical load (E_{Demand}) (Cao, 2013). This is interesting to analyze when comparing to the base scenario with and without storage with the same demand.

$$SS = \frac{E_{PV} + E_{Batt}}{E_{Demand}}$$

3.3 Total net present cost (NPC)

The total net present cost (NPC) of a system is the present value for all the costs the system has over the project lifetime subtracted with the present value of all the revenue the system earns over the project lifetime, when taking the discount rate into account. It is an important parameter to use when comparing an investment.

The costs can be the capital cost, replacement costs, O&M costs, electricity bought from the grid and revenues can be the salvage value of the components at the end of the systems lifetime and the grid sales revenue made from selling excess electricity and provide frequency regulation (HOMER Energy, 2019a). The equation for NPC is shown below. The salvage value of the component is assumed as a linear depreciation to its lifetime and has the value of the investment cost of the module (HOMER Energy, 2019b)

$$NPC = I + \sum_{t=1}^{L} \frac{B_t + C_t}{(1+d)^t} + \frac{S_L}{(1+d)^L}$$

I – Initial capital cost of the system

L – Lifetime of project

B_t – Benefits from the system

C_t – Costs from the system

d – Discount rate

S_L – Salvage value

3.4 Payback time – Simple and Discounted

Another economic matric used is the payback time which calculated the amount of years the investment cost is recovered when compared to the base scenario with no investment (HOMER Energy, 2020). When installing a PV with a battery system an initial investment is done, these provide additional savings and income for each year. HOMER finds the year this cumulative income is equal to the investment cost. The pay-back period is calculated both simple and discounted. The simple payback time add the cumulative savings and income for each year and find the amount of years till it is payed back. The discounted payback time takes the discount rate of the project into account for each year. This parameter shows whether an investment is payed back within the project lifetime, how many years it takes and therefore if it is a valuable investment or not.

The simple payback time:

$$SPT = \frac{I_B}{S_B + R}$$

The discounted savings made throughout the project lifetime:

$$DS = \sum_{t=1}^{L} \frac{S_B + R}{(1 + d)^t}$$

The discounted payback time:

$$DPT = \frac{I_B}{DS}$$

SPT – Simple payback time

DS – Discounted savings

DPT – Discounted payback time

I_B – Initial capital cost of the PV and/or battery

L – Lifetime of project

R – Total revenue from frequency reserves

S_B – Annual saving from PV and/or battery

d – Discount rate

4 General methodology and assumptions

4.1 HOMER Grid

The modulating software HOMER Grid was used to calculate energy balance of PV and battery systems. HOMER stands for hybrid optimization of multiple energy resources and is developed by the National Renewable Energy Laboratory (NREL) which is intended to combine both the technical and economic aspects of an energy system. HOMER Grid focuses on PV together with storage components but also wind, CHP and backup generators can be added, and the software's main focus is to optimize the value of behind-the-meter systems (HOMER Energy, 2019c).

4.1.1 Dispatch strategy

The dispatch strategy of HOMER Grid calculates how the electrical load should be served for every hour by the power generation sources in the system. The software has 48 hours knowledge beforehand from the current time step of the following:

- Electric demand for each time step
- The electricity price and the electricity selling price
- PV production for each time step
- If power fee is included, the dispatch strategy also takes this into account by aiming to reduce the fee for each month (HOMER Energy, 2019d).

Based on this information the dispatch strategy optimizes how to best serve the load for the least cost for each time step. Having a battery in the system, the dispatch strategy also decides whether the battery should be charge or discharge to either the grid or the load for each time step.

The decision variable HOMER Grid optimizes for is to find the least NPC, dispatch strategy of the components and the power fee. For this study, the quantity of PV and battery sizing will be decided beforehand as the potential usage of the components is analyzed and not affected by todays cost of the components (HOMER Energy, 2019e).

The behind-the-meter services that are modeled in HOMER are explained in the next sections and are also shown in Figure 12.

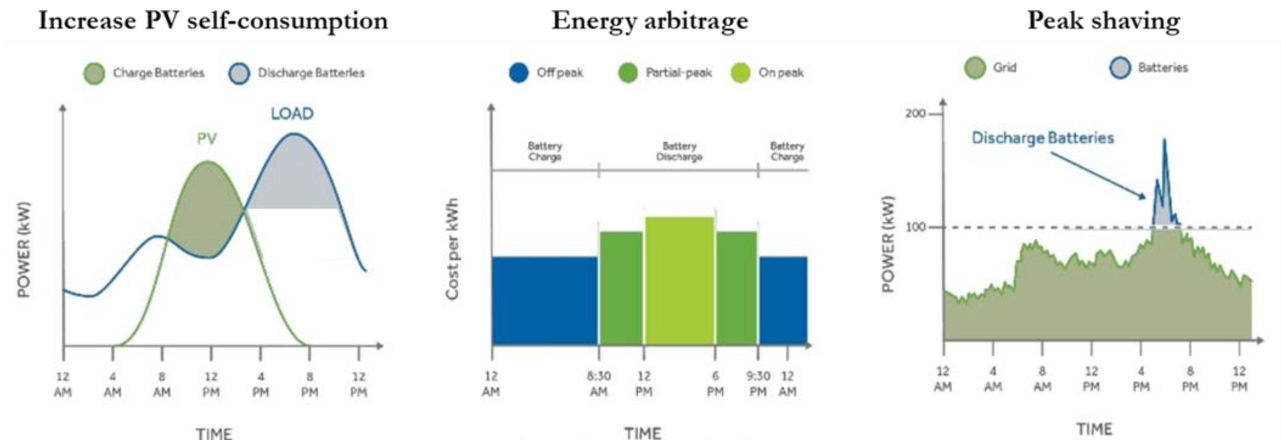

Figure 12: Behind-the-meter services (Nguyen, 2018)

4.1.2 Increase PV self-consumption

The battery aims at storing the excess solar electricity generated rather than it being fed to the grid and discharges it to the household's load as to increase the consumption of locally generated solar electricity. This ultimately reduces the electricity bought from the grid as well.

The software will maximize the PV self-consumption by keeping the state of charge of the battery low when it is anticipated that there will be excess solar electricity. The battery will charge from the excess electricity thereby increasing the self-consumption of the system.

4.1.3 Energy arbitrage

When the electricity price varies during the day, it can be cost beneficial to purchase and store electricity during hours the price is cheaper and use it during the more expensive hours or sell during high electricity selling prices. This service is useful for high volatility in the electricity price, for Swedish households the electricity market in which they can perform energy arbitrage is the spot day-ahead market with hourly price variations decided the day before. The price variations for the households come from the load fee and the spot price, as shown in Appendix A.

With HOMER Grid's dispatch strategy and the beforehand knowledge of the electricity prices, load and PV production, it can opt to charge the battery during these instances and perform energy arbitrage. If HOMER Grid has the option to use the stored electricity to meet the load or to sell it to the grid, it chooses the most cost profitable option (HOMER Energy, 2019d).

4.1.4 Peak shaving

The battery reduces the peak power consumption of the household by discharging during that time in order to avoid the spike in consumption. This reduces the strain on the grid during peak hours. The economic benefits for the household to provide this service is through the price structure from the grid owners. If households also have a power fee that that influences the payment to the grid operator. This power fee is generally higher during peak hours, creating an incentive for the batteries to discharge and generate savings and is explained further in Section 4.2.7.2.

With a power fee included in the electricity price, the software will find a monthly demand limit that utilizes the battery to limit the peak consumption to a certain level for each month while still meeting the load. The demand limit is also chosen as a trade-off between the operating cost of utilizing the battery as well as minimizing the power fee costs and finds the optimal limit (HOMER Energy, 2019d)

The load is also reduced on a larger scale, which is analyzed in the aggregated case studies. With the peak shaving function of HOMER Grid, the minimum electricity drawn from the grid is calculated monthly which reduces the load of the aggregated case studies.

4.2 Modelling process in HOMER Grid

The general methodology used for all case studies is gone through in this section as to not cause repetition in the individual methodologies of each case study in Sections 5 to 8.

4.2.1 System model

The model consists of PV, battery, the load as well as a grid connection. How these are connected in the system model is shown in Figure 13 below. For the case studies with multiple houses, the total load, PV production, inverter size and battery capacity are aggregated and modelled in a similar fashion.

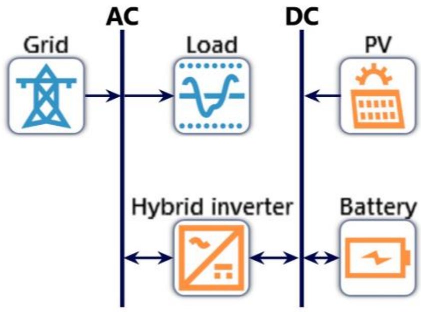

Figure 13: Components connection to the AC and DC bus

4.2.2 General

For the economic analysis a real discount rate, taking the inflation rate into consideration, of 3% was chosen. This percent is based on the expected required return on the investment for small houses made from analyzing different market players (Blomqvist and Unger, 2018). The project lifetime was assumed to be 15 years to mirror the assumed lifetime of the battery.

4.2.3 PV system

The module cost was assumed as the average value from 2018 of 14 600 SEK/kW_p as mentioned in Section 2.4.1. It is assumed that the VAT on the PV system and the capital subsidy given for the solar system take each other out, making it the same cost as the actual system cost.

The lifetime was assumed to be 30 years (Lindahl et al., 2019). The sizing of the PV modules is 10 kW per household for this thesis study. The PV production values for each case study is taken from real measured values and are in AC, this means that the losses from the PV panels and the losses when converting from DC to AC are accounted for in the measured values used as input data for the model. The inverter losses mentioned in Section 4.2.4 are therefore not used for the PV panel in the model.

For the Single family house case and the National case, the PV production curve is taken as an average production of 400 installed PV systems around Sweden been sold by Vattenfall and who's on-line measurement have shown to have an annual production above 800 kWh/kW. The average of the 60 systems PV production curve is shown in Figure 14 below. An average of multiple buildings issued to capture the smoothing effect of geographically dispersed systems with a variety of orientations and tilts. The measured profile is assumed to produce 850 kWh/kW annually (Swedensol, 2020). Since the location of the households for both these cases is arbitrary, using an average PV profile from several sources was deemed to give the most correct. This curve is scaled to the assumed capacity of each case study.

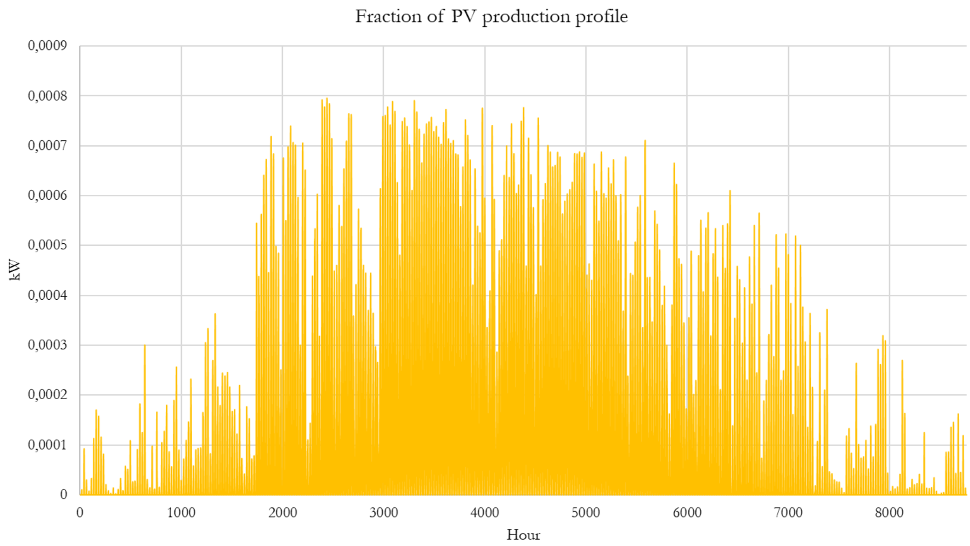

Figure 14: Fraction of the measured annual PV production during each hour of the year

For the Transformer overload case and the Energy community case studies the PV production profile was taken from a PV system nearby both cases study's location. The installed capacity of the PV system is 7.3 kW with an assumed annual production 7.4 kWh. The production curve for 2018 was altered for the periods no electricity was generated during the year with other years data. The altered PV production profile is shown in Figure 15. This curve and capacity were scaled for each respective case studies assumption of installed capacity.

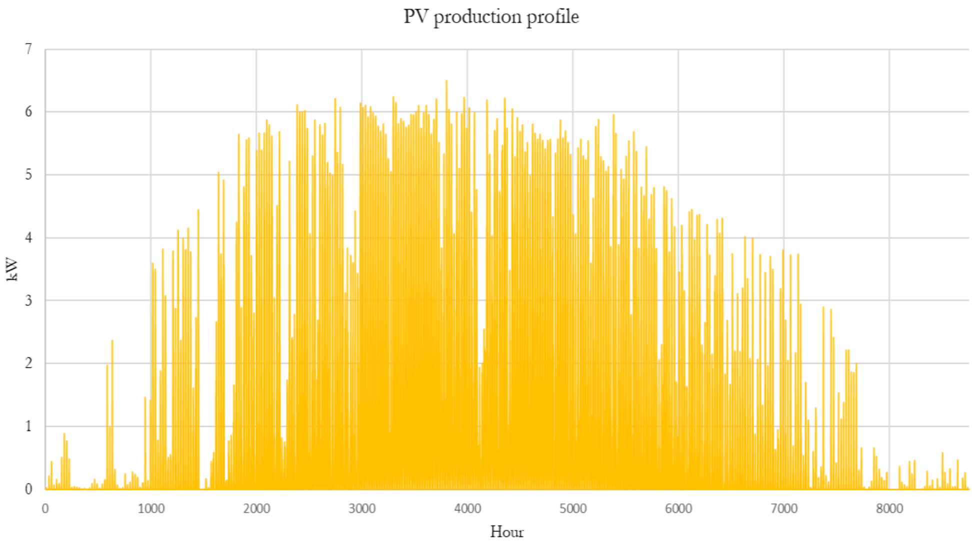

Figure 15: PV production profile for a PV system near Transformer overload and the Energy community case

4.2.4 Inverter

The inverter used is the RCT Power Inverter DC with an assumed yearly cost of 100 SEK/kW, which includes its investment cost and replacement cost. The lifetime of the inverter is assumed to be 15 years (Lindahl et al., 2019). The number of inverters will be optimized by the dispatch system for each case study.

The inverter (DC to AC) losses and rectifier (AC to DC) losses are taken from the technical specification sheet of the inverter and are used in the model (RCT Power, 2019a). The total efficiency cycle, also called the turn cycle efficiency is around 95% of the inverter, the assumed efficiencies are shown in Table 3. Based on the University HTW Berlins energy storage inspection, the RCT power was evaluated as one of the top performers with a system performance index of 92.6% for solar storage systems (RCT Power, 2020). The measured efficiencies of the inverter, PV to battery efficiency and the turn cycle efficiency is also shown in Table 3. Comparing the assumed values form the technical specification sheet with the measured values, the assumed efficiency used is higher than the measured efficiency but only with around 2%

Table 3: Inverter's assumed efficiency and measured efficiency

	Inverter	PV to battery	Rectifier loss	Turn cycle efficiency
Assumed efficiency	98.16%	N/A	96.24%	94.47%
Measured efficiency	96.3% - 96.5%[1]	97% - 97.5%[1]	-	92.6%

4.2.5 Battery

The battery chosen is the RCT Power Battery pack. The cost for buying the battery pack was based on the cost from the Vattenfall subsidy and wholesale electricity retailer Borås elhandel. Purchasing a battery with a capacity of 3.8 kWh and a control unit together with a PV system would make the battery cost of 16 000 SEK, including VAT and the battery subsidy. Assuming each household installed a battery size of 7.6 kWh, an increase of 3.8 kWh energy storage capacity gives an additional cost of 9 600 SEK. The total cost of the battery is then 25 600 SEK for the battery (Borås Elhandel, 2019).

The battery's specifications were taken from its specification sheets and are listed in Table 4 (RCT Power, 2019b). The assumed lifetime of the battery is set to 15 years.

Table 4: RCT battery specifications

Installed capacity	Usable capacity	Max charge/discharge current	Nominal voltage
7.68 kWh	6.91 kWh	20 A	307 V

No losses to the stored energy within the battery was assumed, as that would make the modelling of this component more complex.

4.2.6 Electric load

Based on the studies performed by the Swedish Energy Agency and Profu mentioned in Section 2.2 on the potential sites for PV systems in Sweden, it is concluded that households holds the highest potential. Therefore, this thesis aims at primarily focusing on decentralized consumers of single-family households. The load profile for these consumers for each of the case studies will be described in each case study individually.

4.2.7 Electricity price and sellback price for households

The total electricity bill households pay is divided into three parts, the bill consists of a grid contract, an electricity supply contract and energy tax (Konsumenternas Energimarknadsbyrå, 2020b). The grid contract is with the grid operator who is responsible for the power lines to the house and for measuring the electricity consumption. The electricity supplier provides the electricity to the house and can be chosen by the

[1] Span from 30-100% of nominal power

household. Finally, the bill includes the energy tax which is payed to the government and is usually included in the grid contract.

For this thesis, the electricity bill will depict a household whose grid operator and electricity supplier are Vattenfall. The assumed electricity cost for the year 2018 is shown in Appendix A. The fixed costs from both the electricity supply contract and the grid contract are neglected because they are paid regardless of installing a PV and battery system, therefore they are not considered. For simplicity, it is assumed that these costs and subsidies will be constant throughout the project lifetime.

4.2.7.1 Electricity supply contract

The electricity supply contract chosen for this study is with variable hourly electricity rate which follow the spot prices from Nord Pool spot day-ahead market (Nord Pool, 2020). This is assumed because the potential highs and lows of the electricity rate can provide the energy arbitrage service the energy storage will be analyzed for. The savings from producing solar electricity are also dependent on this price. The spot prices are taken from the SE 3 region of Sweden (Nord Pool, 2020). The supply contract also includes the electricity trading surcharge and the cost of green electricity certificate which are shown below Table 5 (SKM, 2020; Vattenfall, 2020a).

Table 5: Electricity supply contract costs

Average Nord Pool's spot price	~ 0.46 SEK/kWh
Electricity trading surcharge	0.04 SEK/kWh
Green electricity certificate	~ 0.15 SEK/kWh

4.2.7.2 Grid contract

The grid contract consists of a fixed grid charge depending on the fuse rate of the house and a variable grid charge. The fixed grid charge is payed annually independent of amount of used electricity and therefore is not considered. The purpose of the variable grid charge is to make the household reduce their demand during congested hours by having a higher rate during those hours. This charge can be divided into two parts, the load fee and the power fee. The load price is taken from the Vattenfall time tariff, T4, for a fuse rate of 20 A (Vattenfall, 2020b). Instead of a constant transfer fee of 0.34 kSEK/kWh customer can opt for a higher load fee during the congestion hours 06-22 on the weekdays, Monday to Friday for the months November to March and be compensated with a lower fee at other times, as shown in Table 6 below.

Table 6: Load prices for 20A fuse rating

Peak load fee	0.7 SEK/kWh
Load fee	0.185 SEK/kWh

For analyzing the demand rate charges and the battery's value for peak shaving the power fee of the N3T grid contract from Vattenfall are used (Vattenfall, 2020b). This grid contract is used for consumers with a fuse rating of 63 A or higher. As Vattenfall currently does not have demand charges for fuse rates lower than 63 A, these costs are used. The grid contract of N3T from Vattenfall is shown in Table 7.

Table 7: Power fee N3T contract

Peak power fee	92.5 SEK/kW, month
Power fee	37.5 SEK/kW, month

4.2.7.3 Energy tax and VAT

Lastly, the Energy tax of 2018 and VAT which is taken on the whole electricity bill and are shown in Table 7 above (Konsumenternas Energimarknadsbyrå, 2019; Skatteverket, 2020a).

Table 8: Energy tax and VAT

Energy tax	0.331 SEK/kWh
VAT	25%

4.2.7.4 Electricity selling price

The values for the incentives available for prosumers explained in Section 2.3 which are used for this thesis are shown in Table 9 below. No VAT is taken on the sellback prices as the renumeration is not expected to exceed a saving of 30 000 SEK/year. The household will generate a revenue through this selling price by feeding its excess solar electricity back into the grid (Nord Pool, 2020; Skatteverket, 2020b; SKM, 2020; Svensk Solenergi, 2018; Vattenfall, 2018).

Table 9: Electricity sellback to the grid prices

Average Nord Pool's spot price	~ 0.46 SEK/kWh
Tax credit	0.6 SEK/kWh
Grid compensation from Vattenfall	0.06 SEK/kWh
Green electricity certificate	~ 0.15 SEK/kWh
Guarantees of origin	~ 0.01 SEK/kWh

4.3 Frequency regulation

As mentioned in Section 2.7, Li-ion batteries characteristics of having fast response times, high efficiency and high controllability makes them suitable for providing frequency regulation faster than other conventional methods such as hydropower today (Tian et al., 2018).

The frequency regulation service will only be modelled for the national scale, and the batteries will for the duration it provides the reserves meet the historical values of 2018 the different reserves. Since HOMER Grid does not have a specific function to model this, it is simulated in Microsoft Excel ignoring losses. The methodology for this is explained further in the National case study, Section 8.2.2.

5 Single family house case

In the Single family house case study, the services PV and battery can provide to a one household will be analyzed. The services analyzed are energy arbitrage, peak shaving and increasing the self-consumption. This case study is aimed to show the value a single battery can provide for an individual household and whether it is economical to invest in one.

5.1 Methodology for Single family house case

The Single family household's system build in HOMER Grid is similar to configuration shown Figure 13, the general assumption of the components are explained in Section 4.2. The PV production profile is taken as shown in Figure 14 above with a PV sizing of 10 kW.

5.1.1 Load profile

The load used for the Single family house is taken from a house located in central Sweden. The house has installed an air to water heat pump. The load data is taken from the year 2018 for the house and is shown in Figure 16 below

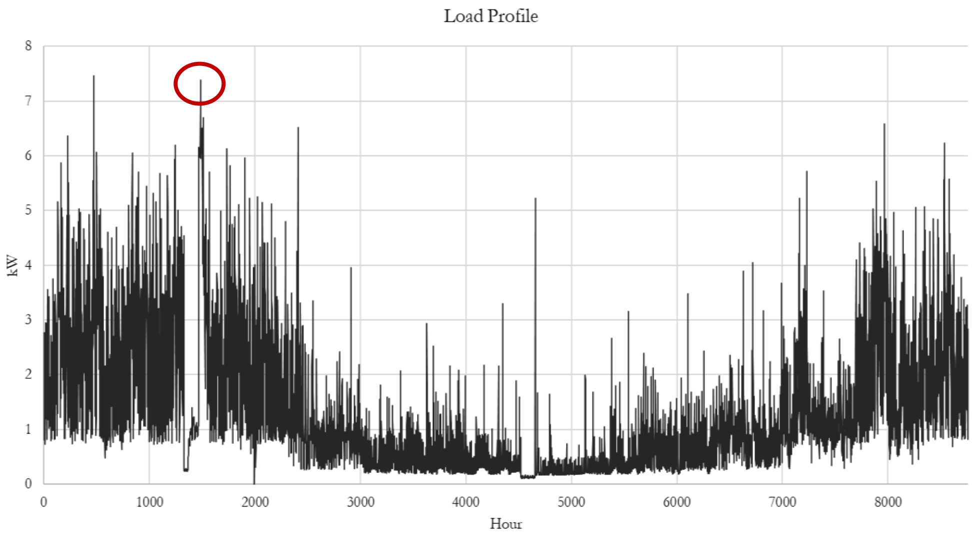

Figure 16: Load profile for Single family house case

Figure 16 shows that the load is generally higher during the winter and less during summer. This is true since the electricity consumption increases during the colder seasons. The load varies significantly throughout the year and the variations also increase during the colder periods of the year. There are also periods the electricity demand becomes close to zero, this is because the residents are away and have set a lower indoors temperature. The second largest peak and summer peak is right after such a stagnant period when hot water and house are heated back to normal temperatures, marked in the figure above.

5.1.2 Modelling process

The value of installing a PV system with and without a battery will be shown by modelling different scenarios for the initial load curve. These are then compared to the same system with a reference scenario with only a grid connection. The comparison will include an energy and economic analysis.

The first scenario is PV scenario with only a PV system installed for the household. This will show how the electricity fed and drawn for the household and the PV self-consumption would be with only a PV system installed.

The battery installation together with PV will be modelled in two separate scenarios where the services analyzed differ. The IE scenario will analyze the value of Increasing the self-consumption and Energy arbitrage, where I stands for Increase self-consumption and E for energy arbitrage. This scenario is modelled for the case when the electricity supply contract does not include the power fee, as many grid utilities do not have this in their grid contract. The final scenario is the IEP scenario where the additional service of peak shaving will also be combined with the previous services of increasing the self-consumption and energy arbitrage.

5.2 Results and discussion for Single family house case

The energy flow will be shown in detail for two days of summer and winter for the modelled year. The year is divided into these two periods depending on the times the grid contract has the peak load and the peak power fee as shown in Table 6 and Table 7 above.

The energy flow for the scenarios for a whole year can be seen in Appendix A, excluding the reference grid scenario.

5.2.1 PV scenario

Two typical days for both Winter and Summer are shown in Figure 17 to show how the load and PV production profile looks like.

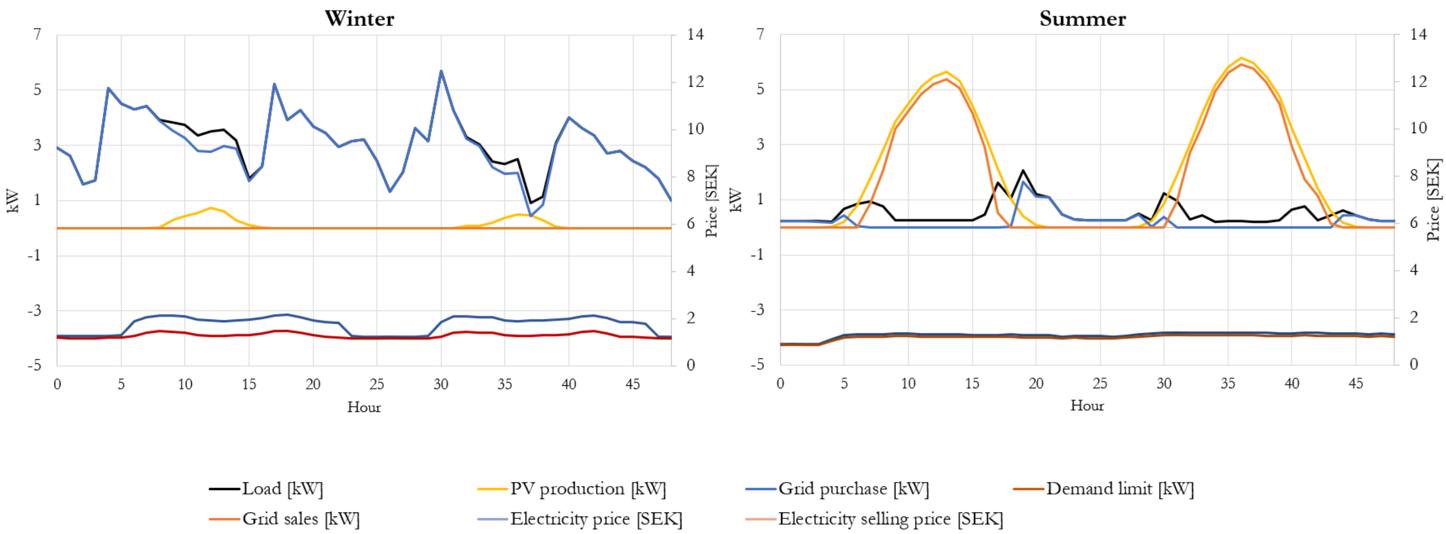

Figure 17: PV scenario profile for Winter (left) and Summer (right) for Single family house case

The black curve represents the electricity load of the household and shows that there are normally two peaks during the day. The first one comes in the early morning, around 06:00 and the second one in the evening beginning at 17:00 for both seasons, but with higher magnitude during winter. The electricity consumption of the two seasons, the blue curve, shows that for winter times almost all of the electric load is met through electricity drawn from the grid. The PV production, shown as the yellow curve, also goes to meeting the load during wintertime. During summer, the solar production exceeds the load it is fed to the grid which is shown as the orange curve. This is because the majority of the solar production occurs during the middle of the day when load of the house is less. The electricity price and electricity selling price are also shown in the figure, where during winter the price increases during the day due to the peak load fee being in affect from 06-22. During the summer the variation in both selling and purchasing electricity is less varied as shown in right of the Figure 17.

5.2.2 Battery IE scenario

With the IE scenario with both a PV and battery installed, the services of energy arbitrage and increasing self-consumption are analyzed and there is no power fee. Two typical days of winter and summer are shown in Figure 18.

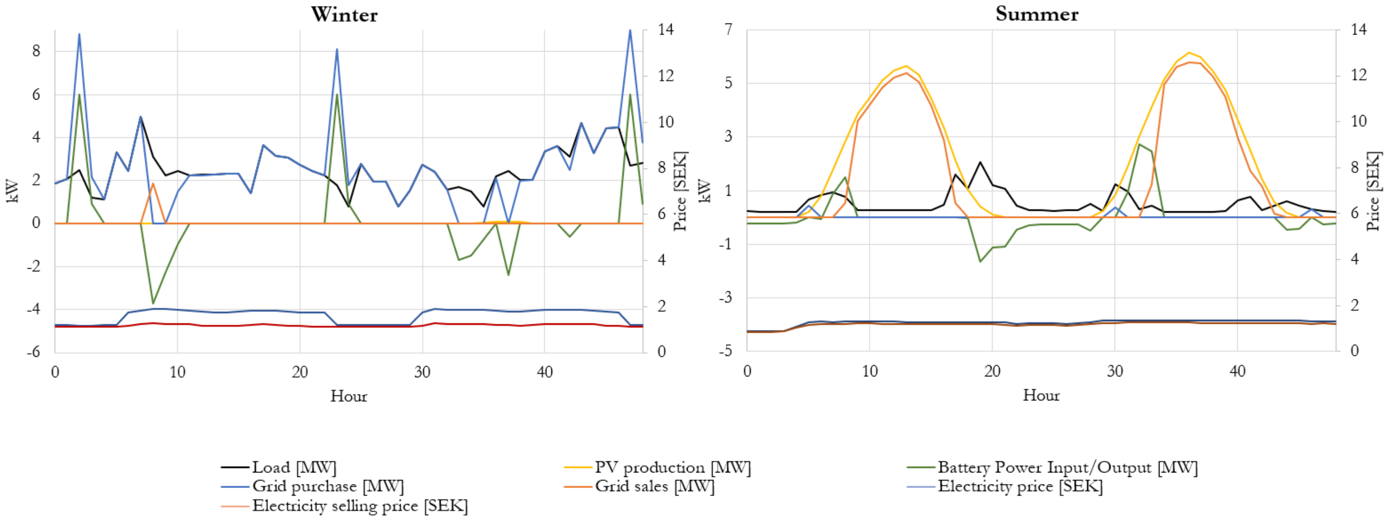

Figure 18: PV + Battery IE scenario profile for Winter (left) and Summer (right) for Single family house case

Between performing both arbitrage and increase the PV self-consumption, it can be seen in Figure 18 that the battery is mainly engaging in arbitrage during winter. It charges during load fee hours usually right after the peak load fee ends, at around 23:00 and discharges during peak load hours as can be seen in Figure 18. The hour of discharge is usually when the electricity price is the highest during the day. Since the battery is not limited to any power rate it can draw from the grid, the battery opts to charge almost to 100% during a single hour.

During Summer, the battery mainly charges from the excess PV production, and discharges when solar electricity is not enough to meet the load. The battery has enough capacity to meet the load during the night since the load is quite low during summer.

The battery discharge and charge hours are only affected by the variations of the electricity supply contract and the load fee from the grid contract explained in Section 4.2.7 for the IE scenario. Due to the battery often charging from than the grid during wintertime, the electricity consumption increases at night, usually right when the peak load fee ends. The strain on the grid is certainly reduced during the more congested hours of the winter days, however, the grid is strained to higher levels during the night than before, as can be seen from the large charging peaks in Figure 18. This increases the monthly peak of electricity drawn from the grid compared to the PV scenario, shown in Figure 20. The load fee, with the intention to reduce the strain on the grid, is in actuality furthering it. For the batteries to not create these peaks during the winter, other incentives than the load fee will be necessary.

5.2.3 PV + Battery IEP Scenario

In this scenario all household services: energy arbitrage, peak shaving and increasing the house self-consumption are analyzed. How the battery acts for two typical winter and summer days are shown in Figure 19 below.

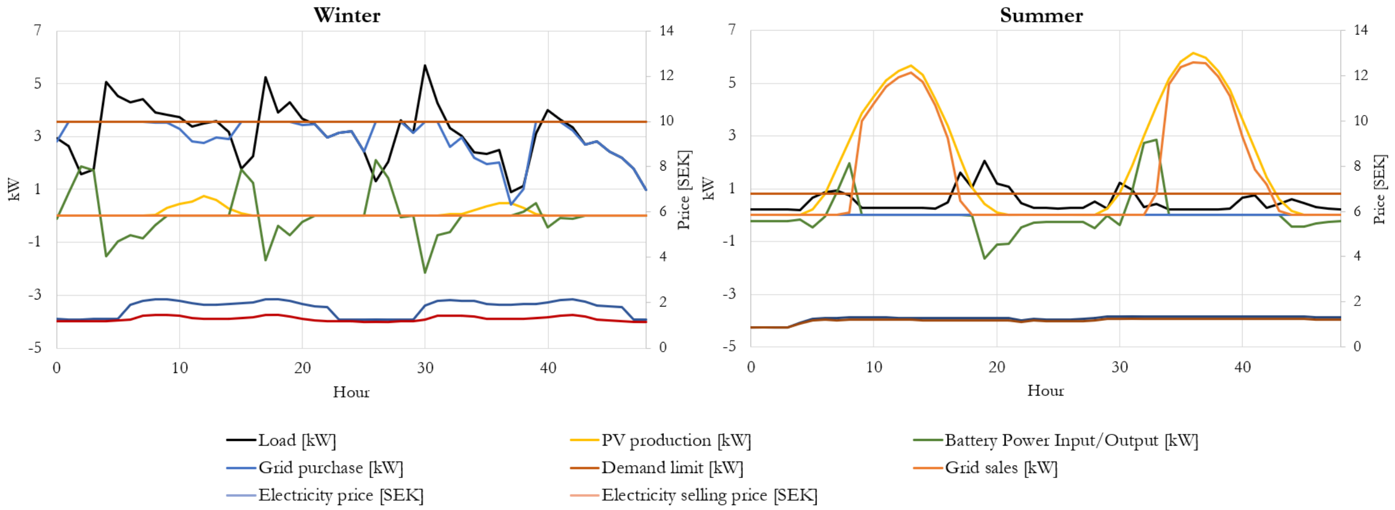

Figure 19: PV + Battery IEP scenario profile for Winter (left) and Summer (right) for Single family house case

It can be seen from the winter days on the left of Figure 19 that the battery provides both energy arbitrage and peak shaving simultaneously. The battery charges for the majority of times, during cheaper electricity hours after 22:00 and discharges during the peak load hours of the day, usually in the morning and evening peaks. The peak limit, also named demand limit, for the month is shown by the red curve. The battery may even charge once again during the day prior to the evening peak hours as to reduce the load again during winter in order to reduce the monthly peak power fee. This is due to purchasing electricity with a high load fee is still cheaper than paying a higher power fee for that month. The battery also decreases the peaks of the summer months when there is not enough solar electricity production to meet the load.

During the summer the battery increases the self-consumption of solar electricity and peak shaves as well, this is shown in Figure 19 where the electricity drawn from the grid does not go exceed the power limit, the red curve. By utilizing the battery's capacity efficiently, almost no external electricity is needed to meet the electricity load.

Overall, for both the season the battery discharging hours are more directed to the peak hours of the electricity consumption, effectively decreasing the electricity costs of the house.

5.2.4 Energy and Economical Analysis for Single family house case

The peak demand for all scenarios is shown in Figure 20. By installing only PV, the peaks are decreased for a few months as the PV production is generally not during the peak hours. From the IE scenario, it shows that the battery increases the monthly peaks when no power fee is in effect. For the IEP scenario however, it shows that the overall peaks were reduced with a battery as it focused on peak shaving.

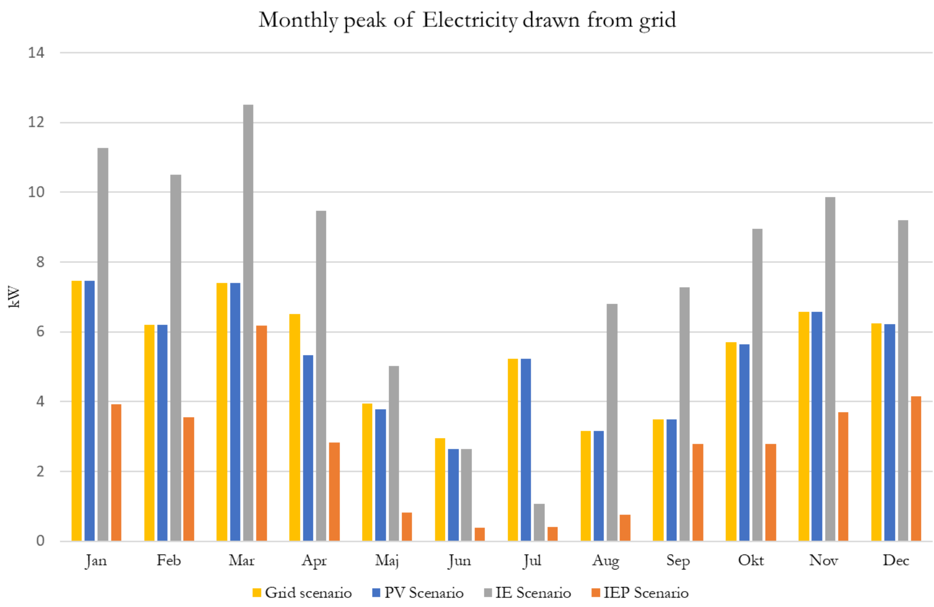

Figure 20: Monthly peaks of electricity drawn for all scenarios for Single family house case

The energy values for each scenario is shown in Table 10. By installing a PV, the purchase of electricity decreases for the household, but as electricity is also being produces locally and sold to the grid, the total transmission is increased to 15%. This means that the yearly load on the grid increases when taking both electricity to and from the grid. By installing a battery, the strain on the grid is reduced for both scenarios with the largest decrease for the IEP scenario. This shows that by having a battery the burden on the grid is lessened. The PV self-consumption and the self-sufficiency of the house increases also by having a battery and the most for the IEP scenario.

Table 10: Energy analysis for Single family household case

	Drawn from Grid [MWh]	Fed to grid [MWh]	Total transmission [MWh]	Transmission change [%]	PV Self-consumption [%]	Self-sufficiency [%]
Grid scenario	11.1	0	11.1	-	-	-
PV scenario	8.9	6.3	15.2	37	25.7	19.8
PV + Battery IE scenario	8.1	5.5	13.6	23	39.6	30.4
PV + Battery IEP scenario	7.9	5.3	13.2	15	41	31.5

The savings made for the scenarios are shown in Table 11. By only PV installed, the highest savings are from increasing the self-consumption and selling excess electricity which are both included in electricity charge savings. Peak shaving also provide savings for the PV scenario due to some of the solar electricity being generated at peak hours which reduced the power fee for certain months. However, due to the non-controllable nature of solar electricity this saving can vary significantly depending on whether the load coincide with solar production or not.

The investment cost is payed back in around 13 years not taking the discount rate into account and little more than 14 years including it. This shows that this is an attractive investment with the current prices. This also shows with the NPC of the scenario being cheaper than the grid scenario where the whole system cost becomes cheaper.

Table 11: Economic analysis Single family household case

	Electricity charge savings [SEK]	Peak shaving savings [SEK]	Annual savings [SEK]	Simple payback time [yr]	NPC [kSEK]	Discounted payback time [yr]
Grid only scenario	-	-	-	-	257	-
PV scenario	11 733	142	11 874	12.3	221	14.2
PV + Battery IE scenario	12 212	-	12 212	14	272	14.6
PV +Battery IEP scenario	12 175	1 756	13 931	12.3	222	14.3

Including a battery to this system, the electricity charge savings are higher than the PV scenario, this is due to energy arbitrage savings. Between the battery scenarios, the electricity charge savings are higher for the IE scenario than for IEP. This is because the battery could fully charge on the cheapest hour of a day without being limited by a power fee, as explained in Section 5.2.2. However, by having a battery only perform energy arbitrage the simple payback time and discounted payback time increases even though it still is within the project lifetime frame. The total cost of the system also increases to 272, around 15 kSEK more than the grid scenario. This means that the investment in PV and battery is not attractive if the battery only performs energy arbitrage and increases the self-consumption of PV. The NPC increases due to the higher monthly electricity consumption peak, as shown in Figure 20, resulting in a higher power fee.

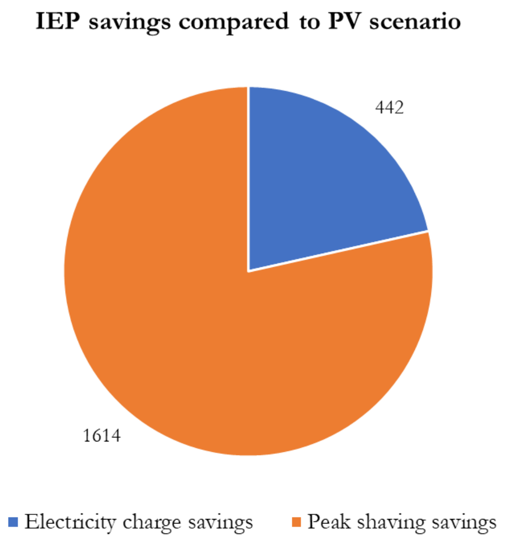

Figure 21: IEP scenario savings compared to PV scenario for Single family house case

The IEP scenario gives the highest savings for the household where all three services are combined. Comparing the IEP and the PV scenario, the electricity charge savings increases with 442 SEK per year and the peak shaving savings is increased with 1 614 SEK per year. This shows that the battery's highest savings come from decreasing the peak power demand, shown in Figure 20, ultimately reducing the power fee costs. The additional savings from installing a battery for the IEP scenario compared to the PV scenario are shown in Figure 21. The simple payback time is within the project lifetime within 13 years and discounted payback period is around 14 years.

This shows that an addition of a battery can be paid back within the project lifetime and is paid back faster with a power fee in affect.

When comparing the NPC of the IEP scenario with the PV scenario, it has increased. The reason for this is that the additional investment cost of the battery increases the overall cost of the system. Just the battery's discounted payback time is around 15.8 years. Due to the relatively high income from selling electricity to the grid there is little economic gain from increased self-consumption, meaning that the investment cost of the battery is not covered by the savings made from energy arbitrage and peak shaving for either the IE or IEP scenario.

It is also important to note that these results are for this individual house load, the economical and energy analysis can vary significantly depending on the load profile and the annual consumption of the house.

6 Overloaded Transformer case

When a transformer becomes loaded above its nameplate rating for a longer duration of time, it strains the transformer, reducing its lifetime. One solution is to reduce the peaks that overload the transformer by having an energy storage discharging during those peak times. This can be considered as a service that defers the transformers investment, as the transformer would not need to be replaced as often. This case study will analyze how much of the load can be mitigated by aggregating the household's batteries together and using them during the peak load hours.

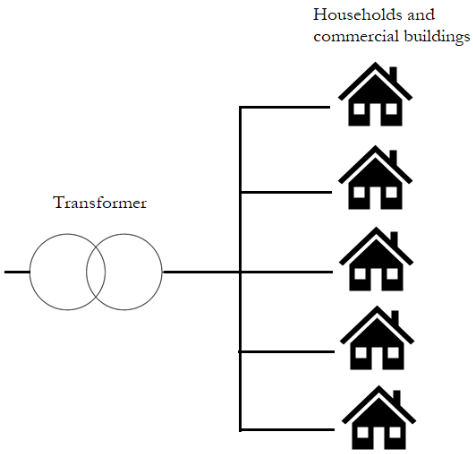

Figure 22: System layout for the Transformer overload case

The transformer used in this case study is located in central Sweden with 12 consumers connected to it. The users are mainly houses, both permanent residents and summer houses, and commercial buildings. Summer houses are residentials which are mostly occupied during holidays and weekends. Today, the consumers located at this transformer do not have a PV system nor a battery installed. The nameplate apparent power of the transformer is 100 kVA. A conceptual system layout for the transformer is shown in Figure 22.

6.1 Methodology for Transformer overload case

In order to calculate the rated power of the transformer the equation below is used. The power factor is assumed to be 0.99.

$$S = \frac{P}{\cos\varphi}$$

S – Rated Power [VA]

P – Power [W]

$\cos\varphi$ – Power factor

6.1.1 Assumed installations of PV and Battery systems

In order to analyze what value these consumers could provide if they were to install a battery an assumption was made on what share of these consumers could have a PV and battery system installed. The total value of PV and battery capacity that could exist are then aggregated to one large capacity value for both technologies. This meant the transformer could be modelled in a similar fashion as the single family's system with a PV and battery component, only larger in capacity size.

The assumption on how large share of these consumers would opt to install a PV system and also a battery was based on trying to find the best case where the majority of the consumers were to install both the components and is shown in Table 12. It was assumed that every other permanent house would install a PV system. Following the trend of Germany where half of the households who install a PV system also install a battery, the same assumption was made for the permanent residents. Since the residents of the summer houses only reside in these houses during seasonal periods, a lesser share of PV system was assumed, and even smaller share had a battery. This is argued for because the subsidy schemes in Sweden penalizes feeding in more PV production than annual consumption making residents in summer houses less willing to install PV. It was assumed that all commercial buildings would have a PV system with a battery installed.

Table 12: Assumed percentages for Overloaded transformer case

Transformer	Consumer with PV installed	Consumer with Battery installed	Total PV capacity [kW]	Total Battery capacity [kWh]
Summer house	3	1	30	6.9
Permanent residents	5	5	50	35
Commercial buildings	4	4	40	27.6
Total	12 Units	10 Units	120	69.1

6.1.2 Load profile for Transformer overload

The load is taken for the households and commercial buildings located for the base year 2018. The transformer exceeds it maximum capacity the day 28/2 with a maximum rated power of 109.1 kW which is 109.2 kVA, marked in Figure 23. One contributing factor to the load increasing during this period is the winter school holiday, where presumably more residents live in their summer houses than usual. As can be seen from the singe family house case, the load profile here is also dependent on the ambient temperature, where during the colder periods of the year the load increases.

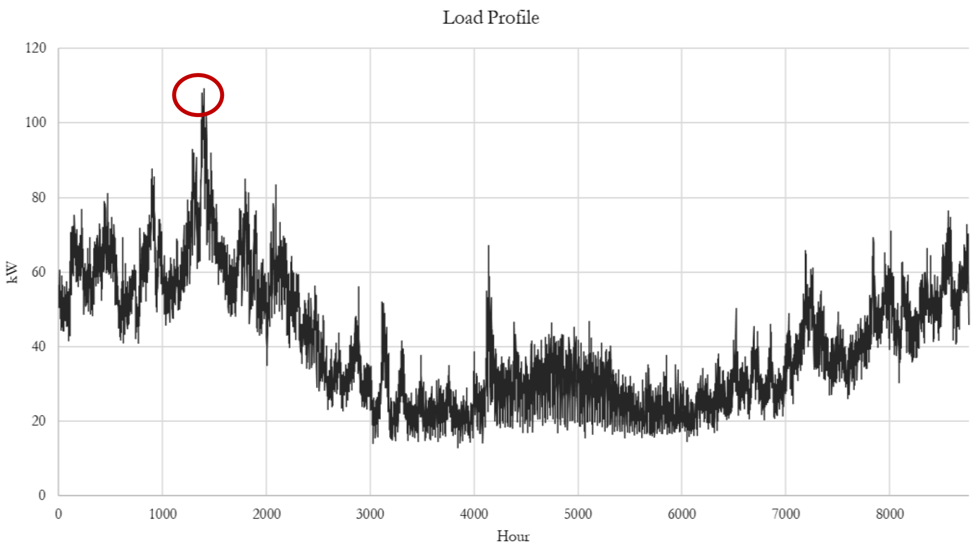

Figure 23: Load profile for Transformer overload case

6.1.3 Modelling process

To analyze what extent the decentralized batteries can reduce the load during the peak period, one scenario with a system consisting of both PV and battery is modelled. The services of increasing the self-consumption, energy arbitrage and peak shaving will be analyzed. This is because it is through the individual household's economical interest to gain savings by providing these services, that peak shaving that is studied for the transformer.

6.2 Results and discussion for Transformer overload case

Figure 24 shows the winter school holiday from 27/2 to 1/3 where the transformer is overloaded by the electricity load on the 28/2, as the black curve. The aggregated batteries charge, and discharge power is shown in green, where it is charging with positive values and discharging with negative values. The electricity drawn from the grid is shown as the blue curve and shows that the battery is sometimes charging by drawing electricity from the grid and sometimes by the PV production, the yellow curve. The figure shows that the battery charges by the PV production prior to the peak load and discharges to reduce the load, highlighted in the figure. Aggregating the batteries, the peak of 109.1 kW is reduced to a rated power of 96.9 kW, a reduction of 12 kW. This reduces the power to 97 kVA, reducing it to below the max capacity the transformer could withstand.

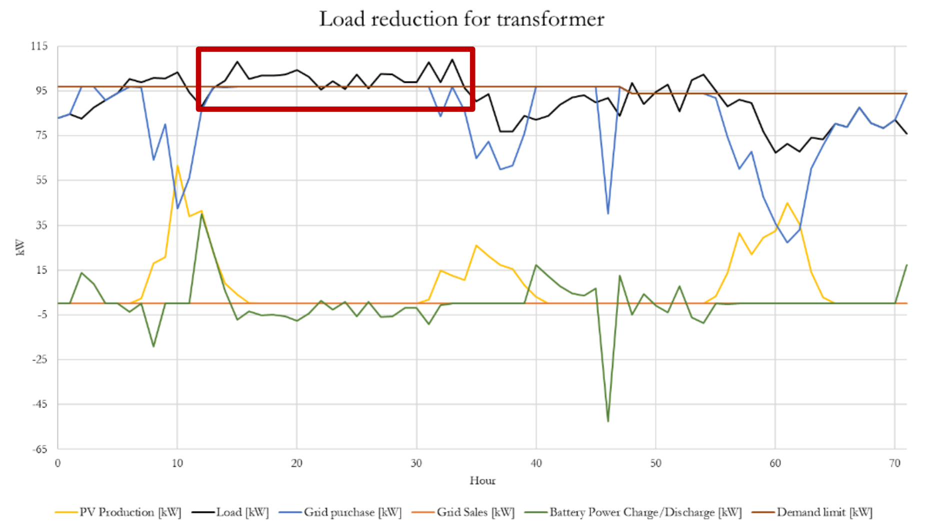

Figure 24: Battery dispatch for Transformer overload case for three winter days

The power reduced during the peak hours is only about one fifth of the peak power (kW) the installed batteries have, this is due the long duration of the overload. Aggregating the load of multiple users will create a peak period over several hours, as opposed to a single house with sharper hourly load variations, as shown in Figure 16 for an individual house. With sharper loads, the battery could meet the peak hour and recharge before the next peak load as explained in Section 5.2.3. This shows that individual batteries are a good solution for sharper peaks but with the aggregated load of multiple users, the decentralized batteries do not have enough capacity to reduce the peaks significantly. Thus, a larger capacity compared to peak power is required to make the same peak shaving as for a single household.

The annual energy flow for the transformer overload case is shown in Appendix C.

7 Energy community case on an Island

In order to analyze the services for both the households and the distribution grid, this case study is used where an energy community on an island is analyzed. The island is located in central Sweden with around 200 grid customers consisting of houses, both permanent and summer houses, and commercial buildings. The energy community on the island consists of the houses that have both PV and an energy storage installed, so that they can provide the services. The majority of the consumers are summer houses, where the residents only visit the island during holidays and weekends. For the rest of the consumers it is assumed that around 40 are permanent houses, where residents live all year long, and 10 consumers are commercial buildings such as convenience stores and smaller industries. Today, only few of the households have PV systems installed on the island. The system layout of the case study is shown in Figure 25 where it is assumed that some of the houses install PV and a PV and battery system.

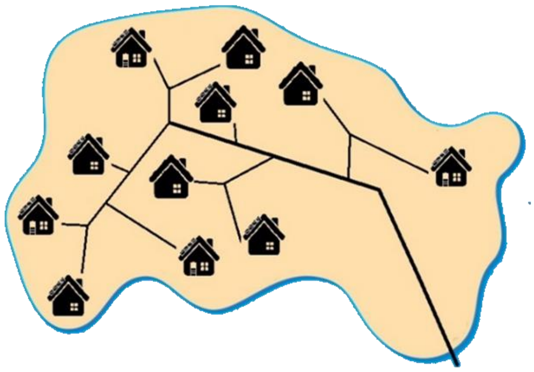

Figure 25: System layout for Island case (Pngitem, 2020; Vecteezy, 2020)

The household services are energy arbitrage, peak shaving, increasing the self-consumption of solar electricity and for the distribution grid it is analyzed how much of the load is reduced for the year.

7.1 Methodology for the Energy community case

7.1.1 Assumed installations of PV and Battery

To analyze the amount of load reduction that can be achieved for the energy community, first an assumption was made on what share of these consumers would install a PV system with and without a battery is done. This is inspired by the Swedish solar energy target and battery installation trend of Germany. The assumed share each consumer group has installed PV and battery is shown in Table 13.

Table 13: Assumed PV and battery unit percentages for the Energy community case

Energy community case	Consumer PV installed	Consumer Battery installed	Total PV capacity [kW]	Total Battery capacity [kWh]
Summer house	35	18	350	125.8
Permanent residents	20	20	200	138.2
Commercial buildings	10	10	100	69.1
Total	65 Units	48 Units	650	333.1

It was assumed that every other permanent house would install a PV system with battery. Since the summer houses are mainly occupied during seasonal periods, a lesser share of PV system was assumed. This is argued for that it is assumed that not all such residents would not be as willing to install a battery for their house to increase their self-consumption. It was assumed that all commercial buildings would have a PV system with a battery installed, with the same capacity size as houses.

To model the impact the energy community's battery units would have on the distribution grid, the total capacity of the batteries is aggregated to become one large battery which is then modelled as one component on HOMER Grid. This was also done for the assumed PV capacity for the energy community.

7.1.2 Load profile for Energy community case

The load profile is taken for the energy community which consists of consumers that are assumed to install both PV and battery system. This is because it is these household's electricity consumption that will change when providing the services analyzed. Comparing to the total load of the island, the energy community load as shown in Figure 26, contains 63% of the total load. This is because it is the permanent houses and commercial buildings that consume the largest amount of electricity on the island. All of the commercial buildings are assumed to have both PV and battery and half of the permanent houses load is taken with since they have the components as well and therefore are taken in this analysis.

The load profile for these consumers are taken for the year 2018 and is shown in Figure 26. The peaks of the electricity consumption are largely during the weekends and certain holidays due to the majority of residents of the seasonal houses occupy their houses. The peaks shown in Figure 26 can directly be linked to holidays such as the highlighted peak in the figure is around midsummers day, the 23rd June 2018.

The figure below shows the load is the highest during the periods with low temperature at the beginning and end of the year, causing the highest strain on the grid.

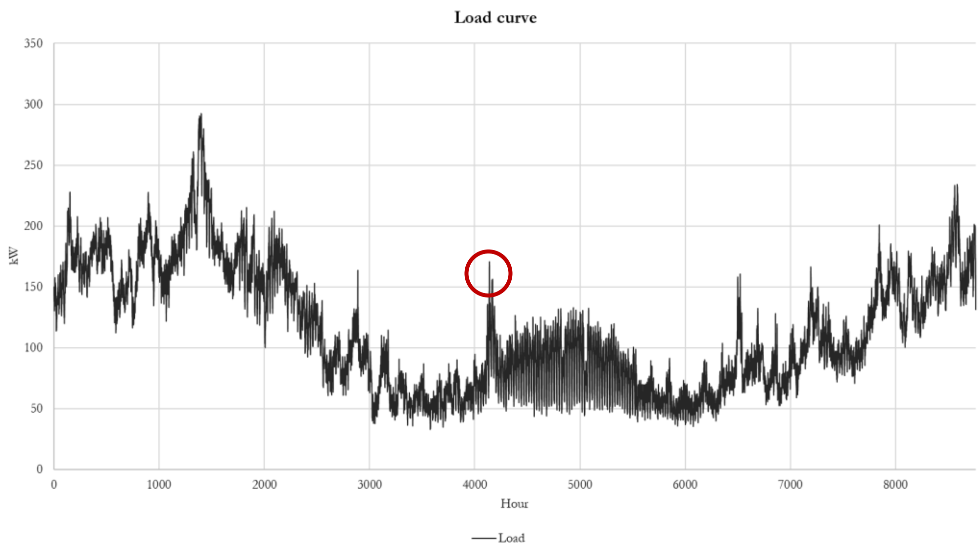

Figure 26: Load profile for Energy community case

7.1.3 Modelling process

In order to analyze the value for the energy community when installing a PV system with and without a battery two, scenarios are modelled which are then compared to the base scenario of only a grid connection The PV scenario will study the energy and economical value of a PV system. The PV + Battery IEP scenario is modelled to show the added value of installing a battery with the PV system for the energy community. The household services the batteries will perform are to increase the PV self-consumption, energy arbitrage and peak shaving. The system modelled in HOMER will aggregate the total PV and battery capacity into one large component, so that the system looks like in Figure 13. As the components are aggregated, the total load reduction of the energy community can be studied for both scenarios as well.

7.2 Results and discussion for Energy community case

Two typical days for both summer and winter are chosen to portrait how the electricity load, PV production and grid transmission vary with the scenarios. The winter period is when a peak load or peak power fee is active, the other months are considered summer. These are then compared to the grid scenario for the energy and economic analysis. The annual energy flow for both PV and IEP scenarios are shown in Appendix D.

7.2.1 PV scenario

Two typical days for both winter and summer are shown in Figure 27. The electricity load, the black curve, is quite uniform during winter times with small variations during the day. Most of the load is met through electricity from the grid, the blue curve, unless there is some PV production from the houses, shown in yellow. Due to the peak load fee the electricity price increases during the day for the winter season from 06-22, whereas the electricity selling price stays more or less constant.

For the summer, there is large amount of excess solar production during the day, which is being fed to the grid, shown as the orange curve. The electricity load varies more than during the winter with peaks in the morning and evening. The higher variation is due to the summer houses also being occupied due to the summer holidays. The electricity price and selling price are also shown and have little variation throughout the summer days.

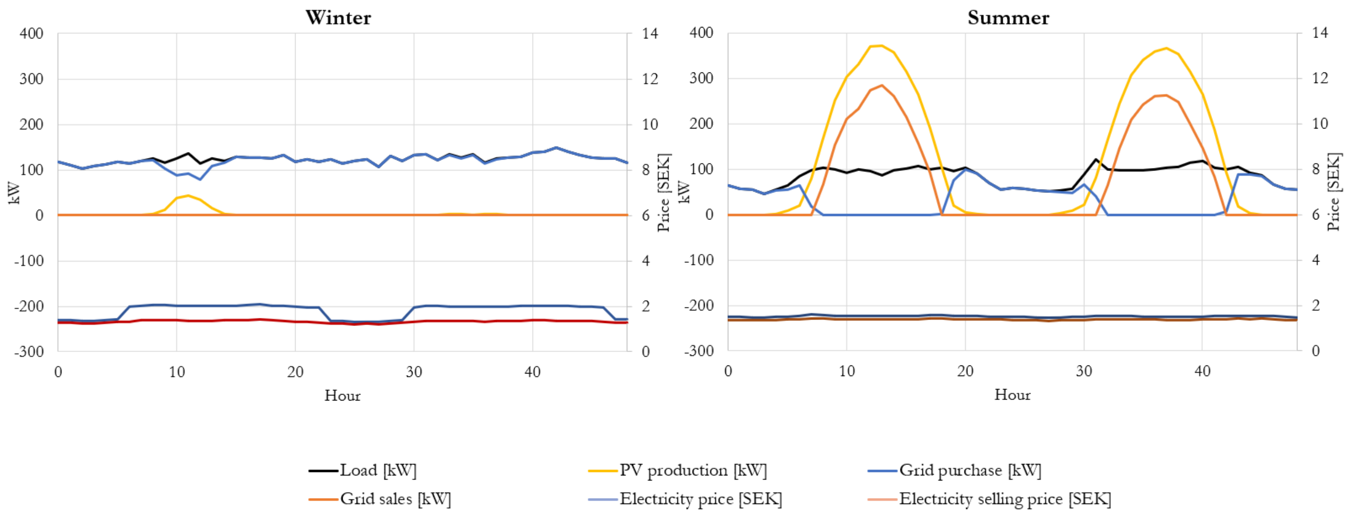

Figure 27: PV scenario for Winter (left) and Summer (right) for Energy community case

7.2.2 PV + Battery IEP scenario

How the typical winter and summer look like for the IEP scenario is shown in Figure 28.

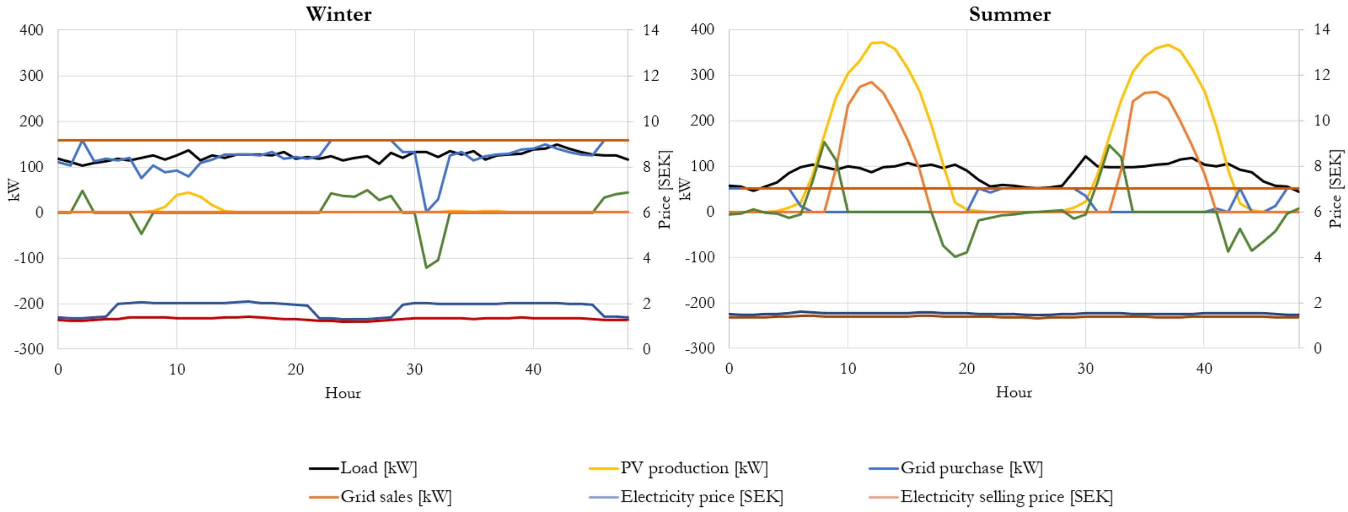

Figure 28: PV + Battery IEP scenario for Winter (left) and Summer (right) for Energy community case

Due to the demand limit optimized by HOMER Grid, the batteries are charging for several hours and with less power to not exceed the limit, shown as the green curve. This is mostly apparent during the winter times, when there is little to no solar production for the batteries to charge from and so charges from the grid instead. Due to small variations in the load, the burden on the grid is increased by having batteries in the system. The battery engages in energy arbitrage during winter where it charges during the night and discharges during the hours the peak load fee is in effect. Since the electricity load does not vary significantly during winter season, there is little peak shaving for the battery to do.

During the summer the battery charges as soon as there is excess solar production, which is usually in the morning and then discharges in the evening. With more significant peaks during the summer, the batteries are often peak shaving to reduce the evening peaks together with the PV, ultimately reducing the power fee.

7.2.3 Energy and Economical Analysis for Energy community case

Figure 29 shows the monthly peaks of electricity drawn from the grid for the different scenarios. The peaks are not decreased with only PV installed for the energy community. During winter for the IEP scenario, the batteries charge from the grid. As there are low variations in the daily electricity consumption, this causes the monthly peak power drawn from the grid to increase for January and March, compared to the grid and PV scenarios. Because the peak is increased the grid is strained further by having the batteries, which can also be seen from the annual energy flow in Appendix D. However, for the other months, the batteries are decreasing the peak electricity consumption.

For the summer, the load reduction is more evident with the demand limit decreasing with around 100 kW for July and August, largely due to high PV production for the energy community.

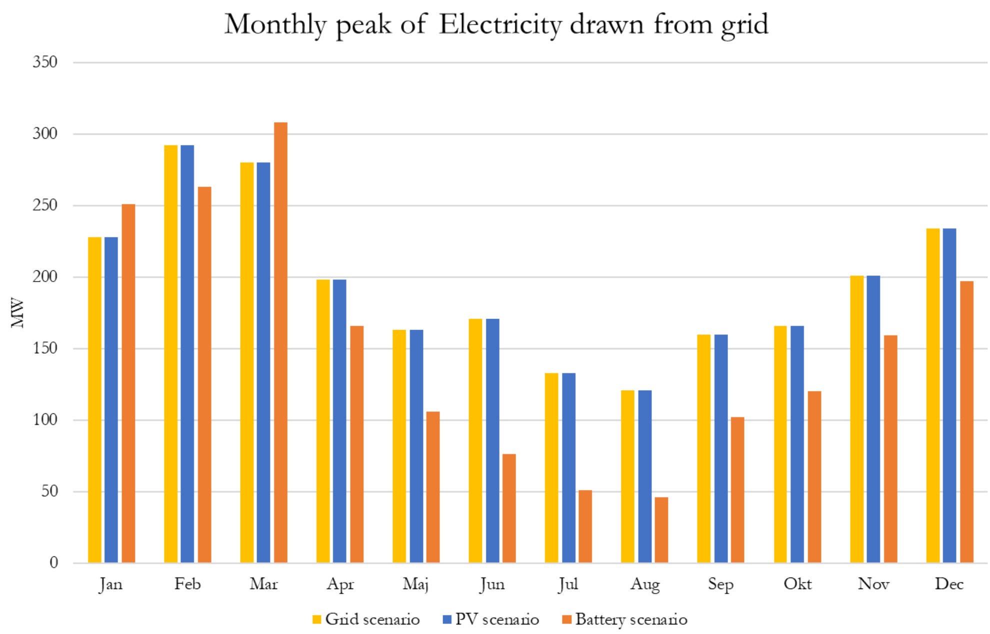

Figure 29: Monthly peaks of electricity drawn for all scenarios for Energy community case

In general, for the colder seasons, it is the one or two spikes in consumption that sets the demand limit for the month, meaning the daily peaks can be much less than the demand limit set by HOMER. This is shown in Figure 30, where for the winter months the demand limit is higher than the average electricity consumption. Having a higher demand limit causes the battery to charge from the grid with more power till it reaches that demand limit which results in a higher strain on the grid even for the daily peaks, which can also be seen in Appendix D. This shows decentralized batteries do not provide relief to the grid during winter, the most strenuous period of the year.

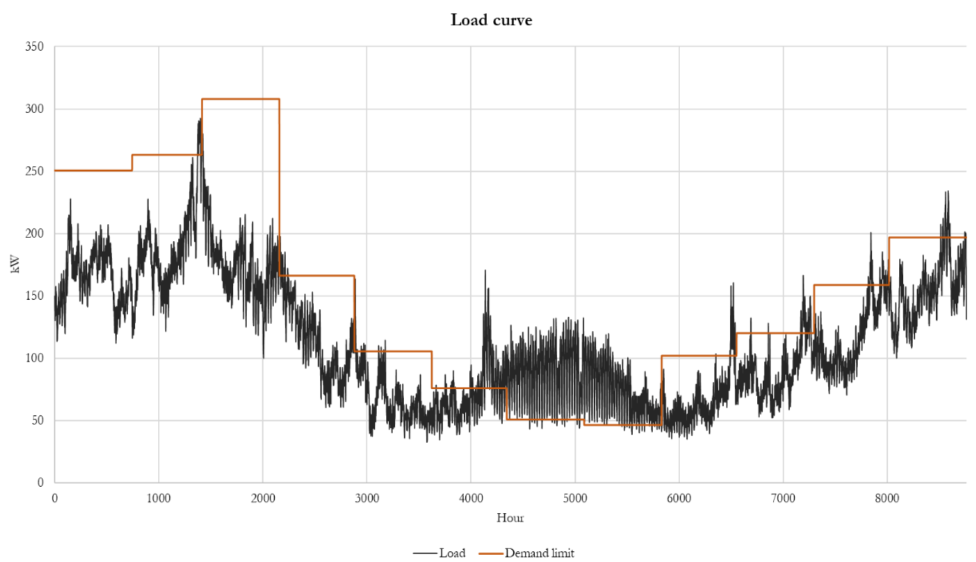

Figure 30: Load profile and monthly power limit for IEP scenario for Energy community case

The energy related values are shown in Table 14. For the PV scenario, the total transmission on the grid is increased even though the amount drawn from the grid decreases. This is due to the local generation that does not go to meet the electricity load, is fed to the grid. The self-consumption is around 45%, this is much higher than for the single family house case in Section 5.2.4 due to the electricity consumption being higher during the summer, which means a larger portion of the solar electricity goes to meeting the load. The consumption is higher mainly because of the many summer houses that are occupied during summer. The self-sufficiency is around 22%, similar to the Single family house case since the hours the PV can provide electricity is during a fixed, for the rest of the day it needs to be bought, which is similar for both cases. For the IEP scenario self-consumption and self-sufficiency increases with 15% and nearly 7% compared to the PV scenario due to the addition of the batteries. The electricity drawn fed to the grid also decreases due to the battery being able to store electricity to meet the load, actually reducing the total transmission on the grid

Table 14: Energy analysis for Energy community case

	Drawn from Grid [MWh]	Fed to grid [MWh]	Total transmission [MWh]	Transmission change [%]	PV Self-consumption [%]	Self-sufficiency [%]
Grid scenario	991	-	991	-	-	-
PV scenario	769	268	1 037	4.6	45.3	22.4
PV + Battery IEP scenario	709	205	914	-7.7	59.2	29.3

This analysis shows that the value of reducing the distribution load is mainly during the warmer seasons when the grid is not that heavily strained. The strain is also increased further by installing batteries due to arbitrage they perform, this provides an economical benefit, as mentioned in Section 5.2.3 for the individual household, but burdens the grid further. If these batteries were to not only have an incentive to reduce the electricity price for the households but also focus on the grid, the strain could be reduced.

8 National case

The value decentralized batteries can provide on a national scale in Sweden as well to the individual home is analyzed in this case study. It will be analyzed if the batteries can provide national balancing of Sweden's power system together with the household services of increasing the self-consumption, energy arbitrage and peak shaving. The system layout of this case is shown in Figure 31.

Figure 31: System payout for case National (Svenska Kraftnät, 2020d)

8.1.1 Frequency regulation

The renumeration for the activated volume and capacity as well as the historically net-activated volumes for FCR-N, aFRR and mFRR are shown in Table 15 and are taken from Nord Pool (Nord Pool, 2020; Svenska Kraftnät, 2019f). The total volume activated throughout the year is also shown in the Table 15. The data not available is marked with "No data". Due to not having the total activated volume of FCR-N the renumeration is calculated with net activated volumes, where the net activated volume of both up and down is taken. Therefore it may be less than the actual volume renumeration for 2018 (Svenska Kraftnät, 2019b).

Table 15: Historical frequency reserve values of 2018

	FCR-N	FCR-D	aFRR	mFRR
National required power [MW/h]	227	427	150	-
Net average activated volume Up [MWH/h]	53	0.21	71	180
Net average activated volume down [MWH/h]	58	-	82	207
Maximum activated volume in a single hour [MWh/h]	227	17	150	1495
Total activated hours Up [h]	3 802[2]	88[3]	3 870[4]	2 843[4]
Total activated hours Down [h]	4 477[2]	-	3 660[4]	4 046[4]
Total activated Up [GWh]	No data[5]	No data[5]	57.7	494
Total activated Down [GWh]	No data[5]	-	88.3	829
Activated volume renumeration [MSEK]	210	-	67	581
Capacity renumeration [MSEK]	790	705	128	-

FCR-D is activated at maximum of 4% of the procured capacity in 2018, and is activated on average only 0.21 MWh/h (Lindgren, 2019). This shows that FCR-D is used very little throughout the year. mFRR has very large net average activated volumes for both up and down regulation, meaning it is used the most out of the reserves. Both reserves together with the primary reserves activated volumes are shown in Table 15.

8.2 Methodology for National case

The number of households in Sweden that are assumed to install PV and battery systems is based on the target goal from the Swedish Energy Agency and the battery installation trend of Germany. The quantity installations is explained in Appendix F and shown in Table 16 below. Only the houses with both PV and battery are modelled in this case study.

Table 16: Assumed quantities and capacity for battery and PV for National case

National case	Nr of batteries [Quantity]	Battery capacity [GWh]	Nr of PV installations PV [Quantity]	Installed PV [GW_p]
	308 823	2.13	617 000	3.09

[2] The hours with dominating direction of each activated reserve. The total hours activated per reserve is higher.
[3] Activated more than 1%
[4] Up and Down reserves are activated during the same hours
[5] Data was not found

8.2.1 Load and PV production profile

The average of the load curves from all Vattenfall Distribution Sweden customers with a fuse level 20 A is taken for this case study to represent the national households electricity consumption (Vattenfall eldistribution, 2018). The yearly consumption is then scaled to the number of houses that are assumed to have both PV and battery and is shown in Figure 32. This curve is used to analyze the energy flow for the whole nation when installing a PV and a PV with a battery system.

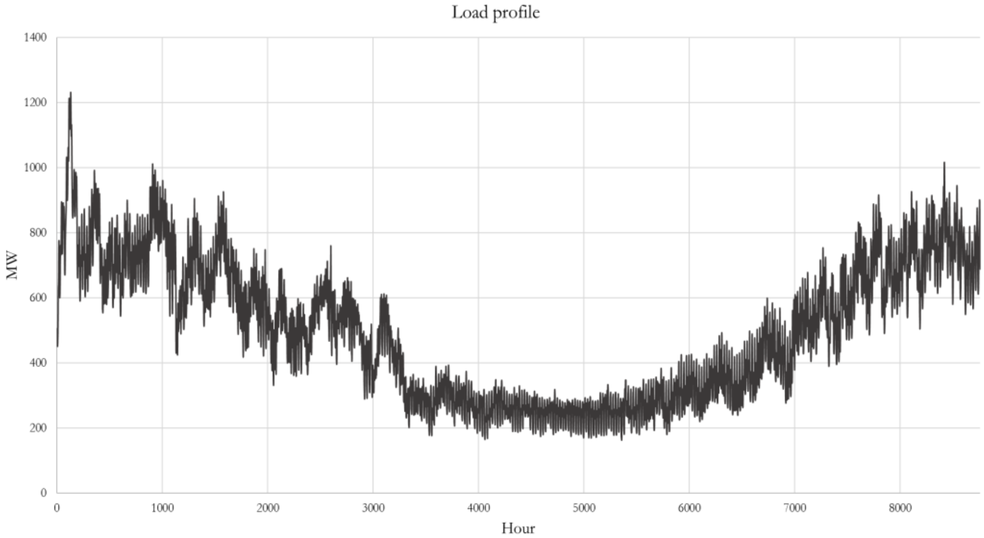

Figure 32: Load profile for National case

Since this is an average load curve, the household's peaks are smoothed out by being aggregated with other houses. The profile reflects the dependence on ambient temperature with higher values consumption during the colder periods and less during the warmer seasons in the middle of the year.

To analyze the savings and costs for each individual household in this case, the load curve from the Single family house case is used, shown in Section 5.1.1. This is because the higher variation in the electricity consumption that each individual house has provides a more accurate image on what savings an individual household would have. Using the average load curve of several households, as shown in the figure above, smooths out the individual variations which would also reduce the savings made for peak shaving.

8.2.2 Modelling of Frequency regulation

To assume what share of the aggregated battery's capacity should be used for frequency regulation, the national required power is used. The highest requirement is for FCR-N, because it is symmetrical a need to either charge or discharge 227 MW during an hour is foreseen, requiring a total reserved capacity from the batteries of 454 MW per hour. It is assumed that each battery will provide the power/capacity ratio of 1 MW/MWh for frequency regulation. In order to provide 454 MW/MWh the aggregated batteries capacity amounts to around 21% of the total capacity of the batteries. The other reserves have smaller required capacity nationally as shown in Table 15, but in order to have as equal assumptions for all the reserves, the same capacity for each reserve is used. In order for each individual household to provide balancing as well as the household services from the battery, it is therefore assumed that around 80% of it is used for the household services and 20% is used for frequency reserves. Each reserve will be modelled individually in order to see what amount of the historical activated volumes can be met and what renumeration there is for providing each reserve. It will then be analyzed if any combination of the reserves is possible for the batteries to provide.

How the battery will charge will vary for each reserve. For FCR-N, aFRR and mFRR the batteries provide both up and down regulation combined, therefore the initial SoC is set to 50%. Since FCR-D only regulates up, the SoC set to be 100%. The secondary reserve, aFRR market is divided into two separate markets for up and down regulation. However, when the batteries provide this reserve, it will be modelled so that the battery can provide for both of the reserves simultaneously, therefore the portion of the battery's dedicated capacity for frequency reserves has an initial SoC set to 50%. The initial SOC for each reserve is shown in Table 17 below.

If every battery preserves 20% of their capacity, it is equal to 1.38 kWh for the individual battery. When providing both up and down regulation simultaneously each regulation's direction will have a capacity of around 0.7 kWh from each battery. Recharging the battery 0.7 kWh takes roughly 7 minutes and to 1.38 kWh around 14 minutes, based on the technical specifications of this battery mentioned in Section 4.2.5. The actual recharge time needed is shown in Table 17 below. However, since the timesteps used in for modelling are hourly the recharge for each reserve will be set to an hour. The recharge will be done once a day for all reserves except for mFRR, this is due to the activated hourly volumes are so high that the battery's capacity is not enough to meet the reserve and therefore needs to be recharged more often. Since FCR-D is activated in small volumes, SoC is assumed to not be affected by activated volume of FCR-D, therefore the battery is also assumed to not be recharged during the day and can provide the reserve at all times.

The recharge hours for FCR-N, FCR-D and aFRR are set for the hour the capacity renumeration is the lowest annually, this is because it is the capacity renumeration, rather than the activated volume renumeration, that gives the highest revenue, also shown in Table 15 above.

Table 17: Battery characteristics for providing frequency regulation

	FCR-N	FCR-D	aFRR	mFRR
Initial Soc	50%	100%	50%	50%
Recharge time [min]	6.8	13.6	6.8	6.8
Recharge hour	12:00	-	19:00	Every third hour

The duration the battery can provide frequency regulation will depend on the volume activated and the SoC of the battery, as long as it can provide the reserve it will continue to do so. This is different to the way the frequency reserves are procured today as the bid volumes are pre-decided when they are bid. However, as the purpose of this thesis is to analyze the potential usage the battery can provide for frequency regulation, this deviation from current market design was made.

The renumeration given for the activated energy will only account for the net activated volume each hour for both up and down regulation of the reserves. This is a limitation done when calculating since the timespan was hourly, since the battery will be able to charge and discharge throughout the hour, only the SoC at the end of the hour is considered. It is this SoC that is used when calculating the activated volume renumeration. This means that the actual volume renumeration is larger than the one calculated. The net volume activated is multiplied with that direction's regulating price to find the renumeration.

The capacity renumeration is taken as the aggregated batteries available capacity at the beginning of the hour which is multiplied with the market price for each reserve's capacity.

How the discharge and charge of the battery for frequency regulation is affected by the household's own load or PV production is not considered in this study, rather it is simulated as two separate services done from the same battery unit.

8.2.3 Modelling process

Three scenarios are modelled where the first is the reference scenario, called grid scenario, where all households are only grid connected. This is then compared to two scenarios, the PV scenario and the IEPF scenario.

In the PV scenario the households that install PV based on the previous mentioned assumptions will be modelled. The IEPF scenario is with the assumed PV and battery installation. Here the behind-the-meter services looked into are increasing the PV self-consumption, energy arbitrage and peaks shaving. The aggregated services are to reduce the total transmission load on the grid and to provide frequency regulation.

The flexibility of the DER is analyzed for the whole electricity load, PV production and batteries capacity combined. This is done so that the total load on the grid can be analyzed. For the economic analyzed for the individual household so that the savings and costs of each household are shown.

8.3 Results and discussion for National case

Two days in winter and summer season are chosen in order to show the variation of the energy flow for the two scenarios. The seasons are divided into Apr-Oct without peak load fee and Nov-Mar with peak load fee. These are then compared to the grid scenario for the energy analysis. The economic analysis for the national case is done together with the results from the individual household's case where 80% of the battery is used for the household services.

The annual energy flow for all the scenarios for National scale are shown in Appendix E.

8.3.1 PV Scenario

Two typical days for both winter and summer are shown in Figure 33. The electricity load, the black curve, is higher during the winter than summer due to heating of the houses and with larger variations during the day. Most of the load is met through electricity from the grid for winter, the blue curve, unless there is some PV production from the houses, shown in yellow. Due to the peak load fee the electricity price increases during the day for the winter season from 06-22, whereas the electricity selling price stays more or less constant.

For the summer, there is large amount of excess solar production during the day, which is being fed to the grid, shown as the orange curve. The electricity load becomes larger during the day with two peaks in the consumption. The electricity price and selling price are also shown and have little variation throughout the summer days.

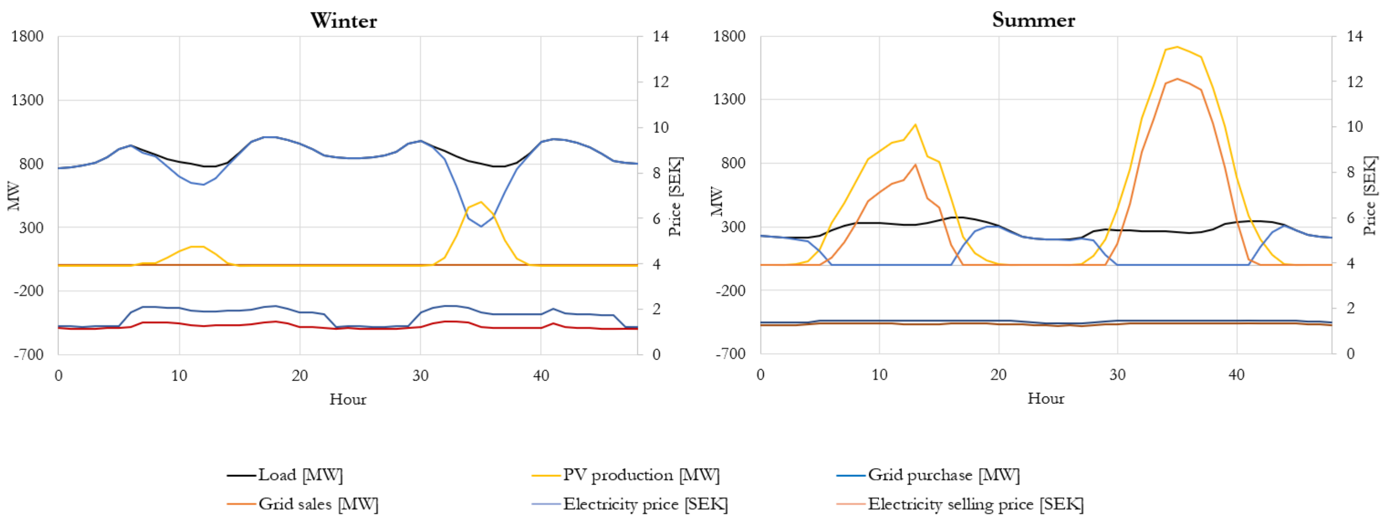

Figure 33: PV scenario for Winter (left) and Summer (right) for National case

8.3.2 PV + Battery IEPF Scenario

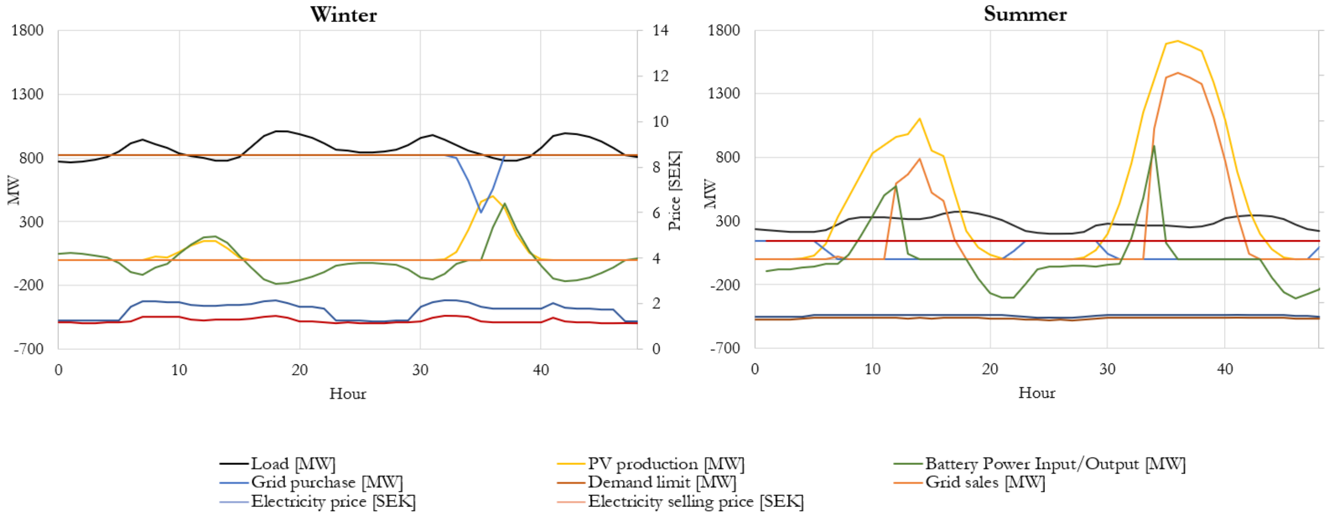

Figure 34: PV + Battery IEPF scenario for Winter (left) and Summer (right) for National case

For the IEPF Scenario, 80% of the aggregated batteries capacity is used for the household's services and the energy flow for the two days with the battery installed is shown in Figure 34 above. During the winter season, the battery is mainly engaging in peak shaving and arbitrage. It charges and discharges mainly to decrease the monthly peak power consumption. During these days the battery could charge by the little solar production the households had and use it to discharge during the day and again charge between the two peaks that occur during the day as can be seen in Figure 34 above. This brings down the monthly peaks during winter and are shown in Figure 35 below.

During summer, the battery opts to charge as soon as there is excess PV production and discharge normally during the evening as can be seen from on the right in Figure 34. Even here the load is being peak shaved with PV meeting the load during the day and the battery discharging in the evening and night.

Using the remaining 20% of the aggregated batteries capacity for the different frequency reserves the revenue gained and the number of hours the batteries could provide the reserves for is shown in the Table 18.

Table 18: Revenue and volume met by Frequency regulation for National case

	FCR-N	FCR-D	aFRR	mFRR
Energy [MSEK]	168	-	49	182
Capacity [MSEK]	622	705	121	-
Total [MSEK]	**791**	**705**	**170**	**182**
Historical volume met in 2018 [%]	80%	100%	68%	32%

From the results above, FCR-N gives the highest revenue for the battery with around 791 MSEK in total, if batteries provide FCR-D it generates second highest revenue of 705 MSEK. As the FCR-N reserve is the first reserve to be activated it is used the most frequently of all the reserves, this means that it will also degrade the battery more than FCR-D. A large volume of aFRR could also be met, but since it is not activated for all hours of the year, the total revenue is less than for the primary reserves. aFRR could potentially reach the same revenue values as for the primary reserves when it is activated at all times in the future. The historical activated volumes of mFRR are much larger than for the other reserves which resulted in the batteries not having enough capacity to meet the volumes. As the only renumeration for mFRR is through the activated energy, it yields the least revenue for the battery's capacity.

8.3.3 Energy and Economic analysis for National case

The peak electricity demand for grid, PV and IEPF scenarios are shown in Figure 35. For each month the batteries lowered the peak electricity drawn by peak shaving, while only installing PV did not decrease the monthly peaks. The peaks are shaved the most during summer as both PV and battery could reduce the load together, so that the battery is dispatched only for the hours there is little to no PV production, also shown to the right on Figure 34.

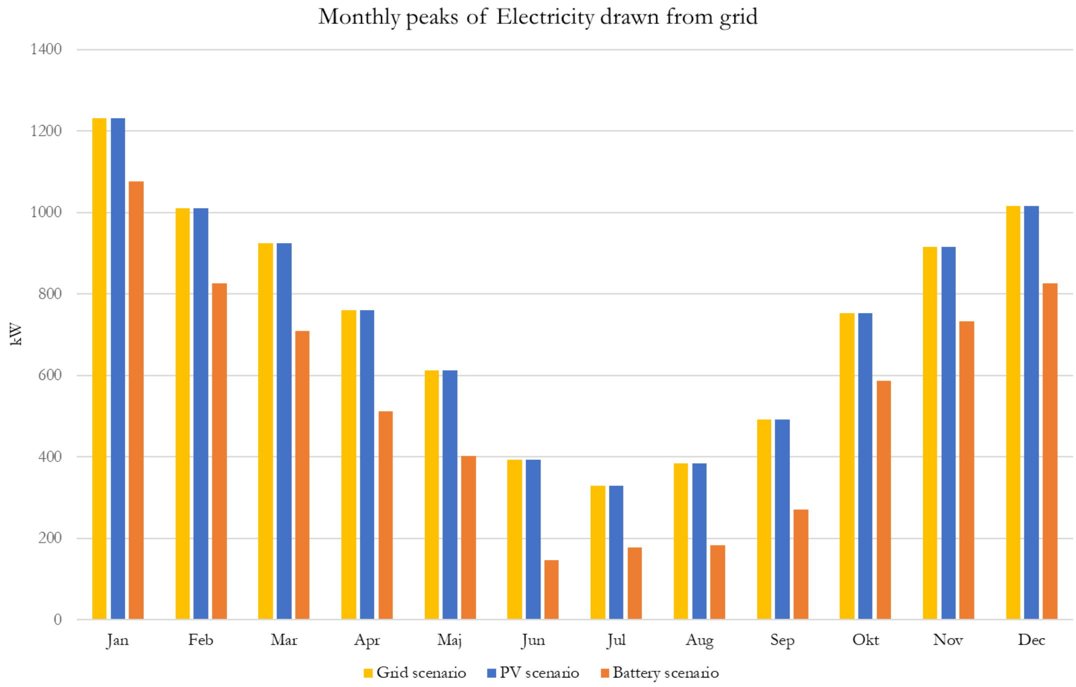

Figure 35: Monthly peaks of electricity drawn for all scenarios for scenarios for National case

The energy analysis shows that similar for both the Single family house case and the energy community case, the load on the transmission grid increases when installing on a PV system compared to the Grid scenario and decreases when installing both PV and a battery. The grid is strained with around 11% with the excess PV production, as shown in Table 19. However, as this excess electricity is at the distribution side of the grid, other households or consumers can draw this electricity instead, thereby reducing the transmission on the national grid. With a battery installed, each household becomes more self-sufficient and relies on the grid less, as also shown in Table 19.

Table 19: Energy analysis for National case

	Drawn from Grid [GWh]	Fed to grid [GWh]	Total transmission [GWh]	Transmission change [%]	PV Self-consumption [%]	Self-sufficiency [%]
Grid scenario	4 314	-	4 313	-	-	-
PV scenario	3 264	1 569	4 834	10.7	40	24.4
PV + Battery scenario IEPF (80% of battery capacity)	2 934	1 229	4 163	-3.6%	53.8	32.7

The savings made for each individual house in the National case are found to be much less due to the aggregation of their electricity consumption, therefore the savings made from the Single family house case is used instead in Section 5.2.4. Here, 80% of the battery's capacity is used for the household services. The economic analysis, shown in Table 20, shows that by only installing a PV system, the largest savings are from the electricity charge savings. For the IEPF scenario with a battery included, an additional 57% savings can be achieved from providing frequency regulation. Since FCR-D is activated very seldom and with small volumes, a combination of providing both FCR-N and FCR-D was found to maximize the revenue generated by the decentralized batteries. 80% of the battery's capacity could be able to meet both the household services and at times, the FCR-D when used. The remaining 20% is only used for FCR-N so that it is always available. If both the behind-the meter services and frequency regulation would be needed at the same time, the battery opts to balance the grid, as that provides the highest revenue for the batteries, as shown in Figure 36.

The payback time of the scenarios is the least when the battery is used for both primary reserves and the household services, the simple payback time is around 9 years and the discounted payback time is around 11 years. For the IEPF scenario with only FCR-N, the discounted payback time is roughly 2 years more, with around 13 years.

Comparing the NPC values of each scenario, it shows that every scenario is economically beneficial compared to the grid scenario and NPC is the least when providing frequency regulation. However, it is also important to mention that the battery is used more extensively when providing the reserves and taking the battery losses into account could potentially decrease the profit and also decrease the battery's lifetime by more extensive use.

Table 20: Economic analysis for National case with 20% battery's capacity for frequency regulation and 80% of battery's capacity from single household case

	Electricity charge savings	Peak shaving savings [SEK]	Annual frequency regulation revenue [SEK]	Annual savings + revenue [KSEK]	Simple payback time [yr]	NPC [kSEK]	Discounted payback time [yr]
Only grid	-	-	-	-	-	257	-
PV scenario	11 733	142	0	11 874	12.3	221	14.2
PV + Battery IEPF scenario (FCR-N)	12 115	1 623	2 563[6]	16 301	10.5	194	12.8
PV + Battery IEPF scenario (FCR-N + FCR-D)	12 115	1 623	4 846[7]	18 584	9.2	167	11

The added savings from the battery are shown when comparing the IEPF scenario with PV scenario in Figure 36. Here, 80% of the savings made from the single family house is shown together with the revenue from providing FCR-N with and without FCR-D. The figures show that the largest revenue made by the battery is by providing frequency regulation with around 2.5 kSEK from FCR-N and 2 kSEK from FCR-D, from the household services it is the peak shaving that provide the highest savings with a little less than 1.5 kSEK per year.

[6] Revenue for FCR-N per household

[7] Revenue for FCR-D (2 283 SEK) and FCR-N (2 563) per household

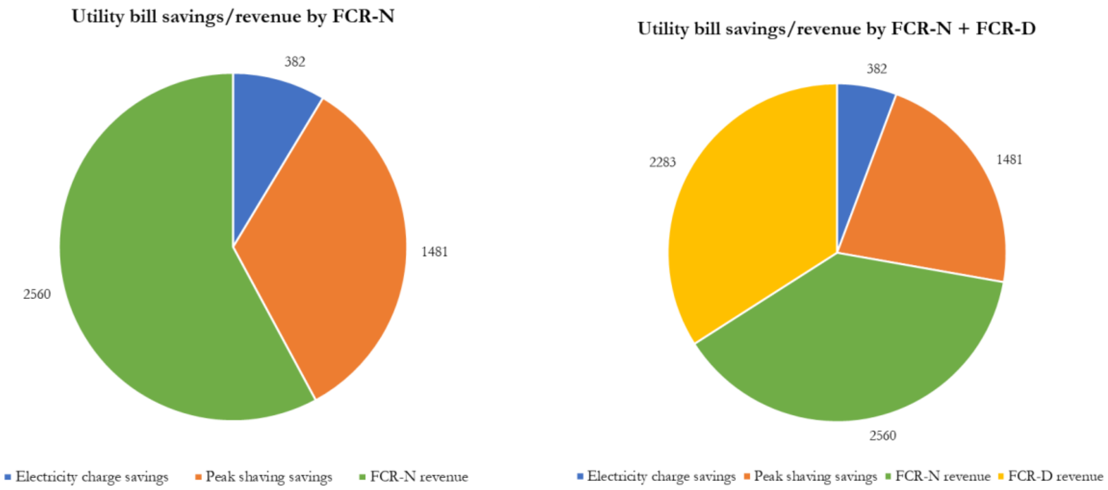

Figure 36: IEPF scenario savings compared to PV scenario for National case

9 Sensitivity analysis

Between the PV and the battery, the household batteries are still in maturing phase. It was therefore chosen as the component to perform the sensitivity analysis on to pinpoint which of the costs related to the battery's payback time that are the most sensitive. The sensitivity analysis is done for the single family house IEP scenario where the battery's discounted payback time was around 15.8 years, as mentioned in Section 5.2.4. Each cost is increased and decreased with 20% while all other costs are kept the same, how each cost variation affects the payback time is shown in Figure 37 below.

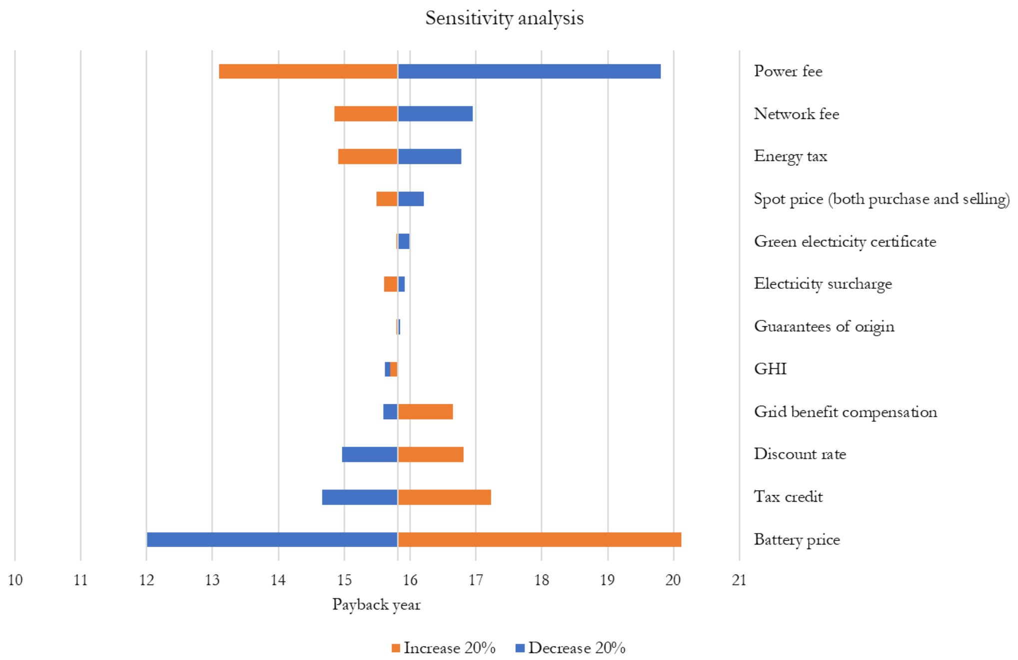

Figure 37: Sensitivity analysis for the discounted payback time of the battery

The highest sensitivity value is the investment cost of the battery where increasing the cost 20% results in a payback time increasing with more than 4 years. This end price for the residential homeowner is highly dependent on subsidies, but as the trend for decentralized battery show, the costs are likely to reduce and may compensate for any decrease in subsidies. If total battery system cost reduces with 20% the discounted payback time could be reduced with 4 years and be as little as 12 years in total. Another value with high sensitivity is the power fee. This makes sense as it was the peak shaving that made the highest savings for the battery seen in Figure 21. With a 20% higher power fee, the payback time would reduce to almost 13 years.

Increasing the costs of the battery such as the power fee, load fee, energy tax, electricity surcharge and spot price, creates higher savings for the battery to store excess electricity and increase the self-sufficiency of the house. This ultimately decreases the payback time of the battery.

Increasing the subsidy values such as the tax credit, grid benefit compensation and guarantees of origin, show that the battery's payback time is increased. This can be because it is more economically beneficial to sell the excess solar electricity rather than storing it, prolonging the payback time.

Increasing and decreasing the irradiation for the solar panels both decreased the payback period of the battery. This is because with less irradiation the savings made from peak shaving are higher than the reference scenario making the summed savings higher than for the original irradiation values. With 20% higher GHI the energy arbitrage savings are higher for the original radiation resulting in higher annual savings. Both the alteration decreases the payback time but marginally. If the payback time of the total system with PV was considered, the savings of PV would have been decreased with less GHI and similarly increased with higher GHI.

The energy tax alteration created a larger variation on the electricity price than when the spot price is changed, this is because the variations has a higher impact on the energy arbitrage and therefore higher savings can be made with an increase of the energy tax.

10 General Discussion

From the case studies, it can be deduced that batteries are a great source for short-time load variations when the magnitudes are smaller than the battery's capacity. This was shown clearest in the Single family house case, however with the larger case studies with larger peak values, such as the transformer case, the batteries are less efficient at peak shaving.

Decentralized PV and batteries that only work on decreasing the household bill do not always provide relief for the grid simultaneously. More detailed price schemes may be needed, for example a power fee that is not only set on the highest peak of the month but several peaks so that the grid is not strained further, as in the energy community case. The current power and load fees may have the opposite effect on the grid than intended when it actually might increase the peaks. This is mainly an effect of the simulation software charging and discharging at time when the grid transfer fees alters. What sort of cost schemes for power and load fees that could prove to be more useful for the grid should be studied further as well as if additional measures need to be taken to ensure all storage units do not change behavior at the same time.

Installing PV is a great way to increase renewable power generation and consumption for prosumers such as households, but it does little to provide relief for the grid. As solar electricity peak production and peak load of the households are at different times of the day, it cannot be used to peak shave alone. Also, as shown for Germany, too high installed capacity of PV can also increase the strain on the grid during peak production hours, making matter worse for the power system. Batteries can be used to decrease the peak power produced, but as seen from the results, a control mechanism will be needed where the battery charges during certain hours and not as soon as there is excess PV production. If not, the battery may already be fully charged before the peak solar electricity is generated and not capable of reducing the burden.

The main reason the scenarios IEP with PV and a battery system shown in the Single family house case has a payback time within the project lifetime is due to the residual value of the PV. The discounted payback time for only the battery does not pay itself back within the project lifetime due to the high investment cost it has today. This might change, however, in the future if the trend of price decrease still holds for the battery or the costs of the electricity prices increases. From an energy value perspective, the batteries do increase both the PV self-consumption and self-sufficiency of the house with a battery included and reduce the total transmission of electricity to the house. This shows that there is a value of installing a battery for both the household and the grid which may also increase the monetary value of it in the future.

If Sweden meets the solar energy goal and follows the energy storage installation trend of Germany, around 20% of the national battery capacity is enough to meet around 70-100% of the different reserves volume individually, except for mFRR where a much larger capacity would be needed. This means that other technologies will be needed to cover all the reserves, especially since all these reserves are procured together.

For the household batteries to provide balancing of the grid system, one limitation is the bidding market for frequency regulation. The reserve market closes at earliest one day ahead of activation for the automatic reserves, this makes it difficult to predict the household's electricity consumption and PV production for the next day accurately before the bidding period is finished. For the batteries to participate in the frequency regulation market, the bidding period will have to become much shorter. Also, the minimum bid size for each reserve which is at least 0.1 MW also makes it difficult for DER to participate in this market unless they are aggregated. SvK also admits to the market needing a transformation to promote DER participation, as mentioned in Section 2.6.3.

One important note is that the costs for frequency regulation were higher than previous years in 2018 due to a dry summer which made hydropower more expensive (Svenska Kraftnät, 2018). These prices continued to increase in 2019. However, opening the regulating market for other technologies than hydropower, might affect the regulation price this is a large uncertainty for the BES as the revenues achieved from participating in this market heavily affects the payback time of the batteries.

10.1 Environmental impact from batteries

This thesis shows the many synergies and positive impacts Li-ion batteries can have for the power system, and that it can become a key component to promote environmental sustainability as it increases renewable energy integration. Although, li-ion battery is still a relatively new technology and there are parts of its lifecycle that has negative impacts on the environment. Therefore, it is important that the correct battery chemistry and production facilities are included in the evaluation. The whole value chain from mining the minerals, manufacturing the product and finally the collection and recycling of the battery should be assessed under industrial scale production relevant for the mass market products. That said, the recycling and collection process needs to develop further. For domestic appliances only around 10% of the Li-ion batteries are collected in Japan and around 95% of Li-ion batteries in the U.S. are landfilled instead of being recycled (Zubi et al., 2018). It is important larger home and electric vehicle batteries do not end up in landfills where they could pose a risk of contaminating the groundwater and soil from its electrolyte and metals. (Mossali et al., 2020). As the usage of batteries increases, both these issues will become more serious concerns. One way of mitigating this problem is by a more effective and large-scale recycling scheme where home batteries are recycled.

Specific studies will have to be performed for the usages of the battery energy storage to gain a more holistic understanding on its effect on the environment.

11 Conclusion

For the single family household: The load fee which has the intention to reduce the strain on the grid, shows that during wintertime the peaks are actually increasing at night. This has the opposite affect than what these load fee intended. With both the power fee and load fee the battery is targeted more effectively on the peak demand and ultimately generates the highest savings. Only installing a PV system increases the total transmission on the grid, which is reduced with an addition of a battery. All scenarios are payed back within the project lifetime at around 14 years, however the PV scenario is the least cost solution.

For the transformer: The aggregated batteries connected at a transformer does reduce the peak load so that the transformer is no longer overloaded, but the peak reduction is only reduced by a fifth of the batteries total capacity. This is due to the peak occurring for several hours where the battery is discharging for a long period of time and shows that batteries are better suited for peak loads that are short-term and don't occur for more than a few hours.

For the energy community: With varied consumers of households, summer houses and commercial buildings, the load curve has less variations during the winter. Because of this, installing batteries increases the load consumption during this period, and causes load reduction during the summer. However, the monthly peaks are in general reduced for the year and the solar consumption and household's self-sufficiency in increased the most with the installations on batteries. In general, the DER which follow the price schemes of households do not always create benefits for both the households and the grid simultaneously.

For the national: By providing 20% of the aggregated batteries capacity for frequency regulation, around 70-100% of each of the reserve's volumes can be met. For the individual household, the highest savings are generated when the battery is providing both the primary reserves with the household services, the discounted payback time amounts to around 11 years, however it should also be noted that the battery's lifetime may decrease with higher usage providing frequency regulation.

11.1 Future work

The combination of providing both frequency regulation and behind-the-meter services was studied in in this thesis by reserving a dedicated proportion of the batteries capacity to each service. For an optimal partition of the battery should be studied further. The complement of curtailing solar production to provide frequency reserves with both up and down regulation would also be interesting so that all the components of the system are used together. An additional potential income would be to use the batteries on the intra-day market that could have similar economic gains as those studied in this paper.

A sensitivity analysis on how the profit is affected by the losses from the PV and battery system should be done for frequency regulation, in order to gain an understanding of what impact that may have. Especially considering the often smaller efficiency when only a small fraction of the rated power is charged or discharged to a battery.

For decentralized batteries to provide grid relief on a larger, aggregated scale a smarter system may have to be implemented which knows the SoC of each individual battery and a control algorithm which can charge and discharging of the batteries. This should be studied further in order to implement such aggregated systems for DER.

Using hourly values for regulating the frequency reserves created the limitation that the battery charge and discharge during the hours could not be calculated with. There might have been larger volumes activated within the hour that were not considered as the net hourly volumes were used for the batteries SoC. When aFRR is procured for all hours of the year, the revenue will likely be similar to the primary reserves, therefore a new study should be performed to assess which combination of reserves will be the most beneficial for the batteries to provide.

The subsidies for both the PV and the battery can change with time as the technology matures and the prices continue to decrease, therefore it would also be interesting to perform similar studies for future prices for both these components without the subsidies included. This also means that the prices used in this thesis are likely to change with time and should therefore be used as an indicative for what value the different services can provide economically. Also, since the frequency regulation prices vary for each year, the revenue for the other years should also be studied to gain an understanding of the revenue generated for the batteries.

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A Appendix: Electricity price variations

The variations in the electricity price are from the spot prices which vary per hour and the load fees. It is these costs that create the volatility in the electricity bill that the battery can provide energy arbitrage for. How the total electricity price and electricity selling price varied for the year 2018 with the assumed prices mentioned in Section 4.2.7 is shown in Figure 38 below. The higher electricity price marked in the figure are from the load fees from November to March.

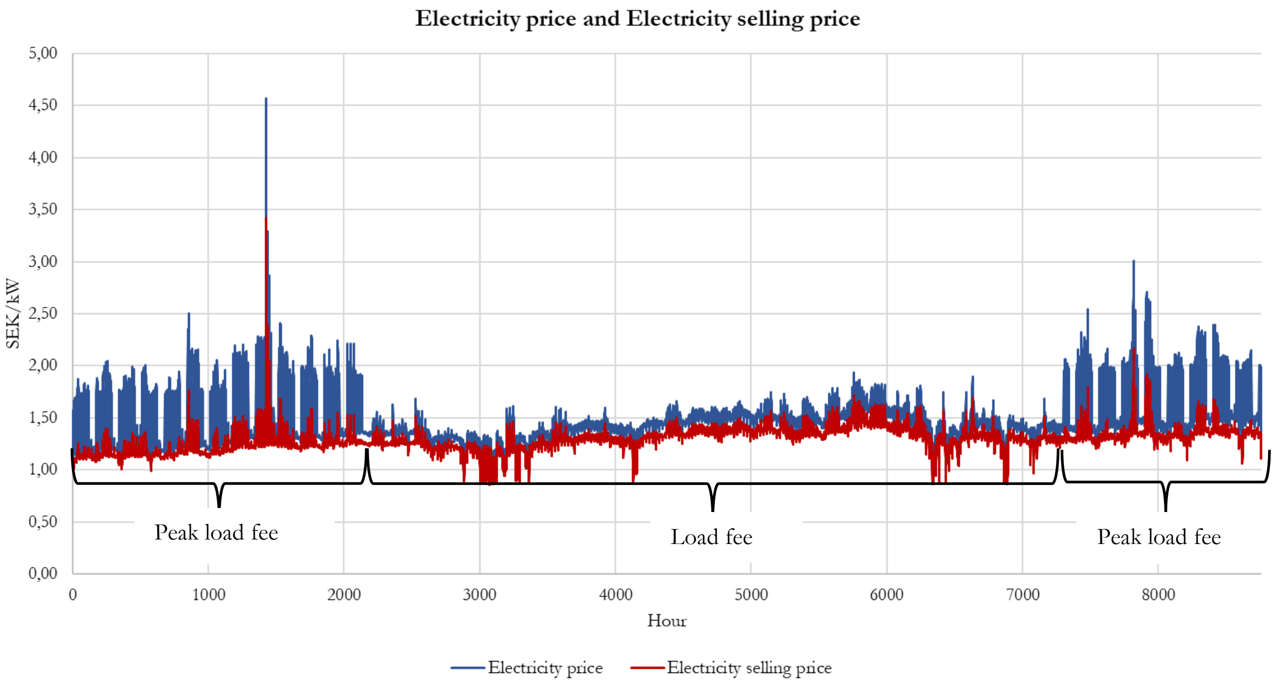

Figure 38: Electricity price and electricity selling price for 2018

B Appendix: Energy flow for Single family house

For all energy flows, the value of electricity fed to the grid is negative.

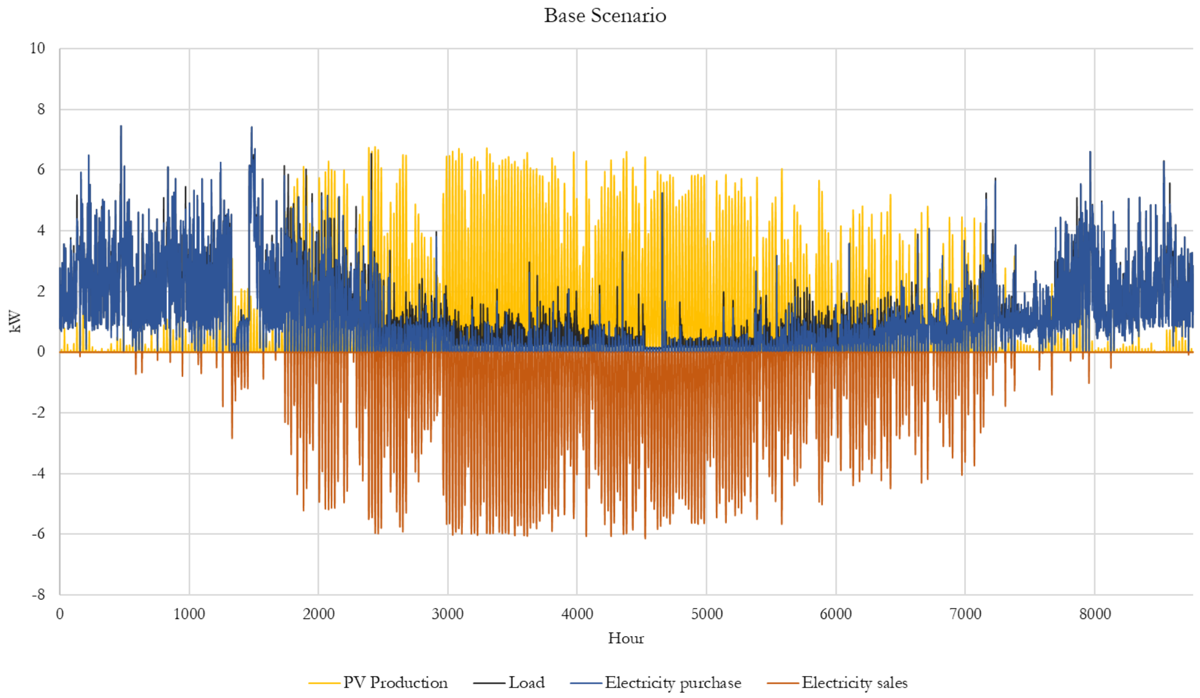

Figure 39: Energy flow for PV scenario in Single family house case

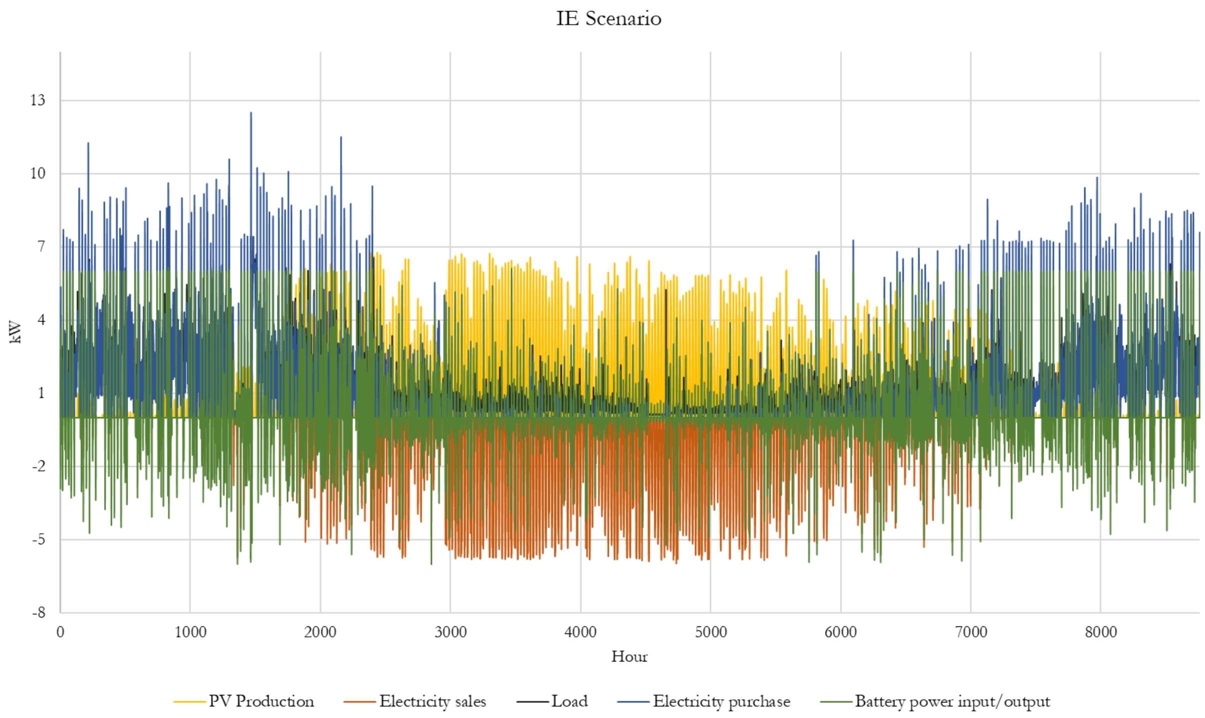

Figure 40: Energy flow for IE scenario in Single family house case

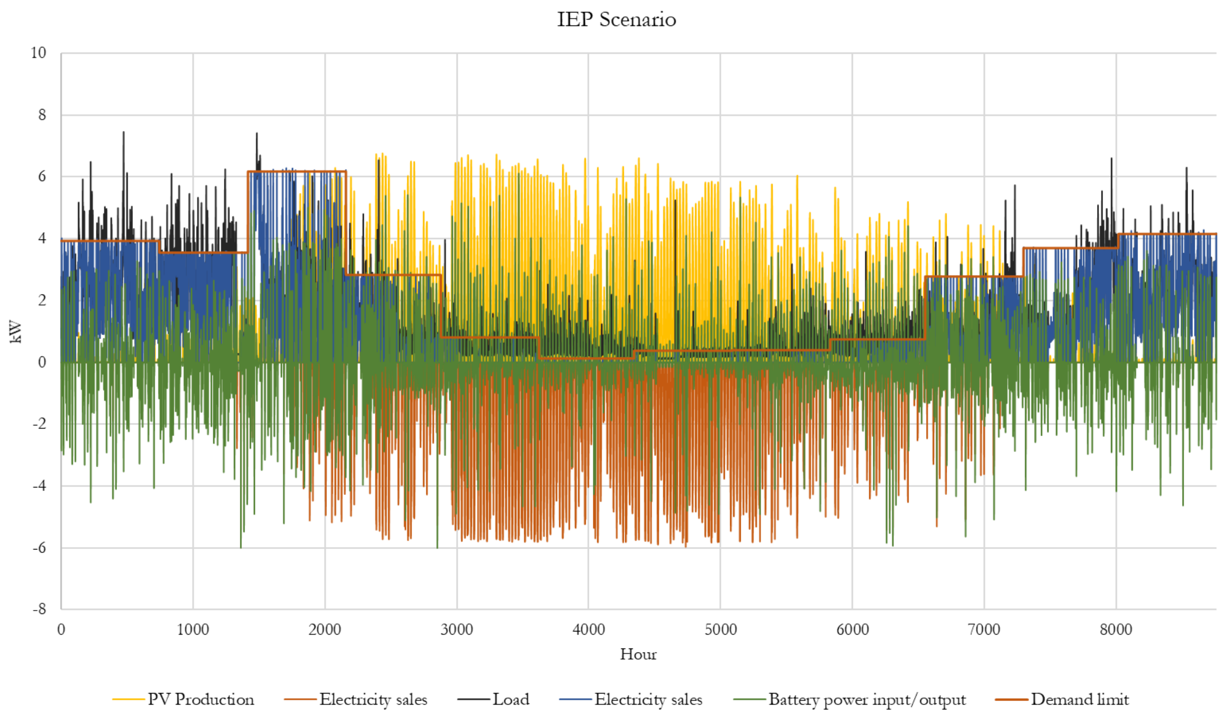

Figure 41: Energy flow for IEP Scenario in Single family house case

C Appendix: Energy flow for Transformer overload

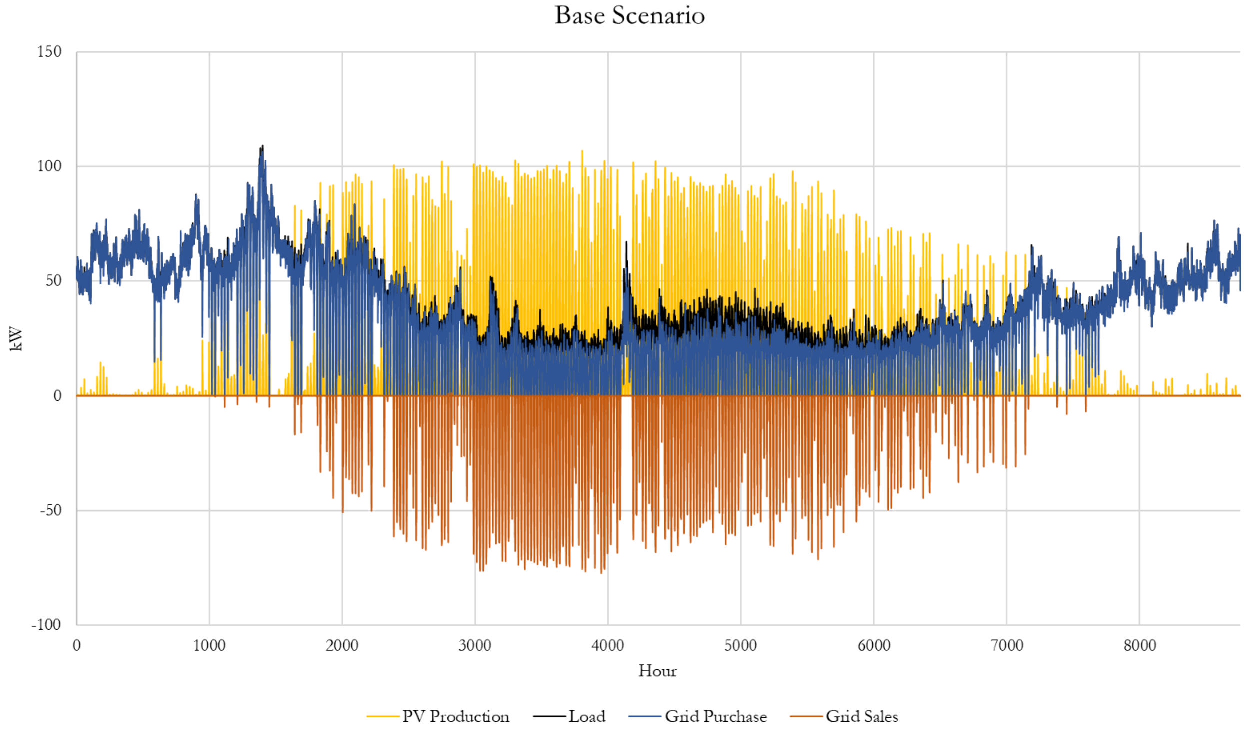

Figure 42: Energy flow for PV scenario in Transformer overload case

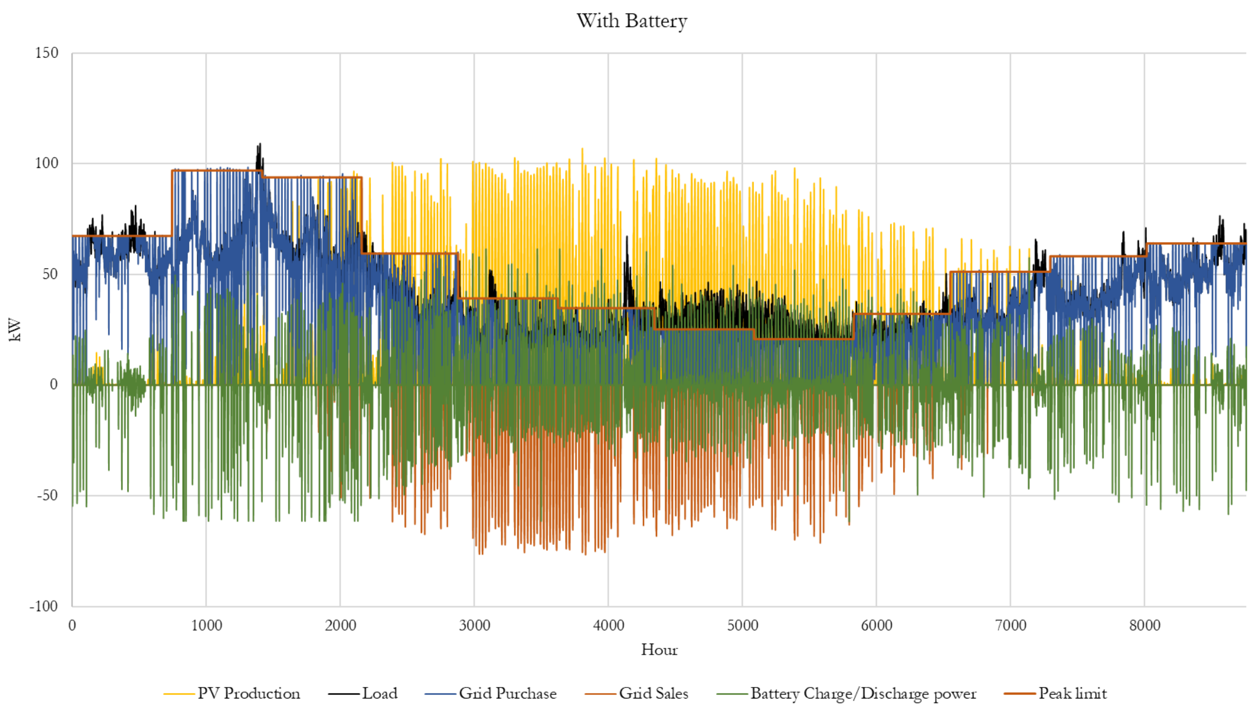

Figure 43: Energy flow for battery scenario in Transformer overload case

D Appendix: Energy flow for Energy community

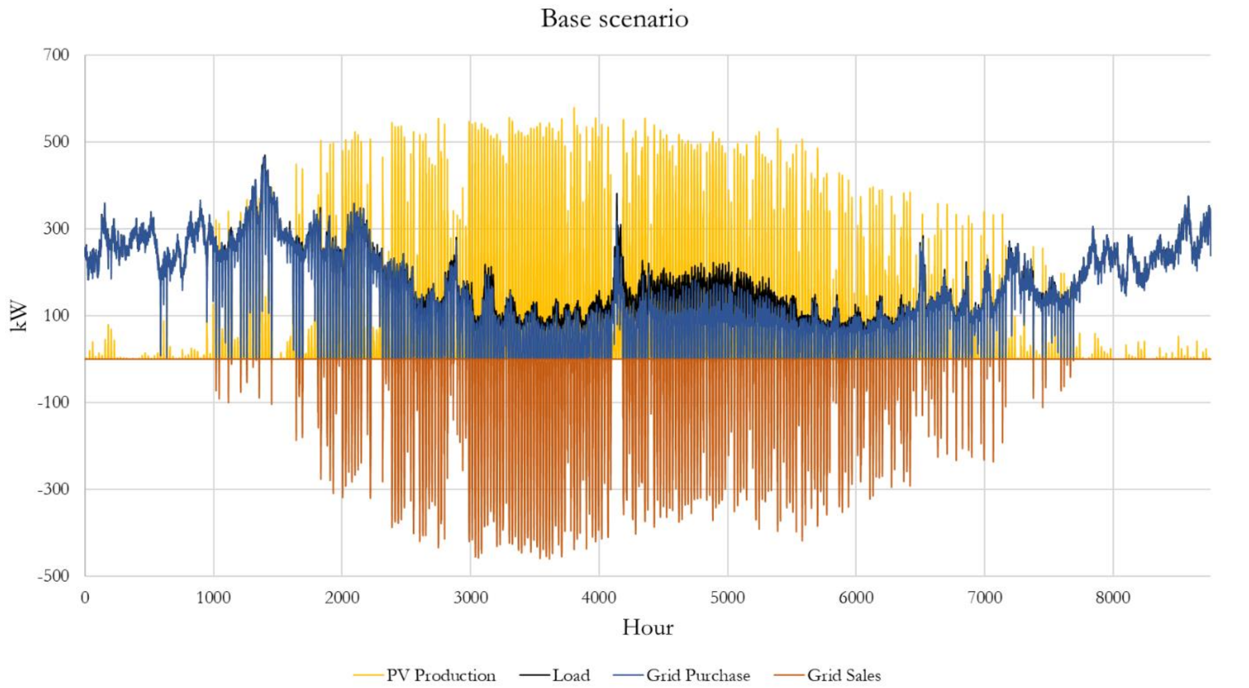

Figure 44: Energy flow for PV scenario in Energy community case

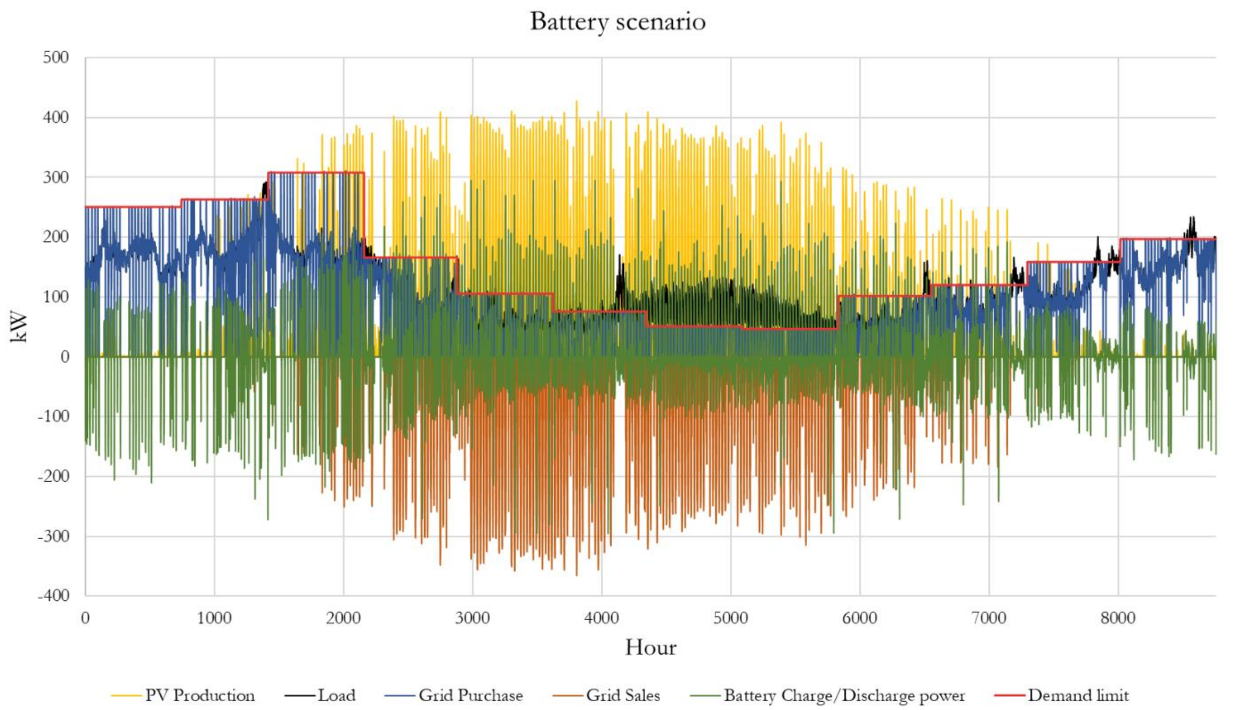

Figure 45: Energy flow for IEP scenario for Energy community case

E Appendix: Energy flow for National

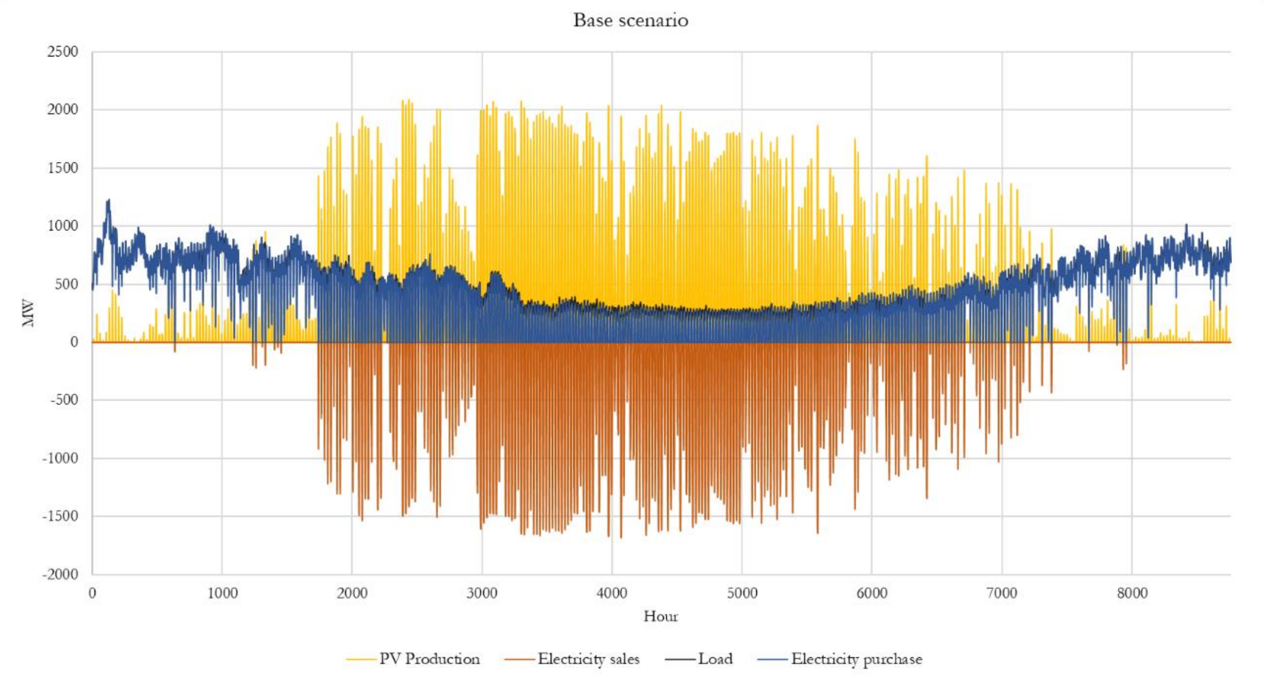

Figure 46: Energy flow for PV scenario for National case

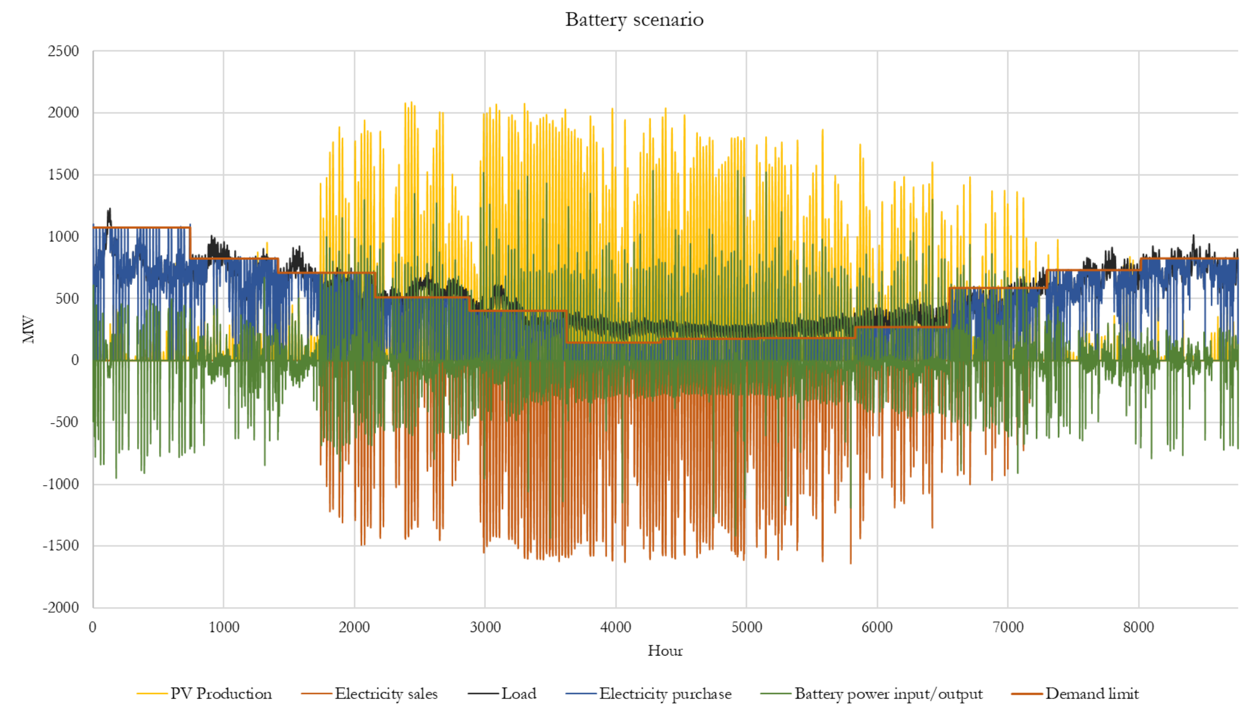

Figure 47: Energy flow for IEPF scenario for National case

F Appendix: Assumed quantities of PV and batteries for National case

Following shows the assumptions and calculations made to assume the total number of households who potentially could have a battery unit installed in Sweden.

Assumption of solar electricity deriving from households:

According to Lindahl, the total solar electricity production in 2018 was around 412 MWp. 46% of this was generated from micro-producers based on reported installations from DSOs, which amounts to 189 MWp (Lindahl et al., 2019). For this thesis, all micro-producers are modelled as single-family households. Not all micro-producers are accounted for in the official statistics from the Swedish Energy Agency, therefore their share is increased to 50% of the total solar electricity generated. This share of households with a PV system is also assumed for the national case.

The amount of installed PV capacity for the national scenario is based on the Swedish Energy agency's goal of 7-14 TWh solar electricity production by 2040 (Energimyndigheten, 2016). Assuming Sweden succeeds in reaching the middle of this goal, 10.5 TWh solar electricity by 2040, 50% of this which is produced by households would be 5.25 TWh.

The annual electricity generation of each installed kWp of solar panels is between 850 – 1 120 kWh/kWp (Swedensol, 2020). Taking the least value of 850 kWh/kWp as the worst case for this study, the total PV capacity needed to fulfill this goal is 6.18 GWp.

The average solar system size for a household is 8 kWp but is assumed to increase to 10 kWp due to increased efficiency of the panels and better roof space management. The number of PV installations and therefore houses is then calculated to be around 617 000 houses.

Assumption on quantities of batteries installed for households:

Following the trend of Germany where every other PV system installation also installs a battery in 2018, half of the households with a PV system would also have a battery installed. This equals to a little less than 309 000 batteries in the Swedish households.

Since only households with both PV and battery units will be modelled the final amount of batteries and PV systems and the total capacity is shown in Table 21 below.

Table 21: Assumed quantities and capacity for battery and PV in case National

National case	Nr of batteries [Quantity]	Battery capacity [MWh]	Nr of PV installations PV [Quantity]	Installed PV [GW_p]
	308 823	2134	617 000	3.09