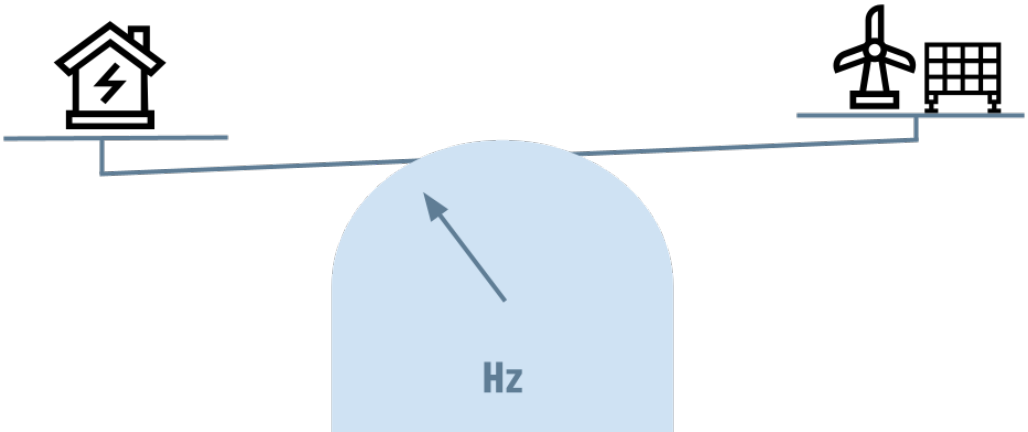

Solar PV and Battery Systems In Sweden:

An investigation of the frequency ancillary market for batteries

Master's thesis in Sustainable Energy Systems and Quality & Operations Management

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Gothenburg, Sweden 2024
www.chalmers.se

Master's thesis 2024

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Master's Thesis 2024
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Cover: Balance between consumption and productin of electricity.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2024

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Abstract

The aim of this thesis was to evaluate the possibilities of tackling the constant changes in the market for frequency ancillary services from batteries, both from a short and long-term perspective. The short-term perspective focused on the possibilities of combining supplying FCR-D to the grid with increasing self-consumption of electricity from solar PV in private homes. This was done in two steps, first historical frequency disturbances were investigated to evaluate the possibilities of increasing the use of batteries thst provide FCR-D. The seond step was done by implementing an algorithm for battery operation that combined FCR-D with increasing self-consumption that was tested on real customer data. The long-term perspective instead focused on service development processes for companies in aggregator positions to give recommendation on how to continuously work with service development to be ready for sudden changes in the market. The result for the short-term perspective showed that 99.7% of disturbances are below five minutes in duration and batteries providing FCR-D never reach any critical levels of not being able to deliver FCR-D during a disturbance. Further, the results from simulating combinations of providing FCR-D and increasing self-consumption showed that a simultaneous operation yielded the highest self-consumption. Using 34% of inverter capacity which had been reserved for recharging gave the highest self-consumption result. Recommendations in the long-term perspective include maintaining close customer relationships and involving them in the service development process, as well as investing in market sensing and structured service development.

Keywords: FCR-D, batteries, solar power, frequency ancillary services, value co-creation.

Acknowledgements

First and foremost, we would like to thank the company CheckWatt for giving us the opportunity to write our thesis with you and for providing us with customer data. Further we want to thank our supervisor Nicholas Etherden for your support and patience. We would also like to thank Johan Wessén for putting time aside to provide us with the digital twin without which our thesis would not have had the same foundation. Last but not least, we wan to thank our examiner and supervisor from Chalmers, Jimmy Ehnberg, for your unwavering support and openness to our ideas.

Karolina Flory Kjellin & Maja Olofsson, Gothenburg, May 2024

List of Acronyms

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

AC	Alternating Current
AEM	Alert state Energy Management
aFRR	Automatic Frequency Restoration Reserve
BESS	Battery Energy Storage Systems
BSP	Balancing Responsible Party
DOD	Depth of Discharge
DSO	Distribution System Operator
FCR-D	Frequency Containment Reserve - Disturbance
FCR-N	Frequency Containment Reserve - Normal
FFR	Fast Frequeny Reserve
LER	Limited Energy Reservoir
mFRR	Manual Frequency Restoration Reserve
NEM	Normal Energy Management
NPD	New Product Development
NSD	New Service Development
PV	Photovoltaic
RES	Renewable-based Energy Sources
SOC	State of Charge
SvK	Svenska Kraftnät
TSO	Transmission System Operator

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1
Introduction

This chapter introduces the reader to the problem which the thesis aims to investigate. It provides background to the problem as well as the limitations of the thesis.

1.1 Background

Frequency ancillary services are essential in the electricity grid as they ensure that generation and consumption of electricity is in equilibrium at all times [1]. The frequency ancillary market is deregulated, where the Swedish transmission system operator (TSO) purchases reserves from different actors on the electricity market to have ready in case of frequency disturbances.

One way to contribute with frequency ancillary services is with battery energy storage systems (BESS), which many private battery owners do. There are several aggregator actors who control a larger pool of batteries that create a virtual power plant that sell frequency ancillary services to the grid. This can be very lucrative for the private owner, but also entail that they keep their battery capacity reserved for frequency disturbances. Therefore, a lot of the time these batteries are not used. For the battery owners who also have solar PV connected, the battery cannot help to increase the self-consumption of electricity generated by solar PV.

As the transition to a more renewable energy system is ongoing, frequency ancillary services will be more and more important as planning production becomes more difficult with increased share of intermittent energy sources. Making demand more flexible with batteries could be an important piece in allowing more renewable energy systems into the energy system. It is an issue that frequency ancillary services and increasing self-consumption cannot be combined as they both play an important part in the energy transition. This thesis will therefore investigate the possibilities of combining the two. As the system is going through a transition and both solar PV and battery technology is quite new, a lot of changes in regulations and trends influence the future of these technologies [2]. The thesis will therefore be separated into two parts, one short term perspective that investigates possibilities of combining supply of frequency ancillary services and self-consumption and one long-term perspective, focusing on having a service development process that can allow for adaptation of services depending on how the market evolves.

1.2 Short-term Perspective

From a short-term perspective, this thesis investigates the possibilities of combining frequency ancillary services with the current regulations and historical behavior of the frequency in the Nordic synchronous area as a foundation for alternative operation for batteries providing FCR-D. Many private battery owners that have connected solar PV's have received a 50 % tax reduction when purchasing their batteries for the purpose of increasing self-consumption of solar produced electricity [3]. As supplying frequency ancillary services has been very profitable, many have instead used their batteries for this purpose instead of increasing self-consumption.

In January 2024, the Swedish Tax Agency announced a new position statement, which included a new interpretation of the tax law which entailed that to be eligible for the tax reduction, the batteries have to be used "exclusively or almost exclusively" for increasing self-consumption [4]. In a clarification, it is stated that this entails that the annual self-consumption should achieve 90-95% of the total maximum annual self-consumption possible in terms of energy [5]. It was in 2021 that the tax reduction for green technology was introduced and between then and 2023, 59 000 individual buyers procured batteries for their homes of which 42 000 in 2023 [6]. In total the Swedish tax agency has disbursed 1900 million SEK for batteries during these three years.

This new interpretation of the tax law might influence private battery owners, both in terms of the income they could lose from not supplying frequency ancillary services, as well as could decrease the investment in batteries. From a sustainability point of view, this could lead to decreased investment and thus also a decreased availability of frequency ancillary services, which in return would make the integration of renewable energy sources more difficult.

1.3 Long-term Perspective

The market for frequency ancillary services are rapidly growing and new companies on the market is increasing [2]. The electricity market is going to go through lots of changes. This opens up for new possibilities, but also challenges. In order to maintain a competitive edge, aggregators providing services in the frequency regulation market must adapt to evolving market conditions. One potential approach to manage the changes in the market for aggregator companies, which offers a service for controlling customer batteries, would be to implement a process for service development.

For technology services the usage of the service might depend on how well the technical features are in line with the value perception of the customer [7]. One way to ensure that new services or technical features will be of value for customers is by adopting value co-creation in the development process. There is existing research and models on how to integrate value co-creation into the development process [7]. This thesis investigates the possibilities to implement a service development process with customer co-creation, as a long-term approach for companies in an aggregator position to be prepared to adapt to the changing conditions on the market.

1.4 Purpose and goal

The purpose of this thesis was to investigate the possibilities of increasing self-consumption of electricity from solar power using batteries, while also providing frequency ancillary services to the Swedish grid. Further the goal of the thesis was to evaluate how customer involvement can be implemented in a service development process for a company in an aggregator position, to increase robustness in an unpredictable market.

1.5 Research Question

The thesis will have two research questions, one which focuses on increasing self-consumption and one that focuses on service development. These are formulated in section 1.5.1, with complementing sub-questions.

1.5.1 Sub-questions

1. Is it possible to increase self consumption of solar produced electricity with batteries in addition to providing frequency ancillary services to the Nordic grid?

   (a) Do the requirements for providing FCR-D align with the characteristics of historical frequency disturbances in the Nordic Synchronous area?

   (b) To what extent does integrating battery operation for FCR-D delivery with self-consumption enhance self-consumption under current technical requirements?

2. How can companies in an aggregator position that provides services structure their service development processes to respond to market changes and maintain long-term viability in the market?

1.6 Limitations

The limitations of this thesis included only looking at FCR-D downwards and upwards, no other frequency regulation services. FCR-N, FFR, aFRR and mFRR were thus not included. Further the thesis only included customer data with an interval of one year from customers with the same type of battery, from the manufacturer Sungrow. The thesis is further limited to private residential users that produce electricity from private solar PV. Further, the technical properties used for the case simulation was scaled to represent an inverter size of 10 kW, battery size of 10 kWh and PV peak size 10 kW as well. For the study on historical frequency disturbances the thesis was limited to an 18 kWh battery and 10 kW inverter. Further it was limited to frequency disturbances between 2015 and 2023. The short-term perspective of the thesis is based on data from ten real customers verified to have typical consumption patterns for Swedish single-family houses. For the long-term perspective part of the thesis that is about service development, it was limited to only a single case company. The thesis does not include any economic calculations of how combining FCR-D with increasing self-consumption would change the income for selling frequency ancillary services.

2

Theory

The chapter presents relevant theoretical background related to the purpose and goal of the thesis, including how the Nordic grid works and what role frequency ancillary services play and what aggregators are. Further the chapter describes self-consumption in the context of the problem and how it is calculated, as well as the role of tax reduction on green investments. Finally the chapter describes the framework used for evaluating the long-term service development.

2.1 The Nordic Power Grid

The Nordic countries Sweden, Norway, Finland and the eastern part of Denmark belong to the same synchronous area, meaning that they are connected by AC grid connections and thus also have the same frequency at all times [8]. Frequency is the balance between production and consumption of electricity and is measured in Hertz (Hz). The Nordic synchronous area has a frequency of 50 Hz and if it deviates more than 0.1 Hz, it is defined as a disturbance [9]. The normal band is thus defined when the frequency is between 49.9 and 50.1 Hz. When the frequency decreases there is too much consumption in relation to production, and if the frequency increases there is too much production in relation to consumption.

2.1.1 Electricity Market

The electricity market in Sweden is deregulated and is also part of the European electricity market, enabling import and export of electricity from countries outside of the Nordic Synchronous area as well [10]. Electricity production is determined on a spot market through trade, managed by Nord Pool [11]. Nord pool is owned by the different national grid companies in the Nordic as well as Baltic countries. Trading takes place both day-ahead and intra-day, where producers place bids on how much capacity they can or want to contribute with and a corresponding price. The spot price is then decided by the marginal price and can be different for different price areas [12].

Even if the electricity market is deregulated in Sweden, the grid network is monopolized [10]. The transmission grid is managed by the Swedish TSO Svenska Kraftnät (SvK) and goes across the entire country as well as connects it to neighboring countries to enable import and export [13]. Large electricity producers and consumers are often connected to the transmission grid as it has a very high voltage, either at 400 kV or 220 kV. Further, there is the regional and the local grid, together called the distribution grid, that connects medium and smaller consumers and producers to the transmission grid [13]. The distribution grid is managed by 170 DSO's across the country [10].

2.1.2 Balancing Market

The balance of production and consumption in the grid is managed by balance responsible parties (BRP) [14]. They are responsible for hourly planning for the balance of the consumption and production based on forecasts within the area which they are responsible. They also bear the economic responsibilities for imbalance between forecasted and actual production and consumption. An hour before the operating hour the balancing plan is sent to SvK, who monitors and regulates the power system in real time. The resources that balance the frequency in the power system are called frequency ancillary services and can be different electricity producers or consumers who the BRP pay to have power available in case of a frequency deviation [14].

Frequency ancillary services are traded on a separate market, where the BRP purchases different services based on the plan they have made. There are several different frequency ancillary services, which are more explained in 2.2, and there is an individual market for each service. There are frequency restoration reserves, frequency containment reserves as well as fast frequency reserves and the different types are important to be able to handle all frequency disturbances. The different services therefore have different technical requirements and are suited for different types of technologies. For many years, hydro power and nuclear power has been the two main sources of electricity in Sweden and therefore hydro power has been the main source of frequency regulation, since it is more flexible [15]. As renewable energy sources like wind power and solar power diffuse on the market, so does the need for frequency regulation since these sources are weather dependent and non-dispatchable, which makes planning more difficult.

2.2 Frequency Ancillary Services

This section describes frequency ancillary services that are operating in Sweden, which are FFR, FCR-N, FCR-D, aFFR and mFRR. The different types of services respond to different type of disturbances and activate at different conditions.

2.2.1 FFR: *Fast Frequency Reserve*

FFR is used to handle large and sudden disturbances when the grid is lacking in rotational inertia [16]. Technologies used for this in 2024 has been energy storage systems and demand flexibility. The endurance requirement for FRR is 30 or 5 seconds depending on what the supplier chooses, and should be ready to reactivate in 15 minutes after a disturbance [17]. The provider is compensated at the bidding occasion, after call off, not for activating the service.

2.2.2 FCR-N: *Fast Frequency Reserve - Normal*

FCR-N handles frequency variations within the normal band that occur due to small changes in production or consumption [16]. The service provider is compensated for the energy that is provided to the grid. FCR-N is mostly regulated by hydro power and wind power, but also from energy storage and CHP (Combined Heat and Power plant) in smaller scale [18].

2.2.3 FCR-D: *Frequncy Containment Reserve - Disturbance*

FCR-D is activated automatically when the frequency goes outside of the normal bandwidth, i.e. below 49.9 Hz or above 50.1 Hz. FCR-D services are today provided from hydropower, batteries, cogeneration, flexible consumption, solar and wind power [18]. As FCR-D operates for disturbances due to both consumption and production deficits, it can be called two different things. *FCR-D upwards* operates when the frequency is between 49.9 and 49.5 Hz and get its name because it should bring the frequency up [19]. *FCR-D downwards* operates between 50.1 and 50.5 Hz and brings the frequency down [20].

The capacity requirement to be approved as a FCR-D provider is 0.1 MW and an endurance requirement of 20 minutes [18]. The allowed size for FCR-D upwards and downwards are dimensioned for disturbances that could occur due to the loss of interconnection and nuclear power plant shutdown [19], [20]. For upwards regulation, these requirements are based on if only one of the two nuclear power plants is operating and for downward regulation if one of the international connection Nordlink or Nordic Sea Link is disconnected.

2.2.4 FRR: *Frequency Restoration Reserve*

There are two types of FRR, aFRR (automatic frequency restoration reserve) and mFRR (manual frequency restoration reserve) [16]. Both are used to restore the frequency to 50 Hz, but aFRR reacts and activates automatically with a signal from SvK when the frequency deviates from 50 Hz. The activation time for aFRR is five minutes [21]. mFRR is activated manually by SvK to relieve the automatic frequency regulation services. The activation time for mFRR is 15 minutes [22].

2.3 Aggregators

Independent aggregators are suppliers on the frequency ancillary market that aggregate several smaller flexible resources into a one larger entity that can be sold on the market [23]. An example is having several small batteries that collectively can act as one large battery. One private battery owner cannot provide frequency ancillary services alone due to the minimum market bid size, but has to belong to an aggregator who in return can make an agreement with the BRP [24].

2.4 Self-Consumption

Self-consumption is defined as the share of produced electricity from solar PV that is consumed in the house where it is produced [25]. In a scenario where there is no battery involved, the self-consumption is the direct use of the produced solar power. In a scenario where the customer has a battery, the self-consumption is the direct use of the produced solar power in addition to excess power that is used to charge the battery. Self-consumption (SC) is defined as

$$SC = \frac{E_{direct} + E_{Batt}}{E_{PV}} \tag{2.1}$$

where E_{PV} is the total produced electrical energy produced in a certain time interval, E_{direct} is the total solar energy that is consumed in the house during the same time interval and E_{Batt} is the electrical energy that the battery is charged with during the interval.

2.5 Four-stage framework for New Service Development

The framework used to evaluate the long-term service development process is called the four-stage framework and is created by Daniel Kindström and Christian Kowalkowski [26]. The framework is about New Service Development (NSD) process and is developed based on the New Product Development (NPD) process. The framework presents four stages in the development process, which are market sensing, development, sales and delivery (figure 2.1). Adopting a structured service development process can increase the efficiency and effectiveness [26]. It is important to highlight that this process is a continuous process, meaning that companies need to go through these stages continuously and not stop after completing one stage [26].

When it comes to services, customers are perceived as active relationship-oriented actors rather than passive transaction-oriented actors, as they are perceived in more traditional product transactions [26]. Therefore, the customer's input can be crucial for designing value adding services [27]. The customer co-creation should be present in all four stages [26].

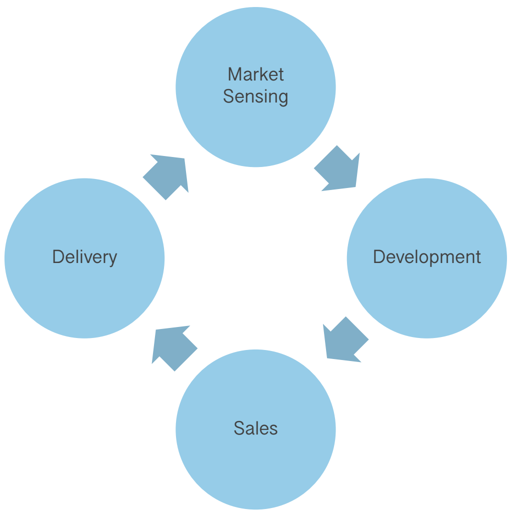

Figure 2.1: Four-stage framework of New Service Development

The first stage is *Market Sensing* and is about the ability to sense the market which is crucial for learning about customers, competitors, and other actors in the business environment [28]. Some important aspects of market sensing include: defining the market and determining specific requirements and market needs; observing the competition; assessing customer value; and gaining customer feedback [28].

Then follows the *Development stage*, and in this framework it follows the NPD process but is adapted to the service offerings [26]. However, the customer involvement is more important as the development of the service, especially new services, the customer involvement has shown a direct effect on the attractiveness and value of the service [29]. The reason being that the value created from the service is harder to visualize in comparison to NPD, as services are intangible and depend on how customers perceive it.

The *Sales stage* of a service is more complex than selling a product. When selling a product or service there needs to be value created for the customer. When discussing value creation two concepts can be used; value-in-exchange and value-in-use [30]. Value-in-exchange refers to what buyers are willing to pay for the product and is determined by market demand, supply, market competition, and market condition. The concept of value-in-use refers to how a customer perceives their benefit or drawback based on experiences related to consumption [30]. For services, value-in-use is important to consider, however, that is also what makes the sales process complex. Value-in-use is very subjective and can differ between the consumers [30]. Therefore, it is important to have great knowledge about how the service can create value for different customers.

The *Delivery stage* for services is often people intensive as the services often take place in an interaction between the customer and supplier [26]. Some companies allocate the contact with the customers to their partners. The partners then take care of the installations and also the customer support.

3
Methods

This chapter describes the method adapted to answer the research questions.

3.1 Summary

For the short term perspective, both historical frequency disturbances as well as current regulations were applied to create a controller that combined self-consumption and supplying FCR-D. Historical frequency data was used to evaluate the character of historical disturbances and how they have influenced a battery with certain specific properties. This was then used as a foundation for creating four different cases and new controller algorithms that were tested on real customer data to evaluate the self-consumption of each case.

Further, for the long-term perspective, a framework was adapted on the service development process to evaluate how aggregators in the market can organize their service development processes to be able to adapt to changes within the area of frequency regulation and battery control.

3.2 Data Collection

This chapter describes how the data used in this thesis was collected and handled.

3.2.1 Historical Frequency Data

The frequency data between 2015 and 2023 was collected from the Finnish TSO *Findgrid*, who has an open database online with the historical frequency. The resolution was in 100 milliseconds. As the controller uses one frequency value per second, the data was reduced to the values on whole seconds. It was discovered that there was a few periods of frequency data missing. However, most cases of incomplete data lasted only a few seconds. Therefore, these periods were disregarded, as it was concluded that they would not have a significant impact on the results for the last nine years. The frequency data is therefore not continuous and though the impact should be minor when looking at such a long time frame, the results could be underestimated.

3.2.2 Customer Data

The customer data was provided by CheckWatt. Customers with Sungrow batteries and solar PV installations, with data going back further than a year was collected, which resulted in ten customer. The smallest resolution was in minutes and was therefore chosen to get as an exact result as possible. Previous work on this matter was studied to evaluate the impact of the resolution. In a single household with fluctuating load, it is recommended to use data with one minute resolution, but if the consumption does not change much over time, then data points every 15 and even 60 minutes can be used [31].

The customer data that was used was PV production, sold electricity and bought electricity. As the customer load was not available, it was calculated with (3.1) h

$$Load = PV\,production\ -\ sold\ +\ bought \tag{3.1}$$

on the ten customers. The data was also made anonymous to protect customer integrity and numbered identifiers were used to distinguish the different customers.

3.3 Evaluating Self-Consumption

This section describes how the possibility of increasing self-consumption was evaluated.

3.3.1 Historical Frequency Disturbances

The historical frequency data was evaluated by identifying usual duration of disturbances as well as how they would have affected a battery providing FCR-D. The duration of historical frequency disturbances was identified by creating a script in Python that identified the start and end times of when the frequency exits and re-entries of the normal bandwidth, between 49.9 Hz and 50.1 Hz. Further, it was calculated how often there were frequency disturbances each year. This was done by summing the time duration of all disturbances each year and dividing it by the total time in a year. This was done for the years 2015 to 2023 as well and an average was made for a general conclusion.

Furthermore, the average inverter activation needed to deliver FCR-D during these nine years was calculated. This means that if a disturbance occurs when the frequency is 49.5 Hz or 50.5 Hz (the limits where FCR-D operates), the inverter activates at 100%. For smaller frequency disturbances, the inverter activation will also be proportionally smaller. This indicated how much the frequency has deviated from the normal bandwidth on average. The activation percentage, a, is proportional to the frequency deviation and is calculated with

$$a_{upwards} = \frac{49.9 - f}{49.9 - 49.5} \cdot 100 \tag{3.2}$$

when the frequency is below 49.9 Hz. f is the frequency in the current second. When the frequency is above 50.1 Hz the activation percentage is calculated with

$$a_{downwards} = \frac{f - 50.1}{50.5 - 50.1} \cdot 100 \tag{3.3}$$

The battery behavior in terms of energy was evaluated by using the historical frequency as input in a digital twin of the CheckWatt controller. The output was the SOC for a 18 kWh battery and 10 kW inverter in second resolution, as well as the FCR-D activation. As mentioned in section 2.2.3, the endurance requirement for FCR-D providing entities is to supply FCR-D for 20 minutes at full bid power. Therefore the battery SOC needs to stay within certain boundaries that ensures there is enough energy to meet the endurance requirement. The objective was to test if or how often the battery reaches these limits.

To evaluate whether or not the battery reaches the SOC limits, the historical frequency obtained from Fingrid between 2015 and 2023 was used as input in the digital twin. The SOC aimed to recharge to 50% and was therefore used as an initial SOC. The controller was run one year at a time, and the output SOC was used as input SOC for the next year. The lower limit is defined by (3.4) as follows

$$SOC_{limit\,lower} = P_{bid} \cdot t \cdot \frac{1}{E} \cdot 100 \tag{3.4}$$

where the limit reflects the theoretical lowest SOC that should be maintained to be able to discharge the battery for 20 minutes with the full bid power. P_{bid} is the pre-qualified power that was bid and accepted on the market, E is the maximum battery capacity in terms of energy and t is the endurance requirement. The upper limit is defined by (3.5) as follows

$$SOC_{limit\,upper} = 100 - \left(P_{bid} \cdot t \cdot \frac{1}{E} \cdot 100\right) \tag{3.5}$$

where the limit reflects the highest theoretical SOC that should be maintained to be able to charge the battery for 20 minutes with the full bid power.

3.3.2 Case simulation

To evaluate the actual self-consumption and how much it could be increased, four cases were simulated with different priorities on FCR-D and self-consumption. In the first case, the controller only allowed the battery to react on FCR-D and keeping the battery SOC within the allowed limits for delivering FCR-D. The second case had the opposite objective, where the only use of the battery was to increase self-consumption. The third case (divided into 3a and 3b) used a combination of FCR-D and self-consumption operation.

The third case was divided into two sub-cases; 3a and 3b. The two cases have different priorities, 3a prioritizes FCR-D and case 3b prioritizes self-consumption. In case 3a, the exact same bidding strategy as in case 1 was used, but the small part reserved for recharging in the inverter was used to increase self-consumption, by charging and discharging when applicable. In this case no revenue was lost since the maximum bid was made every day. Case 3b was instead based on changing the bidding strategy to not bidding upwards and downwards at the same time and thus take advantage of changing the direction of the power in the inverter. For example if a bid was made for FCR-D upwards during the morning, the battery could charge with 100% of the inverter capacity because the inverter would switch direction during an activation.

To evaluate whether the self-consumption result for cases 3a and 3b was high, low or normal, they were compared to the result in case 2, which was the maximum annual self-consumption. This is referred to as the *relative consumption* and is defined as the share of maximum annual self-consumption that case 3a and 3b achieved in percent of self-consumption obtained in case 2. The result of self-consumption from case 1, the direct use of PV production, was also included in analyzing the result, as to see how important the direct use was to the result. As stated in the introduction, the regulations from the Swedish Tax Office states that the batteries have to reach 90-95% of the annual maximum self-consumption possible for the battery owner to be eligible for receiving the green tax reduction. Therefore, the result was also evaluated whether the annual self-consumption reached 90-95%.

As mentioned in 3.2.2 the cases were simulated on data from ten different CheckWatt customers. The thesis was limited to evaluating self-consumption with a 10 kWh battery, 10 kW inverter and 10 kW peak PV capacity. As the PV and battery size of the customers were different, the simulations were ran with normalized production. The production was normalized by converting the production profile to a PV profile (a share of the peak capacity). This was then applied to 10 kW peak PV capacity and used in the simulation. The consumption was kept as their actual values, as it is individual to each customer, regardless of changing battery, inverter or PV peak size. The simulation for each case and each customer was then executed with the battery, inverter an PV peak sizes stated in the limitations.

3.4 Sensitivity Analysis

A sensitivity analysis was performed on the short term perspective case study to evaluate the robustness of the results, but also to see which parameters would affect the results mostly. Thus the sensitivity analysis should also show whether the power of increasing self-consumption mostly lies with the customer, hardware or TSO requirements. The parameters that were included in the sensitivity analysis was the battery and inverter size, the bidding size as well as endurance requirement. The endurance requirement can also be seen as a parameter for the SOC limits, as they are directly proportional to the endurance. The SOC limits are important, as the aging of batteries influence their performance and thus the SOC limits could have to be made more narrow with time. The sensitivity analysis was performed on one customer and this customer was chosen due to having close to the average properties of all the identified customers, in terms of battery, inverter and PV peak size, as well as average annual production and consumption among the tested customers.

3.5 Long Term Service Development Process

The address the long-term perspective part of this thesis a qualitative analysis of service development processes for a company that has an aggregator position and offers services for private customers was conducted.

As the value of the service is based on customer satisfaction, the customer contact and input is an important factor to bring into the service development process. To establish a long-term perspective for the service development process, the approach in this thesis was therefore to adopt a New Service Development process framework and focus on value co-creation to seize innovation opportunities and offer value-adding services for customers.

The case on which the analysis was performed was the company CheckWatt and how they interact with their customers. The analysis was based on observations on site and information from company website to evaluate the way they interact with their customers, in terms of receiving feedback and sharing information and support.

The framework was applied on company to evaluate their adaptability to the changing market as well as how they can increase value for customers. This was done with the four stage framework by Kindström et al. [26] which promotes a continuous process in four stages, creating a cycle of interaction with customers throughout the process to increase value of the service. The framework was made with the focus on manufacturing companies that is transitioning to services.

3.6 Case company

The case company, CheckWatt, has an arrangement with third-party actors that handles the direct contact with their customers [32]. To become a customer, a controller needs to be installed in the residence of the customer, or the facility where the battery is connected. This is handled by this third-party called *partners*. The partners install the hardware and thereafter manages the direct contact with the customers. The case company, CheckWatt, therefore does not have any direct customer contact, but instead communicates through the partners.

4

Case modeling

This chapter describes how the controllers for the different cases were built and how the cases where simulated.

4.1 Case Description

This section describes the assumptions and regulations adapted to creating the cases as well as a description of operation of the different cases.

4.1.1 Assumptions and Limitations

To become and remain a supplier of frequency ancillary services, there are regulations that have to be followed. These regulations were written together by the Nordic TSO's that are a part of the Nordic synchronous area in the document *Technical Requirements for Frequency Containment Reserve Provision in the Nordic Synchronous Area* [33]. The regulations include how much power that should be provided and for how long as well as regulations for recharging. These limitations had to be implemented in the simulation of the three cases and are described in this section.

4.1.1.1 Frequency To Energy

How much energy that is provided from each battery during a disturbance is directly proportional to the duration of the frequency deviation and the bid power of the inverter (P_{bid}). The activation of the inverter (i.e. the share of the bid power that is activated) is proportional to the frequency deviation. If the frequency is at or below 49.5 Hz or at or above 50.5 Hz, the inverter is activated 100% of the bid power in up- or downwards direction respectively. The total energy provided with FCR-D upwards during a low frequency disturbance ($E_{FCR-D\,upwards}$) is defined with (4.1) as

$$E_{FCR-D\,upwards} = \sum_{n=1}^{N} \frac{49.9 - f_n}{49.9 - 49.5} \cdot P_{bid} \cdot t \tag{4.1}$$

where f_n the frequency at the measured time and t is the time resolution of the measured frequency. N is the length of the disturbance with the time resolution. f_n is defined for all frequencies below 49.9. When the frequency is too high, the energy provided ($E_{FCR-D\,downwards}$) was calculated with (4.2) as

$$E_{FCR-D\,downwards} = \sum_{n=1}^{N} \frac{f_n - 50.1}{50.5 - 50.1} \cdot P_{bid} \cdot t \tag{4.2}$$

where f_n is defined for all frequencies above 50.1. The inverter is not activated at full bid power at all frequency disturbance, but activated in proportion to the size of the frequency disturbance. If the frequency goes below 49.5 or above 50.5, the inverter keeps delivering FCR-D at 100% bid power.

4.1.1.2 Energy management

A battery falls under the category *LER*, limited energy reservoir, in the technical requirements for FCR provision in the Nordic synchronous area [33]. LER's must implement energy management schemes to ensure that there is enough energy for the FCR provision. There are two states of energy management - normal state energy management (NEM) and alert state energy management (AEM). NEM is activated when the frequency is in the normal band, but the SOC is either too low to meet the requirements for FCR-D upwards or too high for FCR-D downwards. AEM should be enabled when the energy reservoir is near depletion. During these states the FCR provider needs to take action to restore the SOC to ensure endurance.

For FCR-D, the LER has to reserve between 20% and 34% of the bid power capacity (P_{bid}) for restoring the endurance. If a larger recharging capacity is used, then the bid has to decrease. This is in case an LER is performing recharging to restore endurance and there is a disturbance in the same direction. The LER then has to have capacity to provide FCR-D. It is therefore never possible for a battery to bid the entire power capacity of the inverter for FCR-D when providing FCR-D in both directions. The maximum power bid that can be placed $P_{bid,\,max}$ is defined with (4.3) as

$$P_{bid,\,max} = \frac{C}{1.2} \tag{4.3}$$

where C is the maximum power capacity of the inverter.

The SOC limits for energy management is calculated with (3.4) and (3.5) found in section 3.3.1. When the SOC of the battery goes outside of these limits, the battery should restore the SOC with a factor called $NEM_{current}$. $NEM_{current}$ is calculated with (4.4) as

$$NEM_{current}(t_i) = \frac{1}{N} \sum_{n=1}^{N=300} NEM_{allowed}(t_{i-1}) \tag{4.4}$$

where $NEM_{allowed}$ is a another factor that decide the share of the inverter power that should be used for recharging. It is defined with (4.5) as

$$NEM_{allowed} = \begin{cases} -1, & \text{if } 49.9 < f < 50.1 \text{ and } SOC < SOC_{NEM,lower} \\ 1, & \text{if } 49.9 < f < 50.1 \text{ and } SOC > SOC_{NEM,upper} \\ 0, & \text{otherwise} \end{cases} \tag{4.5}$$

which is then used to decide the power set point $P_{tot,FCR-D}$. The power set point is the total activation of the inverter for FCR-D and for recharging and is defined with (4.6) as

$$P_{tot,FCR-D} = P_{FCR-D} + P_{NEM} = P_{FCR-D} + 0.20 \cdot P_{bid} \cdot NEM_{current}. \tag{4.6}$$

where P_{FCR-D} is the power activation during a disturbance, i.e. the delivery of FCR-D. As the $NEM_{allowed}$ is defined to be zero within the normal bandwidth, either P_{FCR-D} or P_{NEM} is negative, while the other is not.

AEM is entered when the endurance of the battery is shorter than five minutes. The power set point for recharging in this state is set by the magnitude of the frequency deviation and is designed to deactivate the steady state response over five minutes. The power set point is calculated with (4.7) as

$$P_{FCR-D}(t) = P_{bid} \cdot \Delta f(t) = P_{bid} \cdot (f_{ref} - f(t)) \tag{4.7}$$

where f_{ref} is calculated with (4.8) like

$$f_{ref} = \frac{1}{N} \sum_{n=1}^{N=300} f_{AEM} \tag{4.8}$$

and f_{AEM} is calculated with (4.9) in the following manner

$$f_{AEM} = \begin{cases} f_0, & \text{if } SOC \in [SOC_{AEM,lower}\ SOC_{AEM,upper}] \\ f(t), & \text{otherwise} \end{cases} \tag{4.9}$$

When the battery has reached ten minute endurance the AEM is disabled.

4.1.1.3 Utilizing energy management for self-consumption

For case 3a, when FCR-D and self-consumption are combined, the goal was to keep the same size of the bid for FCR-D to not decrease the revenue for the customer. Therefore self-consumption could only be increased by using the reserved 20% of P_{bid} to charge the battery with excess solar power and discharging when the house load allowed. Whether or not this is an allowed method is not clearly stated in the the technical requirements for the Nordic Synchronous area. The requirements presented by ENTSO-E, states that it is encouraged to trade the energy for restored for energy management and use it thereafter in addition to the energy management required according to the rules stated in this chapter [33].

The interpretation by Danish TSO *Energinet* states that the capacity that is reserved for energy management can be used in other markets except for further ancillary services [34]. It is not stated what markets are allowed to trade in. In the document by ENTSO-E, it is stated that the energy that could be extracted during energy management can only be used if it has been sold on another market in advance. In case 3b, the energy management does not have to be considered in the same way as it only provides FCR-D in one direction at a time and therefore does not have any restrictions in how large share of the inverter can be used for self-consumption operation.

4.1.1.4 Self-consumption

According to the Swedish tax office, the purpose of tax reduction for batteries is to increase the annual share of self-produced electrical energy that is used in the property [35]. The self-consumption is therefore defined as the electricity from solar PV directly used in the house and the excess electricity that is charged into the battery, as a share of the total PV production, see (2.1). In the cases where FCR-D is also one of the end uses for the battery, the amount of electricity that goes out to the grid in case of FCR-D upwards and too small load in the house was included in the algorithm. In case of such a situation, the amount of energy sold as FCR-D upwards to the grid from the battery was removed from the self-consumption.

4.1.2 Modeling

This section describes how the model for the controller was developed.

4.1.2.1 Case 1: Only FCR-D

In case 1, the main use of the battery was FCR-D. This means that the PV production is never charged to the battery and the discharge during FCR-D upwards can therefore not be counted as self-consumption. In this case, the self consumption is therefore solely the electricity that is used at the same moment as it is produced. Figure 4.1 demonstrates a flow chart of how case one was modeled. In this case, the maximum bid size was applied and the reserved power for recharging was not used for any other purpose than energy management, and this energy was not used in any other markets. Thus, the only use of the battery was FCR-D. In the recorded data there could have been instances where PV-production and FCR-D downwards occur at the same time, but these quantities of energy are negligible compared to the amount that is charged from the grid. This was concluded from the results of analyzing historical frequency disturbances in the CheckWatt controller, which showed that frequency regulation only occurred on average 2% of the time during a year, see section 5.1.2. Therefore only momentary use of PV electricity was counted as self-consumption.

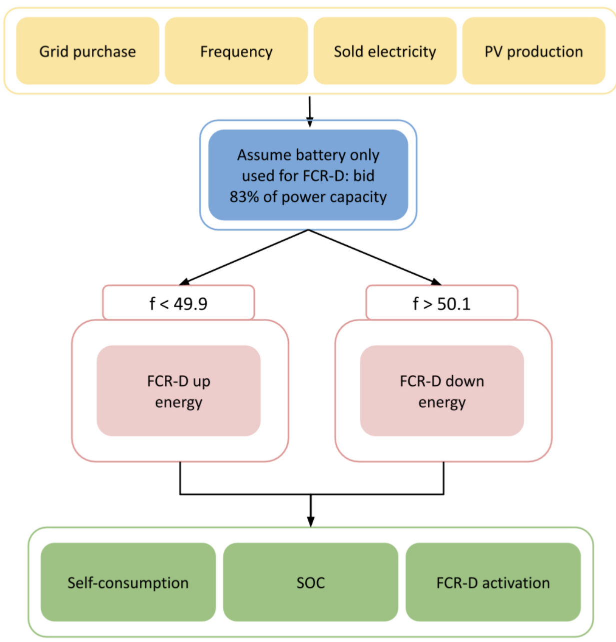

Figure 4.1: Flow chart of operations of case one. The yellow boxes represent input data, the blue assumptions, the red represent the battery operation during different conditions and the green boxes are the output data.

4.1.2.2 Case 2: Only Self-consumption

In case 2, the only use of the battery was to increase self-consumption, which also means that no regulations from SvK had to be applied. This case was modeled to find the maximum possible self-consumption within the limitations of the thesis, for comparison with case 1 and 3. A flow chart of the operation of case 2 is illustrated in Figure 4.2. The aim of the operation was to charge the battery with as much daily excess electricity from the solar PV as possible. Therefore the SOC boundaries that the battery had to range between was 10% and 90%. These boundaries are set due to the cycle life, which is the amount of cycles that at battery can complete before the performance starts to decrease [36]. The cycle life is largely affected by the DoD, which is a measurement of the share of battery capacity being used. Boundaries above 0 % and below 100 % are therefore applied to decrease damage on the batteries.

Ideally the battery would have a low SOC in the morning to be able to charge as much from the excess electricity during the day, which would then be used during the evening and nighttime when the sun has gone down, through battery discharge. The battery discharges to the house if there is a higher consumption than production, because then there is a load in the house and the battery is not charged by excess solar power. The self-consumption in this case was calculated with (2.1).

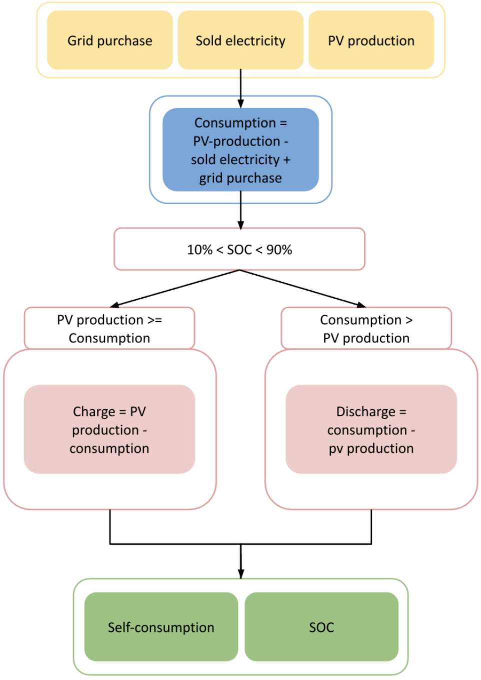

Figure 4.2: Flow chart of operations of case two. The yellow boxes represent input data, the blue assumptions, the red represent the battery operation during different conditions and the green boxes are the output data.

4.1.2.3 Case 3a: Simultaneous FCR-D and Self-Consumption

This case demonstrates a scenario when FCR-D operation is combined with self-consumption. Figure 4.3 demonstrates the operation of the controller for this scenario. The inputs are the same as in case 1 and 2, the frequency for the studied period was also added in order for the battery to activate during disturbances. The same bid size as in case 1 was used and 20% of bid size was used for increasing self-consumption. It was also tested with a 34% recharging rate, which is the maximum rate allowed to reserve for recharging [33]. The operation was based on that when the SoC is between the NEM-limits (within which endurance can be ensured) 20% of P_{bid} is allowed to be used for self-consumption.

As shown in Figure 4.3, if the SOC reaches the SOC limits limits during a self-consumption, the operation will stop and recharging or discharging will start to remain at the boundary. In case of a long disturbance and/or a disturbance with a large frequency deviation, the SOC is allowed to pass these limits to ensure that frequency in the grid is recovered. Due to the regulations that come with delivering FCR-D, delivery and recharging was always prioritized over self-consumption. As

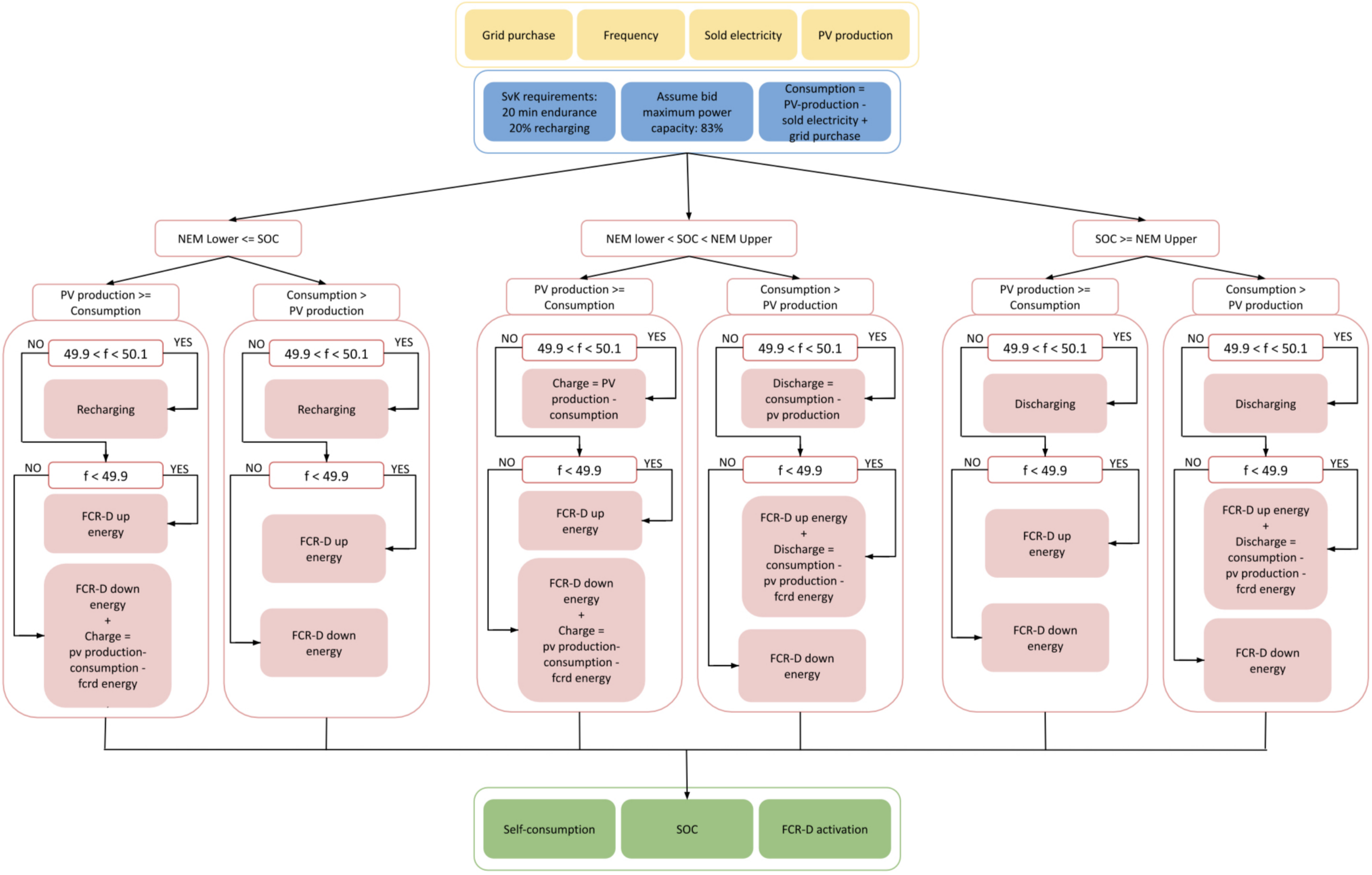

Figure 4.3: Flow chart of the operation of case 3a. The yellow boxes represent input data, the blue assumptions, the red represent the battery operation during different conditions and the green boxes are the output data.

the resolution of the customer data was in minutes, recharging according to (4.4) was not possible, instead recharging at 20% of bid inverter power was applied when SOC reached or passed the NEM-limits. $NEM_{current}$ was in other words always 1 or -1 if recharging was needed.

As the customer data was in minute resolution, the energy that needed to be provided for FCR-D was calculated per second and then summed over one minute. Therefore all frequency disturbances in the algorithm were at least one minute long, even if they in reality were shorter. Thus, the FCR-D supply in the cases were larger than they would have been in reality.

As seen in the figure, if production is larger than consumption, then the battery is charged with the maximum allowed inverter capacity (20% of bid inverter power), provided that there is no frequency disturbance. If the battery on the other hand is delivering FCR-D downwards and the production is larger than the consumption, the battery is charged with the bid inverter power. The maximum bid was used.

Given that consumption is larger than production and there is no frequency disturbance, the battery discharges into the house with maximum allowed inverter capacity. If FCR-D upwards is being delivered and consumption is larger than production, the battery discharges into the house with bid inverter power of the inverter capacity.

The self consumption was calculated with (2.1), as for case 1 and 2, but in this case it was possible that some energy discharged during FCR-D upwards could go out on the grid. This variable was therefore included in the calculation of self-consumption so that the self-consumption level only accounts for energy that was used in the house.

4.1.2.4 Case 3b: Time-separated FCR-D and self-consumption

The case was based on prioritizing self-consumption in a way where 100% of the inverter can be used for charging and discharging, in difference from case 3a. To do this, a bid for FCR-D could not be made in both directions at the same time due to the requirement for recharging. The operation was therefore designed to only charge the battery during the day in case of excess PV production and only discharge during the night when the consumption was higher than the PV production. The battery was in other words not allowed to discharge during the day or to charge during the night in order to be able to bid for FCR-D upwards in the day (which means an activation in the opposite direction than when charging) or FCR-D downwards in the night (which means an activation in the opposite direction than when discharging).

In this case the objective was to charge with as much solar production as possible. The exact times that distinguished day from night was different depending on the season. These times were based on the sunrise and sundown in the middle of Sweden. During winter (Nov, Dec, Jan, Feb), the day is defined between 8 in the day until 16 in the afternoon. During these hours the battery was charged with excess PV production with 100% of the inverter and also activated FCR-D upwards with 100% bid power. The other hours of the day, the battery discharged when there was more consumption than production and activated on FCR-D downwards with 100% bid power. During the spring and fall months (March, April, September and October), the day was defined as 7 in the day until 19 at night and the summer months (May, June, July, August) the day ran from 5 in the day until 21 at night.

The demands from case 3a are therefore different from case 3a. Since the bidding was only done in one direction, only one SOC limit for recharging is demanded (apart from going below 0% and above 100%). For FCR-D upwards there was a lower limit but no upper and for FCR-D downwards there was an upper limit but no lower. These limits were decided by the 20 minute endurance requirement and the maximum bid power. In case the SOC exceeded these limits, recharging (or discharging) would be activated with 100% of the inverter power. This is possible since the FCR-D activation occurs in the opposite direction. During the other hours the battery was not allowed outside of the SOC range 10-90% to not damage the battery. If there was enough excess PV production, it was used during recharging and if there was enough consumption during discharging it was discharged into the house. See figure 4.4 for flow chart of case 3b operation.

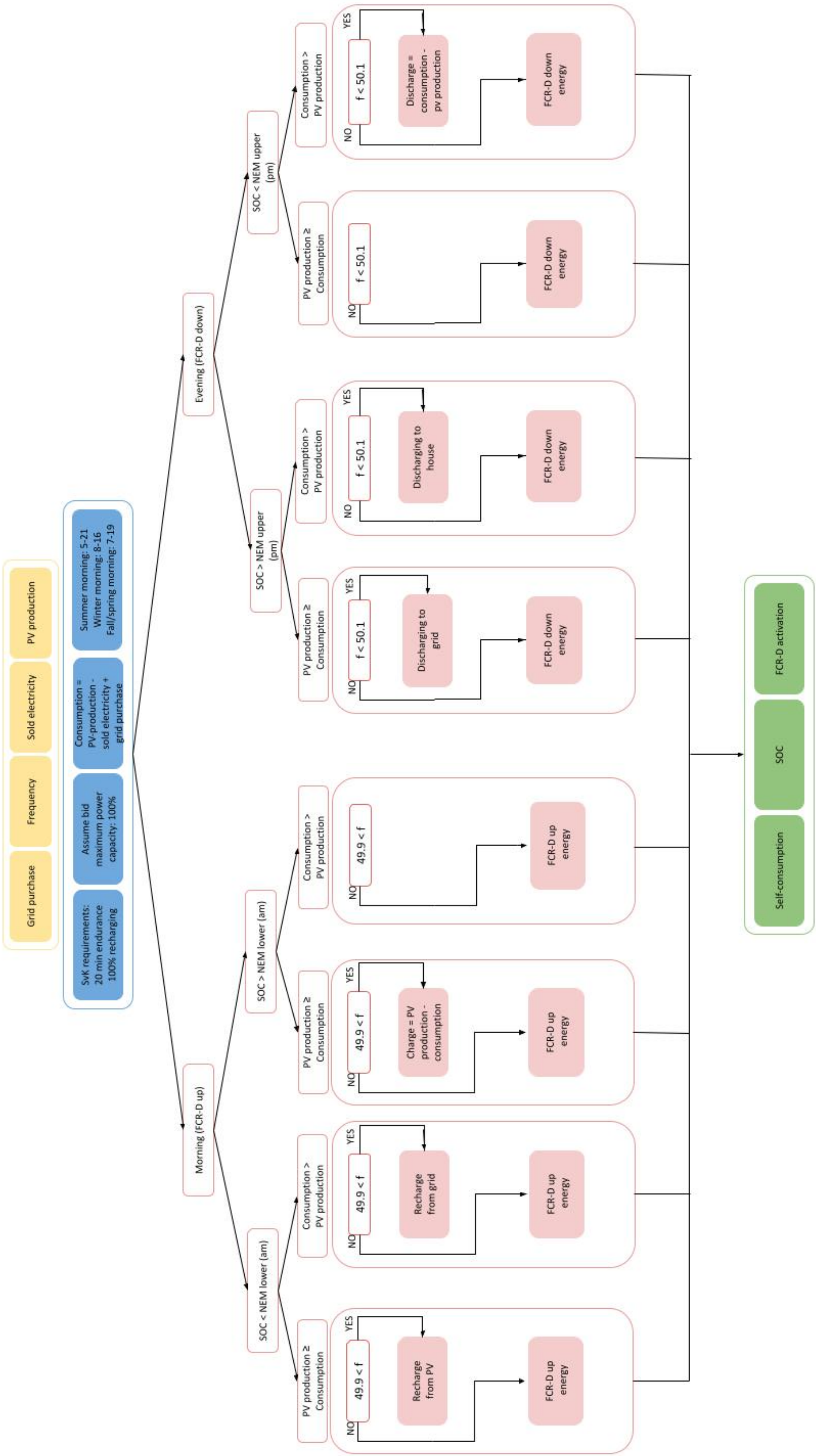

Figure 4.4: Flow chart of operations of case 3b. The yellow boxes represent input data, the blue assumptions, the red represent the battery operation during different conditions and the green boxes are the output data.

5

Results

In the following chapter the results from the different parts of the investigation are presented.

5.1 Historical disturbances

The following section describes the result of how well the characteristics of historical disturbances align with FCR-D requirements.

5.1.1 Historic Distribution of the Duration of Frequency Disturbances

The results showed that there are disturbances on average 2% of the time during a year, which also implies that a battery that only activates on FCR-D is not used 98% of the time of a year. Further, the results showed that the average FCR-D activation was 4.7% of the bid inverter capacity of the inverter. The results of how long disturbances have historically been can be found in figure 5.1. The figure shows on a logarithmic scale how many of the disturbances have been a certain duration. The results show that 48% of the disturbances are shorter than one second, which means that they are not handled by FCR-D, as the real time measuring is done every second. Most disturbances belong in the interval between one second and one minute, which makes 50% of the total amount of disturbances.

If all disturbances below one second is excluded from the statistics, disturbances below one minute has stood for 96% of the total amount of disturbances. Including the next interval, 99.7% of all disturbances were below five minutes. In case of a disturbance longer than five minutes aFRR and mFRR are activated as well, as mentioned in section 2.2, which relieve the FCR-D, even if the FCR-D sources should still have enough energy to endure full power supply for longer.

The figure shows longer disturbances occurred more seldom, and disturbances over 20 minutes only occurred eight times during the nine years. Out of these eight disturbances, the longest was 35 minutes. Further, a longer disturbance does not necessarily mean that it entails delivering FCR-D at full power, as seen by the result of average FCR-D activation of 4.7%. Section 5.1.2 describes how these disturbances would have influenced a battery supplying FCR-D.

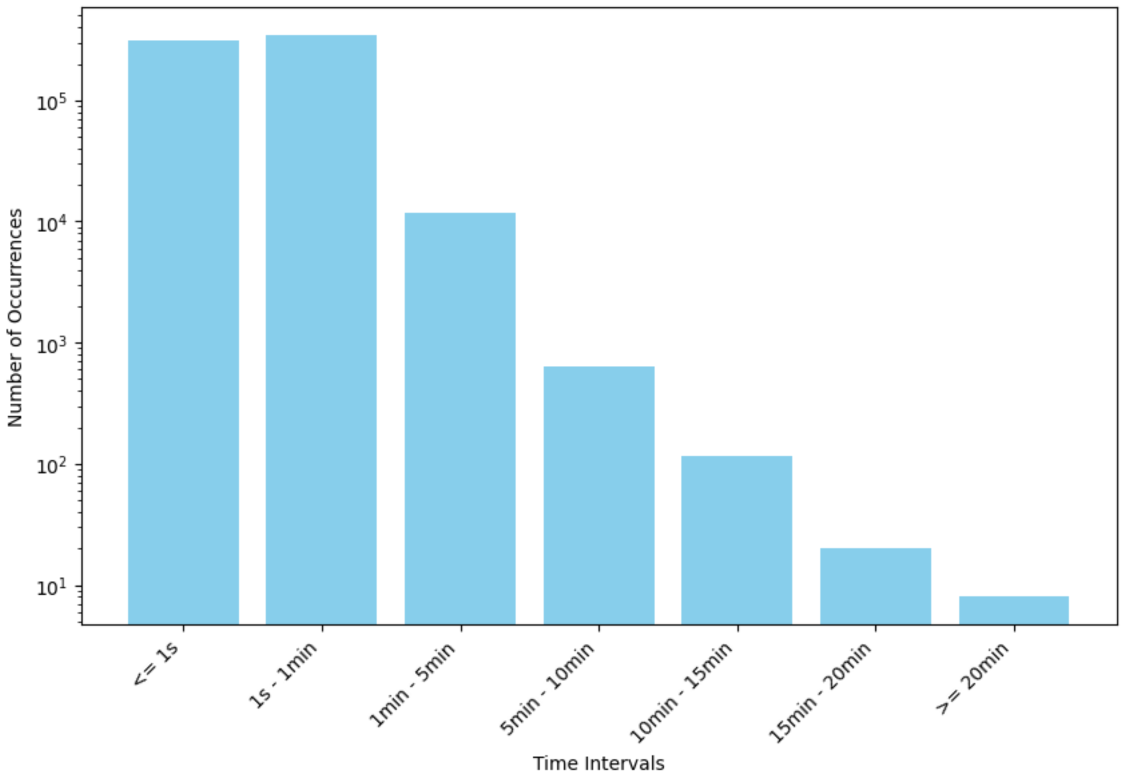

Figure 5.1: Results of durations of frequency disturbances in the Nordic grid between 2015 and 2023 in logarithmic scale showing that over 99% of disturbances are below five minutes long. Eight disturbances have been longer than 20 minutes and have exceeded the endurance requirement for FCR-D.

Figure 5.2 shows the duration of disturbances between March 1st 2023 and April 15th 2024, since it was the interval which the case study was made on. This was to see that the period used in the case simulation could be representative in terms of historical disturbances. As seen in the figure the distribution of duration of disturbances were similar to that of the historical. There were on the other hand two disturbances longer than 20 minutes, both which occurred in 2024. The mean FCR-D activation was 4.7% in upwards direction and 5% in downwards direction.

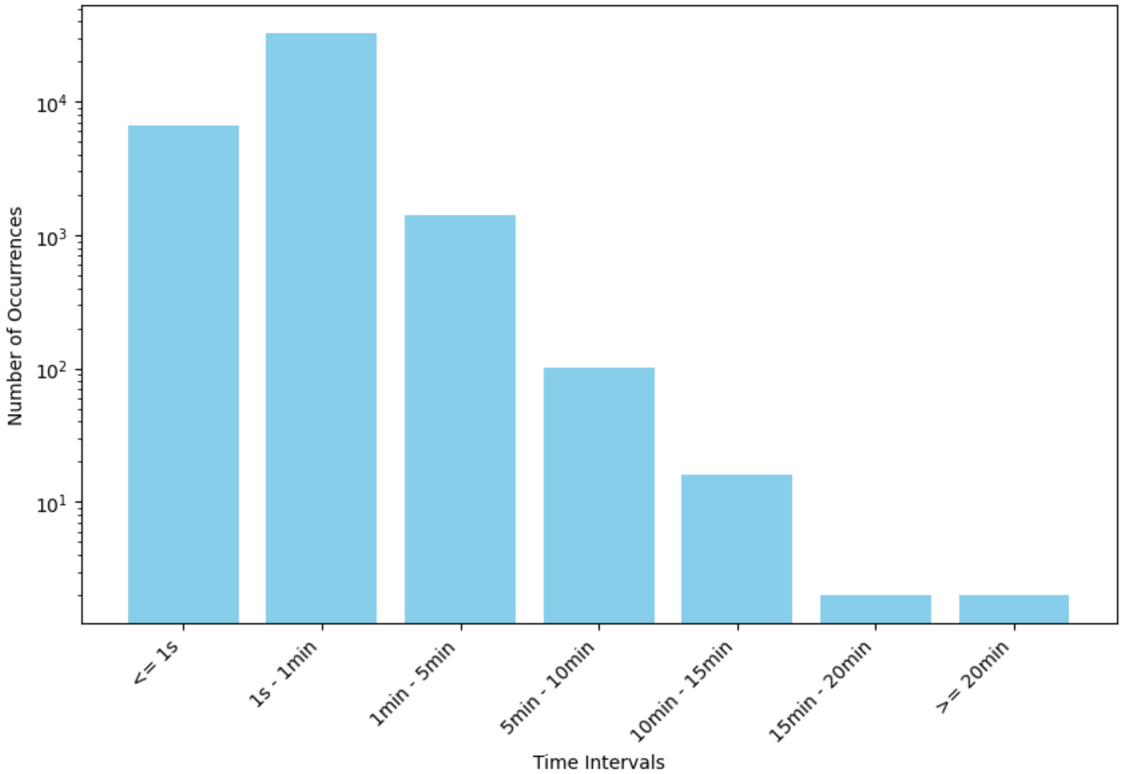

Figure 5.2: Duration of disturbances between March 1st 2023 and April 15th 2024.

5.1.2 Battery behavior

The results from simulating the battery behavior with historical frequency data showed that a for a 18 kWh battery with a 10 kW inverter, the SOC never reached the limits where recharging with NEM was necessary. The maximum SOC reached was 61.8% and the lowest 45.3%. The recharging limits, i.e. where the battery enters NEM, for this type of battery was 15.4% and 84.6% respectively and thus these were never met. A histogram showing the distribution of SOC during the test period can be found in figure 5.3. This shows that with the requirements stated in 4 there is room for using the battery to a larger extent, or reconsidering what technical requirements are optimal for the system they are made.

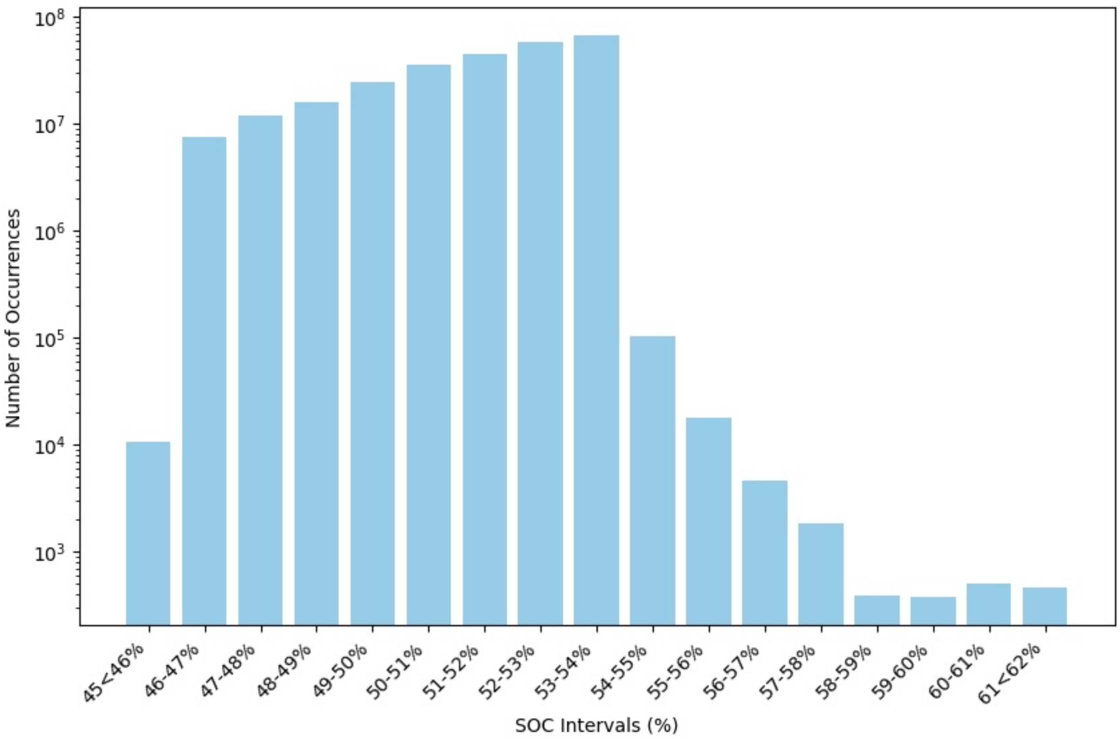

Figure 5.3: Result of how a 18 kWh battery and 10 kW inverter would have behaved in terms of SOC, supplying FCR-D between 2015 and 2023 in CheckWatt controller in logarithmic scale

The case study was made with different parameter and a C-value of 1, which impacts the battery behavior. The battery behavior with the CheckWatt controller for a 10 kWh battery for the case study period can be found in figure 5.4. The SOC limits for NEM is in this case 27.7% lower limit and 72.3% upper limit. As seen in the figure, these limits are never reached. The SOC does on the other hand come closer to the SOC limits than with a lower C-rate (the 18 kWh battery). This is because with a smaller battery the SOC limits become more narrow and with a higher C-rate the battery charges and discharges faster than with a lower.

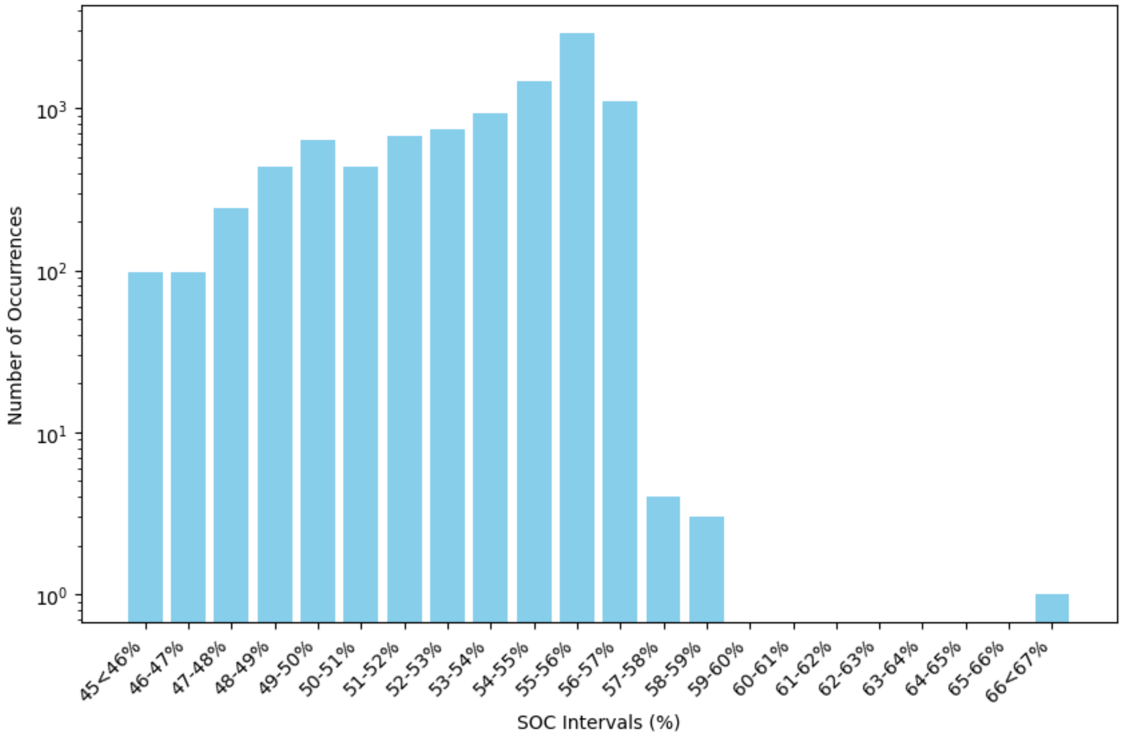

Figure 5.4: Distribution of SOC between March 1st 2023 and April 15th 2024 for 10 kWh battery and 10 kW inverter in CheckWatt controller for delivering FCR-D.

5.2 Case study

Figure 5.5 shows the results of all identified customers' self-consumption in the four different cases. The difference between the customers was the consumption and PV-profile, but had the same PV peak, battery and inverter size. As seen in the figure, case 2 gives the largest possible theoretical self-consumption and case 1 gives the lowest. Between case 3a and 3b, 3a always gave a higher annual self-consumption than 3b. For most customers, the self-consumption increase and decrease with a quite similar share between the cases but for C6 the self-consumption was very low for case 1 and increased a lot for case 2.

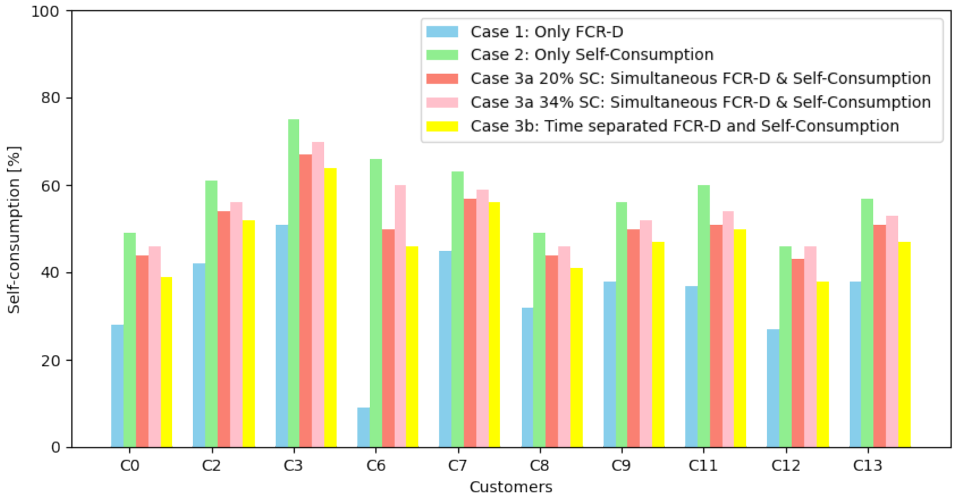

Figure 5.5: Result of self-consumption for all customer in all cases with normalized PV-profiles and same battery, inverter and PV peak capacity size.

5.2.1 Case 1: Only FCR-D

In case 1 the battery was only used for supplying FCR-D upwards and downwards and in this case the self-consumption is the direct use of solar power in the house. The result of self-consumption can be found in figure 5.6. There was no clear trend in higher consumption giving higher self-consumption, but a higher consumption in relation to production tended in some customer cases to lead to a higher self-consumption. Since the self-consumption is a share of the total produced solar power, a higher consumption would lead to a higher self-consumption since a higher share could be sued directly. An important parameter was therefore the consumption pattern. If consumption coincides with production, the self-consumption will be higher, and for customer that had low consumption during the day when production was high, the self-consuption was lower.

As seen in figure 5.6, C3 had the highest self-consumption and also a very large consumption. For C3, the consumption was also very large in relation to the annual production, which would increase self-consumption since more of the produced electricity is used directly when consumption is higher. The same trend can be spotted when comparing C9 and C8, that have very similar annual consumption, but as C8 has a higher production, self-consumption decreases.
On the other hand, the same thing cannot be said when comparing the self-consumption of C0, C11 and C13. They all had very similar annual consumption and production, but C0 differed a lot from C11 and C13. As the self-consumption is the direct

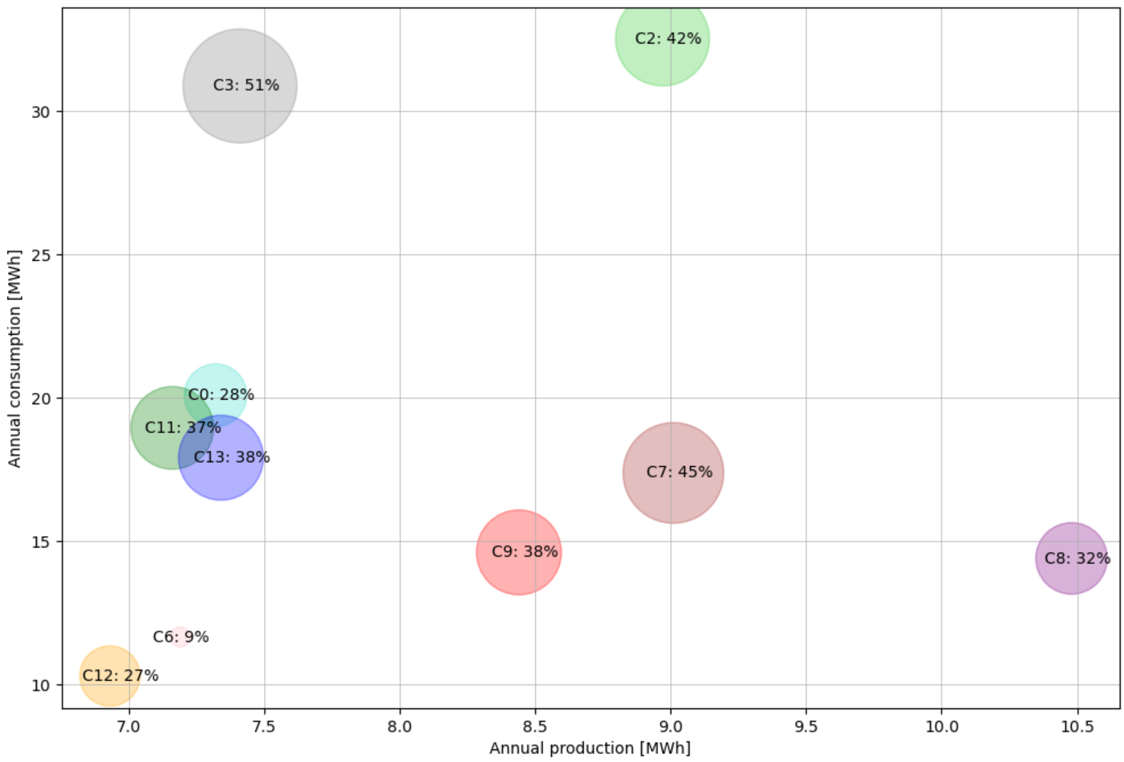

Figure 5.6: Self-consumption result case 1 - only FCR-D. The circles represent the different customers and the percentage inside the circles show the self-consumption of the case.

use of the produced electricity, the consumption pattern could influence the self-consumption. For example for people that spend a lot of time home during the day, their self-consumption has a chance of being higher since their consumption coincide with the production more often. Comparing the consumption between C0, C11 and C13, C0 had a very irregular consumption pattern compared to the others which could be the reason for the lower self-consumption.

Further, looking at C7, it has one of the highest self-consumption rates in this case, but has a quite high production compared to consumption and to the other cases. When looking at the consumption and production patters, it could be seen that the consumption coincided very closely with the production, resulting in a high self-consumption.

C6 had a very low self-consumption compared to the other customers, especially since it had quite a similar consumption and production as many of the other customers. Once again, the consumption pattern is a probable cause for it in this case. C6 had nearly no consumption at all during the hours where there was solar production, which would be a reason for the self-consumption being so low. Therefore the self-consumption of C6 was not included in the general result of the thesis.

5.2.2 Case 2: Only self-consumption

Figure 5.7 shows the result of self-consumption for the different customers compared to their individual consumption and production. For all customers, the self-consumption increased, on an average for all customers the self-consumption increased with 20 percentage points (excluding C6). However, how much the self-consumption increased differed between the customers. C3 still has the largest self-consumption in case 2, but C6, which had the lowest self-consumption in case 1, has the second largest in case 2. As mentioned the consumption was low for this customer during production hours, which would explain why the self-consumption increased so much when the battery was introduce to save the electricity for hours when consumption was higher.

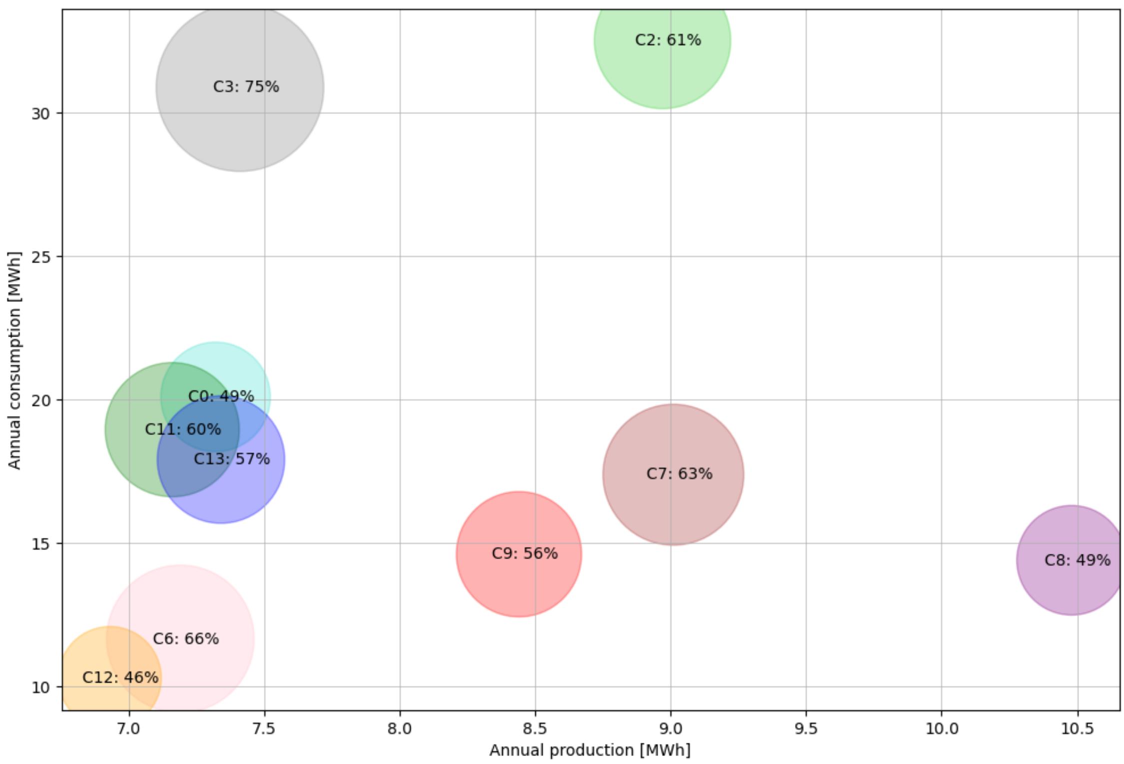

Figure 5.7: Results of self-consumption for all identified customers in case 2 - only self-consumption. The circles represent the different customers and the percentage inside the circles show the self-consumption of the case.

5.2.3 Case 3a: Simultanous FCR-D and self-consumption

The result of self-consumption for case 3a with 20% recharging cpacity can be found in figure 5.8. The result show a very similar pattern to case 2 in terms of ranking largest to smallest self-consumption. On average the self-consumption increased 12.5 percentage points compared to case 1 with oinly FCR-D. Further it was concluded that FCR-D was activated during all disturbances. This was concluded due to that the SOC never reached 100% or 0%. The algorithm was designed to always prioritize FCR-D over self-consumption and thus, the only restriction for the battery would be if there was too little or too much charge. As this never happened, it can be concluded that FCR-D could be activated as in case 1.

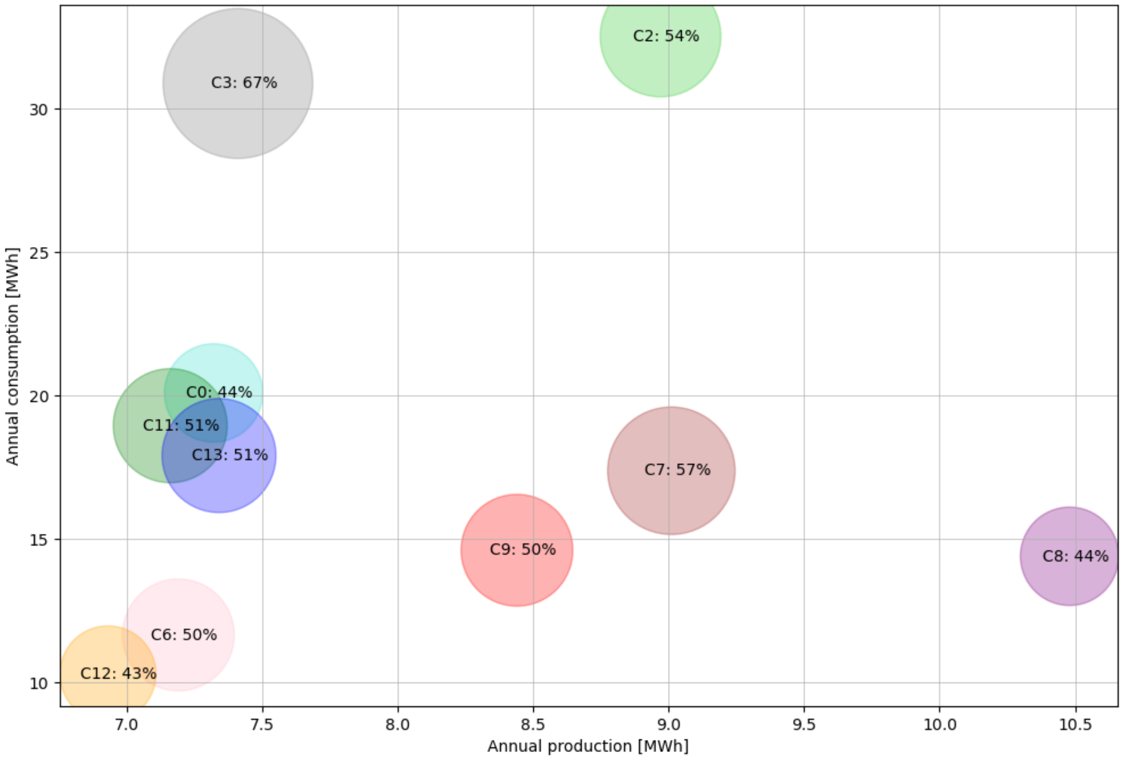

Figure 5.8: Self-consumption in case 3a - simultaneous FCR-D and self-consumption with 20% recharging capacity. The circles represent the different customers and the percentage inside the circles show the self-consumption of the case.

On an average the customers reached 87.6% (C6 excluded) relative self-consumption and the result for each customer can be found in table 5.1. Many reached 89% and three came above 90%. There did not seem to be a correlation between high consumption and reaching above 90% of the result in case 2. The lowest result for comparison between case 2 and 3a was C6 and once again the consumption pattern could be a reason for this. Since the consumption and production do not coincide very well for this customer, the possibilities of storing energy in a battery and inverter becomes important to increase the self-consumption. As the power used for self-consumption operation in case 3a is about 17 % of the one in case 2, the self-consumption decreased quite a bit.

Table 5.1: Share of the annual maximum possible self-consumption case 3a with 20% recharging results for the different customers.

Identifyer	Case 2 [%]	Case 3a [%]	Relative self-consumption [%]
C0	49.2	43.5	88.4
C2	60.6	54.0	89.1
C3	75.0	67.2	89.7
C6	65.8	49.7	75.6
C7	63.2	57.0	90.2
C8	48.7	43.6	89.6
C9	56.3	49.7	88.3
C11	59.6	51.3	86.1
C12	46.4	42.9	92.6
C13	56.7	51.0	90.0

The results from case 3a with 34% recharging capacity can be found in figure 5.9. As seen in the figure a higher recharging capacity resulted in a higher self-consumption. It increased with 15.6 percentage points compared to case 1 with only FCR-D.

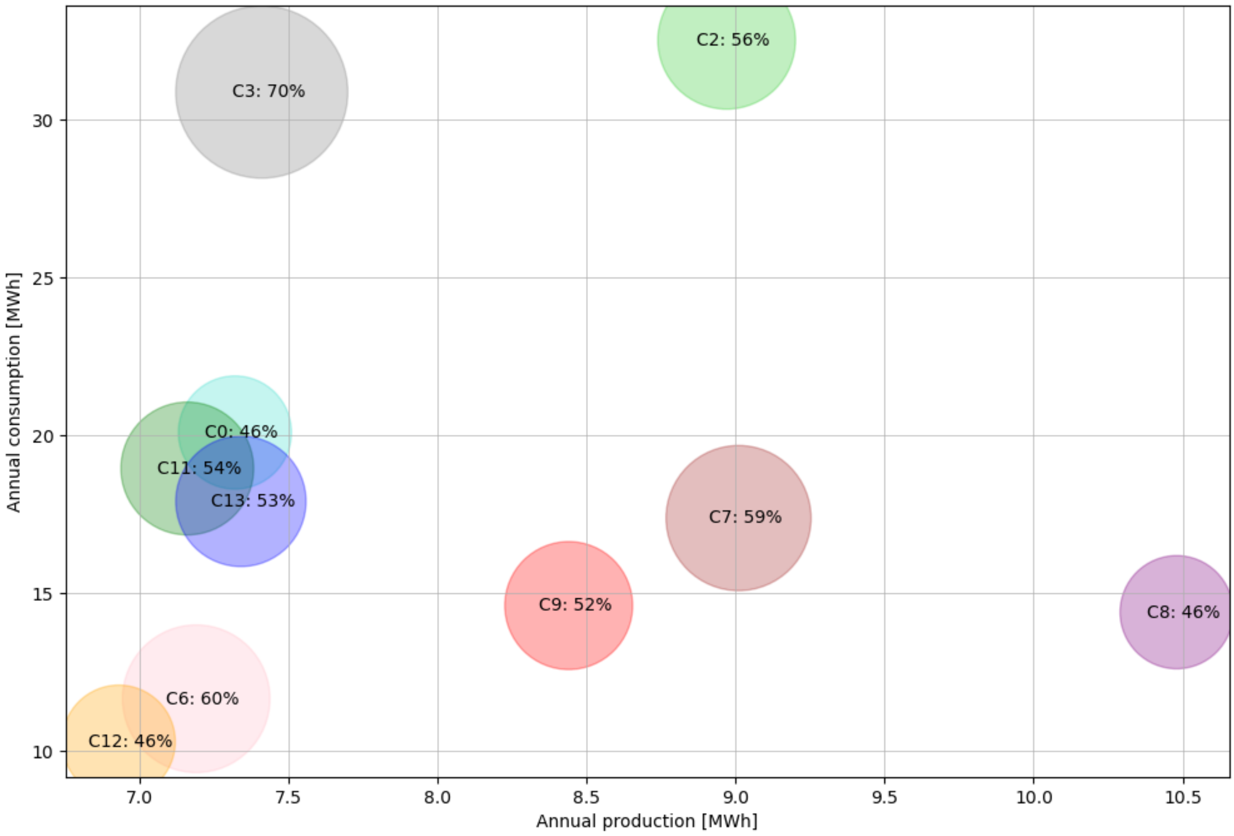

Figure 5.9: Self-consumption in case 3a - simultaneous FCR-D and self-consumption with 34% recharging capacity. The circles represent the different customers and the percentage inside the circles show the self-consumption of the case.

Table 5.2 shows the result of relative consumption which increased to an average of 94% compared to with 20% recharging rate. As seen in the table, the relative consumption for all customers exceeded 90%. An increased recharging capacity entails a lower income for the customer, as the bid was lower.

Table 5.2: Share of the annual maximum possible self-consumption case 3a with 34% recharging results in for the different customers.

Identifyer	Case 2 [%]	Case 3a [%]	Relative self-consumption [%]
C0	49.2	46.3	94.1
C2	60.6	56.4	93.1
C3	75.0	70.2	93.6
C6	65.8	59.9	91.1
C7	63.2	59.4	94.0
C8	48.7	45.9	94.3
C9	56.3	52.2	92.8
C11	59.6	53.9	90.4
C12	46.4	45.8	98.8
C13	56.7	53.3	94.0

5.2.4 Case 3b: Time-separated FCR-D and self-consumption

The self-consumption in case 3b can be found in figure 5.10. The self-consumption increased on average 9 percentage points compared for case 1 woth only FCR-D and thus gave a lower result for self-consumption than case 3a with simultaneous operation did. The reason for the self-consumption being lower was that the operation in case 3b was determined by time of day and not the possibility to charge or discharge. Thus, a lot of chances of increasing self-consumption were missed. Further, it could be seen that FCR-D was activated during all disturbances. As in case 3b, this conclusion could be made since the battery never reached 0 or 100%.

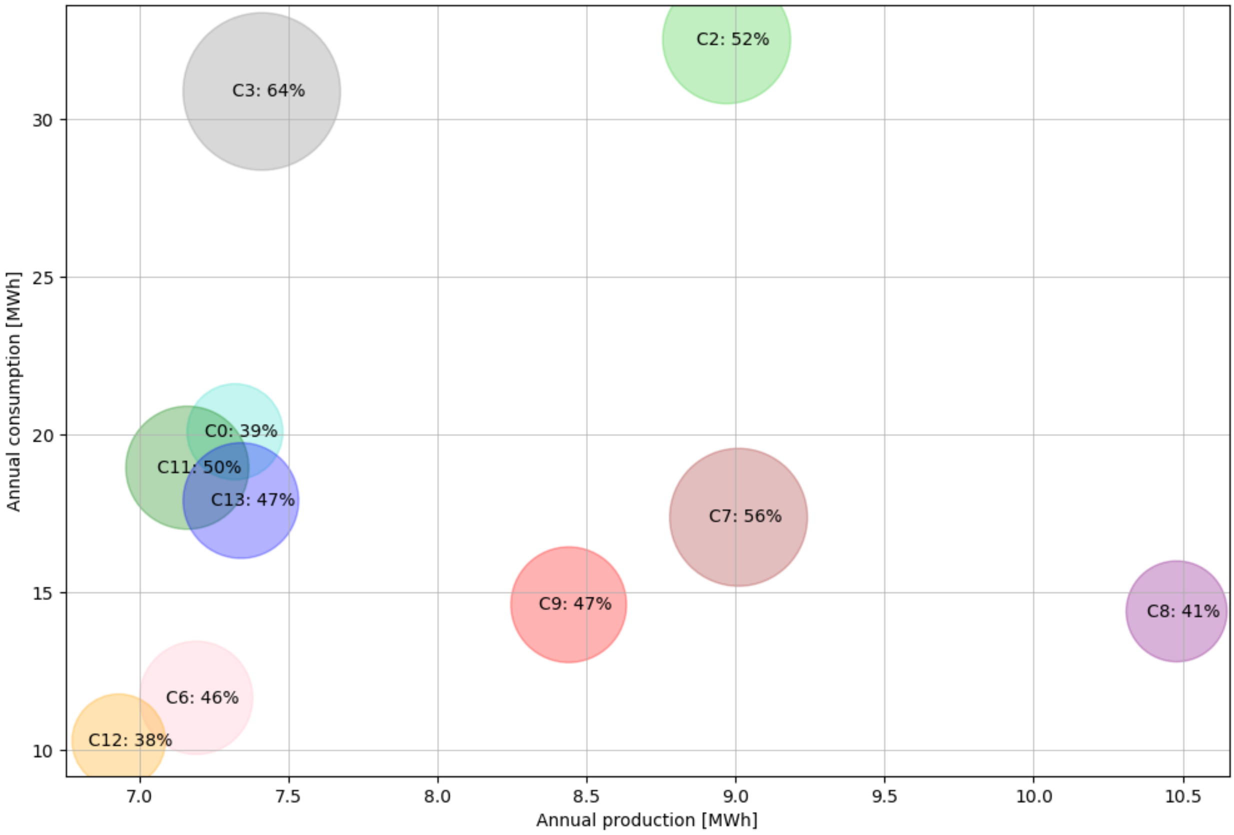

Figure 5.10: Self-consumption result case 3b - time-separated FCR-D and self-consumption. The circles represent the different customers and the percentage inside the circles show the self-consumption of the case.

Comparing to case 2, the relative self-consumption in case 3b did not reach 90%. On an average the relative self-consumption was 81.5% for all customers, when C6 was excluded. Some decreased more than others, like for C0 that decreased their share of case 2 by 10 percent points. For the customers who got closest to 90 % of the corresponding customer results in case 2, their PV profile and consumption could have coincided well with the times that were used for charging and discharging. Looking at the customers annual battery behavior, the ones who reached a higher relative self-consumption managed to discharge more frequently, especially during the summer months. This would indicate that there in cases with higher relative self-consumption, there is more consumption in the house during discharge hours which enable the battery to discharge and charge more the following day during charging hours.

Table 5.3: Share of the annual maximum possible self-consumption case 3b results in for the different customers.

Identifyer	Case 2 [%]	Case 3b [%]	Relative self-consumption [%]
C0	49.2	38.6	78.6
C2	60.6	52.4	86.5
C3	75.0	63.8	85.1
C6	65.8	45.8	69.6
C7	63.2	55.6	87.9
C8	48.7	40.7	83.6
C9	56.3	46.6	82.8
C11	69.6	49.6	83.2
C12	46.4	38.1	82.1
C13	56.7	47.4	83.6

5.3 Sensitivity analysis

The sensitivity analysis was performed on different variables used in the algorithm. The variables were decreased and increased 30 % respectively to analyze how they impacted the self-consumption. See figure 5.11 for the result of the sensitivity analysis. The sensitivity analysis was performed on C13.

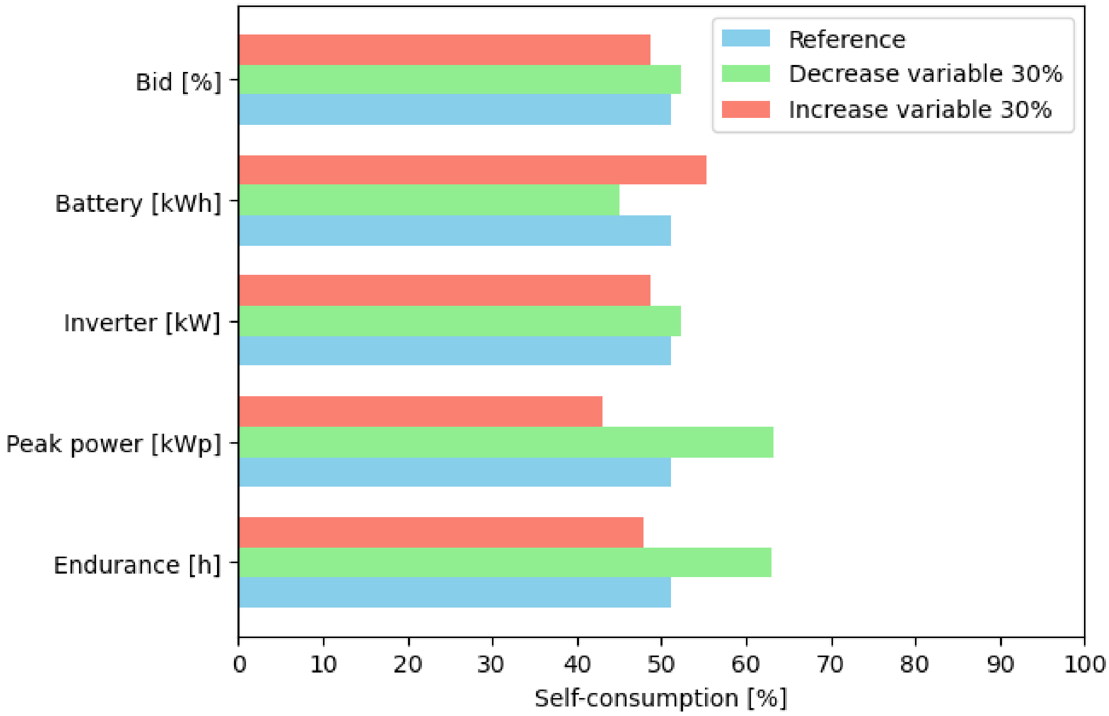

Figure 5.11: Result from sensitivity analysis performed on C13 in case 3a

When it comes to bidding size, increasing the bid would decrease the self-consumption as less capacity of the inverter was available for recharging, i.e. self-consumption. The result for decreasing the inverter size therefore also gave the same result when decreasing and increasing the total size and bidding size, as the battery and PV production was still the same. When instead increasing the bid or the inverter size, the self-consumption increases because more of the produced electricity can be charged or discharged to the battery. Further, when the inverter size decreases, the NEM-limits change so that the upper limits is raised and the lower limit is lowered which gives more room in between the NEM-limits for the battery to be charged.

When it came to battery size, an increase gave a larger self-consumption, which would be because there was more capacity in the battery and more of the produced electricity could charge the battery. When decreasing the size, instead the opposite happen and more produced electricity was sold directly to the grid.

When decreasing the peak power capacity of the solar PV's, the self-consumption increased quite drastically. This would be because with smaller solar cells, the total production decreases and the chance of consuming a larger share of the produced electricity increases, regardless of the consumption pattern. Thus the self-consumption increases, as it is a relative variable to the total production. This is both because the direct use of the produced power increases, but also because also the amount that can be charged to the battery.

When it comes to endurance, the self-consumption also increased a lot with 12 percentage points when decreasing the endurance requirement with 30%. This is because it would allow for the NEM-limits to change so that there would be more capacity to charge the battery, as it did for the inverter. When increasing the endurance by 30%, which means the endurance would be 26 minutes instead of 20, the decrease in self-consumption was not as severe. Therefore, there is a possibility that the NEM-limits could be set a bit more narrow and not lose so much of the self-consumption. As the direct self-consumption is 37%, this will always be the lowest self-consumption. Therefore, the more narrow the gap between the NEM-limits is, the smaller the difference in self-consumption will be.

5.4 Recommendations for Service Development

This section provides recommendations on how to manage the development process from a long-term perspective. There are five recommendations, which are compiled in table 5.4, which are explained more in detail in the following section.

Table 5.4: Recommendations for a service development process for the long-term perspective for companies in aggregator position providing services.

Number	Recommendation
1	It is recommended that the company prioritizes direct interaction with customers and users to gather valuable insights.
2	To manage uncertainty in a new market, it is recommended that companies establish processes that simultaneously manage exploratory and exploitative development, i.e. finding a balance between maintaining existing services and fostering innovation.
3	To improve market insight, companies should actively engage in market sensing activities to monitor market trends and keep updated on competitors.
4	It is important for companies to deeply understand customers' different motivations and perceptions of value, especially in the case of services such as FCR-D, where customer value can vary, requiring a focus on identifying and delivering unique value propositions to remain competitive.
5	To ensure a consistent perception of service value, when the sales and delivery phases are outsourced, it is important to foster deep, transparent relationships with third-party partners, as it facilitates accurate information exchange and aligns the partner's understanding with the company's objectives, thereby ensuring customer satisfaction and service value.

Recommendation 1

An important part of the NSD process is the interaction with the customer. Therefore, the company should aim to have direct contact with the customers and users, instead of allocating it to third-party partners. When having contact with the customers it is beneficial for market sensing, development and sales. One way to receive insights from the customers themselves is through customer feedback. Therefore, having a process that takes care of the customer feedback in such a way that it enables the company to learn about the customers is beneficial for being proactive when new trends and different customer needs appear. Furthermore, introducing services to users early in the development process opens up the possibility of continuous feedback from users, allowing this feedback to be taken into account and the service to be further developed. An example could be pilot studies where customers get to test beta versions of a new service.

Recommendation 2
As this market is relatively new and the future is difficult to predict, it is necessary to have processes that focus on both the existing market and the more unpredictable future market. Companies need to balance exploratory and exploitative market-sensing and development activities to conduct operations in a more cost efficient way [26]. That means that the company needs to have a process that can continue the development of already existing services, as well as having a process that can focus on innovations. This could be accomplished in various ways. One possibility would be to divide the processes of development of existing services and innovation-driven development and have two distinct teams working on each of the processes [37]. Another way to accomplish a balance is for individuals to switch between exploration-oriented and exploitation-oriented work on a daily basis [37].

Recommendation 3
The companies should also put effort into market sensing through interactions with customers. This can be done through interviews, focus groups, questioners and observations. One example of market sensing can be used is in this thesis where new requirements led to new customer needs and were identified through observations of the trends in the market. As the Swedish Tax Agency made a new interpretation of the law regarding green technology tax reductions, it meant new incentives to control the battery for delivering FCR-D. The incentive implied that in order for new customers to buy a battery from the year 2024, self-consumption had to be increased to be eligible for the tax reduction. However, many customers are using the service to support the grid and to gain income from the frequency ancillary services. The tax reduction makes it possible for more people to afford investing in technology equipment used for renewable energy. Hence, a need for a new way of controlling the battery in a way that it would be able to combine increasing self-consumption and frequency ancillary services emerged. The models created in this thesis were based on that emerging need.

Recommendation 4
Selling services requires a comprehensive understanding of customers and how the service can benefit them, this is crucial for services as the value of the service is depending on the customer's perceived value. The customers who are using the

service to provide FCR-D are using it for different reasons. For example, for the models created in this thesis for the short-term perspective, the value created is in the possibility to increase the self-consumption and providing FCR-D at the same time, and also to be granted the green technology tax reduction. However, the value for some customers might be to increase the compensation for frequency ancillary services instead of getting the tax reduction. Therefore, in order for the company to be ahead of its competitors they need to know how the service can benefit the customer and what is value adding for the customers.

Recommendation 5

For companies that allocate the sales and delivery stage to third party partners, the partners have some responsibility about the customer's opinion about the company and service. For services the value is affected by the costumers' perception of the service and therefore the value will also depend on the partners performance [30]. Thus, it is crucial that the company can ensure that the partners provide the customers with accurate information, and for the partners to do that they need to have sufficient and accurate information from the company, as well as an in-depth understanding of the service. Therefore, a deep and trustworthy relationship with the partners is necessary for making sure that the partners are aligned with the company [26].

6

Discussion

6.1 Short-term perspective

This section of the discussion concerns the short-term perspective part of the thesis.

6.1.1 Models

Case 3a, which was designed so that the battery both delivers FCR-D and uses it to increase self-consumption, was built on the idea that it is possible to use the power that is reserved for recharging can be used for self-consumption. However, in the document *Technical Requirements for Frequency Containment Reserve Provision in the Nordic Synchronous Area* by ENTSO-E it does not say that it is allowed to use the recharging power for anything else than restoring the battery. However, the interpretation by Danish TSO *Energinet* states that the capacity that is reserved for energy management can be used in other markets except for further ancillary services, but does not specify which markets this applies to [34]. However, when the battery is only used for delivering FCR-D, it is only being used 2% of the time. Furthermore, the result showed that if the battery had large enough capacity (10 kW inverter and 18 kWh battery) and was only used to deliver FCR-D, the SOC never went under 45% and never exceeded 62%, hence the batteries will not reach the SOC limits where recharging is needed. There was therefore residual charge that was not used. Given large enough battery capacity, using the residual power for self-consumption would lead to more effective use of the battery.

For case 3b, which was designed to separate delivering FCR-D upwards and charging from FCR-D downwards and discharging, the different times of day and night operation was based on the sunrise and sundown times in the middle of Sweden. But since the customers were spread on a larger area, the optimal times for the specific operation should be individualized to reach a larger self-consumption.

It should be noted that the models do not include any battery losses, which mean the self-consumption results are not exact. However, since the main focus was on the relative self-consumption, the main result should sill be reliable. Further, losses in battery and inverter would increase the consumption and thus the decision to exclude losses underestimates the self-consumption. Another aspect is that the battery performance decreases with time and number of cycles. This means that the SOC limits have to be set more restrictively with time to fulfill endurance requirement of FCR-D, which would decrease the self-consumption. The battery considered in the case study was theoretical and therefore did not take this into consideration.

Further it should be noted that the battery sizes in the analysis of historical disturbances and the case study were different and thus do not have the same C-value. In the historical disturbance analysis the C-value is smaller which influences the SOC limits and would allow for more space in the battery to perform other services than FCR-D, which was seen in the sensitivity analysis. If the C-value had been lower in the case study, the self-consumption would therefore have increased.

A further source of errors for the models is the time resolution. As the resolution is in minutes, when there was a frequency disturbance in the models for case 3a and 3b, the entire minute was reserved for FCR-D activation, even if the disturbance only was a few seconds long. It was calculated that the amount of time that was reserved for FCR-D was on average 6% of the time, which is higher than the 2% average that FCR-D is usually activated historically. Therefore, in reality or with second resolution, the model would have had more time for operating to increase self-consumption.

6.1.2 Historical Frequency Disturbances

From the analysis of historical frequency disturbances the result showed that over 99% of the disturbances during that period have been less than 5 minutes long. As described in section 2.2.3, one requirement for delivering FCR-D is that the entity must be able to deliver 20 minutes of full bid power. However, as seen in the result, disturbances that are 20 minutes or longer are very rare and have only occurred eight times in the past eight years. This could mean that there is potential for the system to design the system and the endurance requirement in such a way that it is more suitable for the most commonly occurring durations. This would make it possible to use the battery for other things as well, such as self-consumption. Also, when a disturbance occurs there are other frequency ancillary services that are also being activated, that are described in section 2.2. Further, as showed in section 5.1.2, the inverter activation have on average been 4.7%. Which also means that if a disturbance longer than 20 minutes occur, it is not very likely that it would require full activation. It is therefore likely that it would be possible to lower the endurance requirement and still deliver the energy needed for FCR-D.

The case study was performed on a different time period than the case study, and therefore there is no direct connection between the results. On the other hand, the results from the characteristics of disturbances for the case time span showed a similar pattern, both in terms of duration and battery behavior as for historical frequency. Thus the results from historical frequencies could be applied to the same time period as the case study was performed on.

6.1.3 Case Study

There was no clear connection between higher annual consumption and self-consumption, but the consumption pattern could play a part and thus also the direct use of produced solar power. To some extent though, a larger annual consumption in relation to the annual production tended to result in a higher self-consumption. This also showed in the sensitivity analysis, where decreasing the PV peak size increased the self-consumption by almost 15 percentage points. The decreased production would increase the share of total PV production used directly, partly as the consumption was still the same and partly because a higher share also could be charged to the battery.

From the result of the short-term perspective it was clear that case 3a with simultaneous operation was able to reach the highest self-consumption when combining self-consumption operation with delivering FCR-D. This was because in case 3a, the operation allowed the battery to charge or discharge when the frequency was in the normal band based on if there was excess PV production or a unsatisfied load in the house. When the operation instead was based on time of day, like in case 3b, the battery missed a lot of opportunities to discharge during the day and thus also have capacity in the battery to charge with more of the excess PV. So even though the inverter capacity for self-consumption operation in case 3a was only 20% or 34% of the one in case 3b, casee 3a still got a higher self-consumption.

When simultaneously delivering both FCR-D and enhancing self-consumption like in case 3a, it would be possible to reach a relative self-consumption between 86 and 92%. This would exclude the result of C6, that only achieved 75% due to its consumption pattern. Because of the consumption pattern of C6, the self-consumption rate was very dependent on how much energy can be charged to the battery. Therefore the self-consumption for C6 was very low in case 3a, because the power capacity for self-consumption operation was only 20% of the bid power.

As for case 3b, it was possible to reach a relative self-consumption between 78 and 88% while also responding to FCR-D, excluding C6 that only reached a 70% relative self-consumption. Further, case 3a keeps bidding in both directions at the same time and thus have income from both FCR-D upwards and downwards simultaneously, whereas case 3b only can achieve income from one at a time.

The sensitivity analysis showed that lowering the endurance requirement with 30% increased the self-consumption significantly. Decreasing the endurance with 30%, as in the sensitivity analysis, means that the endurance would be 14 minutes. As shown in 3.3.1, 99.7% of frequency disturbances do not exceed five minutes and the FCR-D activations are on average 4.7%. As there are also other frequency ancillary services that help relieve FCR-D it could be questioned whether the endurance requirement is redundant, but to make such statement, a larger system perspective would have to be adapted to understand how such a decrease would affect the other services.

6.1.4 Impact

The green tax reduction is an incentive to boost the use of renewable energy sources at the consumer level, aiming to enhance self-consumption. However, many consumers invest in batteries to earn income from delivering FCR-D services. Consequently, the current rules for tax reduction may inadvertently hinder the spread of PV battery systems in Sweden. Additionally, the demand for frequency ancillary services is rising, and private home batteries could play an important role in providing these services due to their flexibility. However, technical requirements, particularly regarding endurance, limit the use of these batteries, leaving many potential resources unused. Combining increased self-consumption with the provision of FCR-D services could be an important solution to continue expanding the adoption of solar PV and batteries, thereby contributing to a more renewable, stable, and reliable energy system.

The results and sensitivity analysis show that the biggest impact that the customers themselves can have on their self-consumption is decreasing the PV peak capacity. A smaller production in relation to the consumption generally would lead to a higher self-consumption because a larger share of the produced electricity can be used directly and stored. Having a requirement for a certain degree of self-consumption, as stated by the Swedish Tax Agency, there is a risk that it could lead to a reduction in the sale of solar panels. Further, for customers who have already bought solar panels and do not reach the limit, there is a risk that they would disconnect some of their panels and leave them unused. The law for tax reduction on green technology might therefore have the opposite desired effect and result in a decreased use of solar PV.

Another scenario could be that it would be more profitable to not accept the tax reduction and only supply frequency ancillary services without solar panels involved at all. As stated in the introduction, the estimated income per year for an average customer is 30 000 SEK and the average tax reduction per buyer is 32 000 SEK. In a year, the customer will in other words have earned the money that would have been given from the tax agency. From an environmental perspective, this would halt the sales of solar panels and thus the increase in renewable energy sources in the electricity market, even if solar power only stands for 1.1% of all electricity sources in Sweden [38].

As the energy system moves towards a larger share of renewable energy sources, so does the need for frequency regulation as it becomes more difficult to plan production. The rotational energy can also decrease which also increases the need for these services, especially FFR. It is possible the 90% relative self-consumption limit will decrease the supply of frequency regulation from batteries as the demand for it increases. With increased demand, there is on the other hand a chance that prices for e.g. FCR-D would increase and battery sales thus increase.

6.1.5 Future research

For future research, there are good opportunities to further evaluate the cases by conducting the study on more customers to draw further and more statistically reliable conclusions about the outcome. Further, to ensure generality of conclusions further research on more battery sizes and higher time resolution is needed.

There is also the potential to conduct a thorough economic analysis of the cases and evaluate what would be the most profitable for the average battery owner. Taking into account both the tax reduction and the economic profits of FCR-D, as well as electricity prices.

Since the average FCR-D activation was only 4.7%, it is also recommended to further investigate if the technical requirements of providing full activation for 20 minutes is redundant. Further a larger system perspective should be adapted to evaluate how a potential change of technical requirements for FCR-D would influence other services.

6.2 Long-term perspective

The framework that was used was adapted for manufacturing companies. However, the authors states that the framework is applicable for other services as well. Therefore, the reader should be aware that this framework is not adapted for an aggregator company in the frequency regulations market, but have been used as a guidance for the service development process because of its applicability.

Recommendation 1

As stated in section 5.4 the interaction with the customer is important for creating services and offers that are value-adding for the customers. However, it is important to not only listen to the customers and what they want. Customers' expressed needs tend to already exist in the market. Value is created by customers' practices and therefore the development of the service should be based on a thorough understanding of the customers everyday practices [29]. Another aspect to take into consideration throughout the development when taking customer inputs is that the needs and circumstances tend to be driven by the lead users while developing services. Therefore, in order to reach more customers the development should take several perspectives and different customer segments into consideration and make the service offering more standardized so that it will be attractive for a wider set of customers. Another risk with engaging customers early in a service development process, in for example a pilot study, is that in the frequency ancillary market, there are several parties that have to be satisfied. One of the most important one is the TSO, and the requirements of the TSO have to be followed as it otherwise can jeopardize the aggregator position that the company holds.

Recommendation 2
Finding a way to organize the balance between doing incremental improvements on the existing services and achieving innovations is difficult. There are different organizational strategies to handle this. However, finding a strategy that works might take time and be costly. Having a structured process for the service development can make the service more effective and efficient and also provide coordination for the organization [39][26]. However, innovation often involves uncertainty, complexity and ambiguity [39], and the process needs to allow for creativity and spontaneity. In those cases a less formal approach, i.e. an ad hoc innovation mode, which enables flexibility and responsiveness to deal with shifting conditions can be beneficial. Thus, a balance between having a structured process that brings stability, while having a less formal approach that can promote creativity and flexibility might be appropriate [39].

Recommendation 3
Market sensing is often conducted through available data and therefore tend to focus on incremental development, and overlook innovation opportunities. When interpreting data, there is a risk of bias and a subjective view of the market, which can lead to an incorrect assessment of the market and incorrect decision-making. Also, market sensing tend to only look at the existing competitors and may overlook emerging competitors.

Recommendation 4
The market for using private home batteries for delivering frequency ancillary services is relatively new and complex, and customers' understanding of the services might be a bit insufficient. Therefore, the companies providing these services need to have well established and efficient communication with the customers to give recommendations about what service would be best for them. However, when giving recommendations to customers, there is always a risk that the recommendation did not suit the customer as desired.

Recommendation 5
Having third-party partners that takes care of the customer contact makes it possible for companies to reach more customer without being limited to the number of employees. Thus having partners can be beneficial, especially for growing com-

panies. However, the partners actions will affect the customers' opinion about the company and the services. The partners can have a lot of power in the customer's perception of the service, but not bare the responsibility of it, which would still lie with the company. Therefore, as said in 5.4, it is important to have a good relationship with the partners. However, this can take time and effort for the company and it can still be difficult to ensure that the partners' actions have the desired effect on customers' perceptions.

6.2.1 Future research

For future research there would be potential to test the four-stage NSD framework on more aggregator companies and study the outcome. It would also be interesting to evaluate how companies in the different situations as the case company can balance exploratory and exploitative development.

6.3 Short-term and long-term perspective

The thesis has adapted two different perspectives for dealing with the fast pace of change in the market for aggregators. Companies like aggregators are dependent on their customers to be able to provide grid services, which is where the income comes from and thus the customer satisfaction is very important. This entails both making changes that maximize income for the customers, but the changes also have to be made smoothly in the eyes of the customers and the business structure also has to allow for it. Including both of these perspectives are therefore important to see what possibilities there were for adapting to the current situation, as well as what could be done to make it easier with a potential future market change.

7

Conclusion

The result showed that there have been disturbances longer than 20 minutes eight times between 2015 and 2023. Therefore, the technical requirements regarding endurance align with the characteristics of the technical requirements for FCR-D. However, 99.7% of disturbances are below five minutes long. Also, the average activation of the inverter needed to deliver the energy needed for a frequency disturbance was 4.7% of the bid inverter capacity. However, the technical requirements require reservation for full activation each disturbance. Thus it could be questioned whether the requirement of full activation for 20 minutes is redundant and is recommended to investigate in future work.

Looking at the recharging requirement it was shown that during the investigated years a battery does not reach SOC limits that require recharging, which would indicate that the requirement for recharging is redundant in terms of what the recharging capacity is used for. This also leads to the conclusion that the recharging capacity could be used for other purposes, such as increasing self-consumption.

When combining operation for FCR-D and increasing self-consumption, the self-consumption increased for both the case 3a (simultaneous FCR-D and self-consumption) and case 3b (time-separated FCR-D and self-consumption) when comparing it to case 1 (only FCR-D). Case 3a with 20% recharging rate increased on an average 12.5 percentage points, case 3a with 34% recharging rate increased on an average with 15.6 percentage points and case 3b increased on an average 9 percentage points. For both the combination cases all disturbances were met with FCR-D activation. Further, with case 3a and case 3b it was possible to obtain on average 87.6% respectively 81.5% of the annual maximum self-consumption. Increasing the recharging capacity to 34% in case 3a gave the highest self-consumption at Thus, the result showed that case 3a gave the highest self-consumption without compromising the delivery of FCR-D. Case 3b resulted in less self-consumption and also delivered less FCR-D.

It was concluded that a company in the aggregator position should involve the customers continuously in the service development process to ensure persistent value of the service to the customers and therefore ensure long-term viability. Companies that use a third-party partner for communication, should enable a way for end-customers to express their feedback directly to the company. Companies should also aim to find a balance between developing existing services and pursuing innovation-driven development to stay ahead with market trends and changes.

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