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Identification of Advantages Connected to Aggregation of Several Battery Energy Storage Systems

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Abstract

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In this study, an examination regarding what benefits an aggregated population of Battery Energy Storage Systems (BESSs) could result in compared to when the individual units in the population are being used separately has been executed. The increased flexibility and reduced safety margins as results of the aggregation was also examined. The study was executed on behalf of the smart energy service company CheckWatt AB and the study furthermore rests upon results of earlier performed master theses on behalf of the company.

By investigating previous work and studies through a literature study, the enabling of anumerical study was done. The numerical study was based on a simple model of a Virtual Power Plant (VPP) where several BESSs are smartly controlled in order to be used for both local peak shaving and as common providers of the frequency reserve Frequency Containment Reserve - Normal (FCR-N). The study involved the formation of a numerical model which simulated cases of both aggregated and non-aggregated populations of up to 45 load profile units, this in order for advantages and differences to be distinguished. The data used in the simulations was received mainly from the CheckWatt AB and consisted of photovoltaic (PV) electricity production and load data of 45 customers of the company. A sensibility analysis of the numerical study was also performed, which showed that the studied model and system were quite stable.

The results of the simulations of the case of the study proved that there are some advantages connected to aggregation of several BESSs, and that the aggregation enabled an added value and a higher level of flexibility within the system. The safety margins connected to delivery of FCR-N could be reduced when aggregating several BESS, while a more extensive study is requested regarding safety margins connected to peak shaving. The study's results further showed that an aggregator can be used as a sustainable and flexible solution for balancing the electrical grid in the transition to a sustainable energy system allowing a higher penetration of intermittent energy sources.

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Populärvetenskaplig sammanfattning

Dagens elsystem står inför stora förändringar till följd av nya utmaningar som inkluderar bortkoppling av konventionella kraftverk i kombination med en allt högre grad intermittenta energikällor och ökad elektrifiering av samhället som stort. De nya utmaningarna kräver nya innovativa lösningar, där ökad flexibilitet i kombination med större och smartare lagringsmöjligheter ofta beskrivs som relevanta områden.

Ett exempel på en innovativ lösning där ovanstående exempel inkluderas är aggregatorer och virtuella kraftverk. Aggregatorerna kan samla olika distribuerade energiresurser och smart styra dessa som en gemensam resurs, för att på så vis ofta kunna utvinna mer flexibilitet ur samma hårdvara. Företaget CheckWatt AB har tidigare undersökt möjligheter med att utnyttja ett batterisystem till både effekttoppskapning och för att förse nätet med frekvensregleringsresurser. En intressant fortsättning på ett sådant arbete är vidare att undersöka vilka fördelar aggregering av flera sådana system skulle kunna innebära, jämfört med när enheterna arbetar individuellt. I den här studien har sådana fördelar undersökts närmare och vidare har det undersökts hur säkerhetsmarginaler i ett sådant system kan sänkas till följd av fördelarna.

Studien som presenteras i det här examensarbetet har den tidigare numeriska modellen som konstruerats av CheckWatt AB som grund, men där ett aggregerande lager adderats. Slutsatser som kunde dras av studien var att det fanns fördelar med att aggregera flera batterilagersystem kopplat till ökad flexibilitet och möjligheten till att agera som en starkare marknadsaktör på den svenska frekvensmarknaden frequency containment reserve - normal (FCR-N). Studien visade också att säkerhetsmarginalerna gällande utlovad effekt för frekvensreglering kunde sänkas, medan säkerhetsmarginaler kopplat till lokal effekttoppskapning inte kunde bevisas sänkas i samma utsträckning. Utifrån nämnda resultat verkar aggregatorn och vidare virtuella kraftverk ha en potentiell roll i det framtida elsystemet, där mindre distribuerade energiresurser gemensamt kan öka mängden flexibilitet och därmed möjligheten till ökad andel intermittenta energislag och lägre utsläpp av växthusgaser.

Acknowledgement

This thesis was written as a closure of the socio technical engineering master program at Uppsala University during the spring of 2021. We would like to extend our gratitude to Dan-Eric Archer and all the employees at CheckWatt AB, for giving us the opportunity to perform this study and for believing in our work from the beginning. We felt welcomed and included within the company, despite an ongoing pandemic. Further, we would like to thank Samuel Wingstedt at CheckWatt AB in his role as our supervisor. Samuel provided us with incredible support, wise advices and a great commitment. We would also like to extend our gratitude to our subject reviewer Cecilia Boström at Uppsala University for good advices and support, our opponents Karin Arding and Siri In de Betou who provided us with inestimable point of views and advices regarding the work, and finally also our examiner and the person responsible for our study program, Elísabet Andrésdóttir, for a fantastic commitment throughout the years. Finally, we would like to thank Hamza Shafique at CheckWatt AB for providing us guidance and for giving us insight in his previous work.

Maria Darle and Saga Lindqvist
June, 2021

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Abbreviations

aFRR - Automatic Frequency Recovery Reserves

ARMA - Autoregressive Moving Average

BESS - Battery Energy Storage System

BRP - Balance Responsible Party

DER - Distributed Energy Resources

DES - Distributed Energy Storage

DG - Distributed Generation

DR - Demand Response

DSO - Distribution Service Operator

EMS - Energy Management System

ESS - Energy Storage System

FCR - Frequency Containment Reserve

FCR-D - Frequency Containment Reserve - Disturbance

FCR-N - Frequency Containment Reserve - Normal

FENIX - The European Flexible Electricity Network to Integrate the Expected Energy Evolution

FFR - Fast Frequency Reserve

FR - Frequency Regulation Flagging

FRR - Frequency Recovery Reserves

GHG - Greenhouse Gas

ICT - Information Communication Technology

MD - Mean Deviation

mFRR - Manually Frequency Recovery Reserves

NOSE - No Service Hour

PIFR - Preparation Interval Hour for Frequency Regulation

PIPS - Preparation Interval Hour for Peak Shaving

PS - Peak Shaving Flagging

PV – Photovoltaics

SOC - State of Charge

TSO - Transmission System Operator

VPP - Virtual Power Plant

Nomenclature

$P_L\ (t)$ [kW]: Load power

$P_g\ (t)$ [kW]: Power supplied by the grid

$P_{PV}\ (t)$ [kW]: Power supplied by PV system

$P_{BESS}\ (t)$[kW]: Power supplied by BESS

$P_{safe\ PS}\ (t)$[kW]: Power needed for peak shaving including safety margin

$P_{PS}\ (t)$[kW]: Power needed for peak shaving

P_{act}[kW]: Activated FCR-N power which is actually dispatched

P_{bid} [kW]: FCR-N power bid sent from a local unit to the aggregator during the day ahead

$P_{bid\ total}$ [kW]: $\sum P_{bid}$, The aggregator's sum of the local FCR-N bids, further placed on the FCR-N market

ϵ_{PS}: Peak shaving safety margin

ϵ_{FR}: FCR-N bid safety factor

P_{th} [kW]: Power threshold under which peak shaving should take place

W_{PS} [kWh]: Energy needed to shave a load peak.

W_{CH} [kWh]: Energy that could be used to charge BESS without exceeding the monthly threshold

$W_{BESS,c}$[kWh]: Energy that is currently stored in BESS

HAP [kW]: Hourly Average Power. Average load power during a specific hour taken from the grid to a local unit

SOC_{min}: The minimal state of charge limit for BESS without exceeding safety limit

SOC_c: Current state of charge for BESS

SOC_{max}: The maximal state of charge limit of BESS without exceeding safety limits

$SOC_{C,prog}$: What the current state of charge is supposed to be according to the forecast

$W_{BESS\ size}$[kWh]: The maximum energy that could be stored and used in and from BESS without exceeding the safety limits which could damage the BESS

1. Introduction

The introduction accounts for why the study was conducted and puts potential results of the study in a bigger picture. Furthermore, it accounts for how the study can be found interesting and why it is of significance. The opening part of the introduction presents a background to the concerned area of interest as well as a potential development in the field of research. This is followed by a formulation of the aim of the study and the associated research questions which have been formulated for the aim to be achieved. Finally, the delimitations of the study are presented.

1.1 Opening

The Swedish electricity grid is undergoing changes which will lead to an increased demand for the development and usage of innovative solutions. The challenges that requires new solutions includes for example the increased usage of renewable and intermittent energy sources in combination with an increased electrification of society, regional bottlenecks within the electricity grid, the phase out of nuclear power as an alternative energy source, new technical conditions and economic values. New solutions can be implemented in form of for example new ancillary services within the electrical system, which includes many new possibilities. New use of resources such as batteries, photovoltaics (PV) and digital control further have the potential to contribute to frequency balancing of the electricity grid, which is possible to execute by using ancillary services (Power Circle, 2019). Today, there are several different types of ancillary services in Sweden with different requirements, which all operate in different markets.

Previously, the frequency regulation of the electricity grid has been managed mainly by large generators, but due to the current development of the grid, the role of the consumers is increasing. Ancillary services as aggregated units which are supplying electricity to reserve markets are further a potential alternative to regulate the frequency of the electricity grid in order to obtain power balance of the grid (Saarinen, 2017). These aggregators are controlling different kinds of loads and generators, which can be owned by for example private actors. From the perspective of a consumer, the participation within such a system could contribute with an increased demand flexibility, reduced power consumption from the grid and an added economic value (Edwall, 2020).

A degree project by Hamza Shafique (2020) on behalf of the smart energy service company CheckWatt AB, has previously been completed. The project consisted mainly of a study regarding the usage of a single battery energy storage system (BESS) and how it could be smartly steered in order to provide both local peak shaving and frequency regulation of the grid. Shafique's (2020) study was focused on the control of an individual system. By aggregating several BESSs and using them as a common resource, a virtual power plant (VPP) can further be obtained. An interesting continuation of Shafique's (2020) project could further be to examine the possible benefits of such a system, both regarding advantages connected to upscaling and reduced safety margins regarding promised effect. The hypothesis is that a given aggregated population of BESSs are able to compensate for each other's deviations and further provide a higher rate of flexibility to the electricity system. The hypothesis is further that this fact can result in reduced safety margins within the aggregated system, which implies that a larger benefit could be obtained from the same original hardware. This is further of interest for consumers, network operators and the electricity market due to raised economic values and further increased flexibility and possibilities to a more stable electricity system in terms of frequency. In this thesis a study regarding such a system will be performed on behalf of CheckWatt AB.

1.2 Aim

The aim of the study is to, by expanding a numerical model, examine what benefits an aggregated population of BESSs could result in compared to when the individual units in the population are being used separately. The aim is to investigate the benefits both in terms of increased flexibility and further possibilities for reduced safety margins for promised effect. Lastly, the aim of the study is to examine how a VPP could be implemented as a sustainable and flexible solution for balancing the electrical grid in the transition to a sustainable electric system in order for climate goals that have been set to be achieved.

1.3 Research Questions

The two following research questions have been formulated in order for the aim of the study to be achieved.

- What main advantages can be obtained when an upscaling population of BESSs, with differences in between the individual units, are being used as aggregated demand flexibility for ancillary services to the electricity system, compared to when not being aggregated?

- Further, how can these advantages potentially affect the safety margins regarding total promised power of such a system?

1.4 Delimitations

- **Geographical Area**

The thesis is delimited to investigate the subject within Sweden as the geographical area. A large part of the work could easily be applied to another country, but since different market rules apply in different countries, it is necessary to delimit to a specific geographical area. Sweden was a reasonable choice since the thesis is written on behalf of the Swedish company CheckWatt AB.

- **Numerical Model**

The investigated system is of numerical character and does not include real-time control. The numerical model is based on a numerical model developed by CheckWatt AB. The model includes an algorithm for smart steering of a single BESS tied to a PV, which can be used for local peak shaving and for delivery of frequency regulation through the product frequency containment reserve - normal (FCR-N). The model is delimited to be a *binary model,* which is explained further in Chapter 4: *Methodology*. This was requested by the company and is therefore the delimitation of this thesis. The other choices and components connected to the algorithm will be motivated and explained further in the Chapter 4: *Methodology*.

- **Frequency Reserve**

The study is delimited to investigate the research questions by using FCR-N as the choice of frequency reserve to build the numerical model. The conclusions can therefore only be drawn regarding VPPs delivering power through this product. The delimitation of frequency reserve is motivated by previous studies performed by CheckWatt AB, and by the fact that the market is of interest for the company. The choice is further motivated in Chapter 4: *Methodology*.

- **Electricity Market Bidding Area**

According to FCR-N market rules, power bids can only be put in one electricity market bidding area at the time, which motivates a delimitation to a single electrical area. Area SE3 was chosen, which is the central part of Sweden. This choice is motivated by the fact this is the largest area, although the choice did not have any major impact on the results.

- **Technical and Numerical Focus**

The study focuses on answering the aim through a technical and numerical point of view, which implies that the thesis is delimited from an economical focus with for example economical optimizations in order to achieve the maximum profit of the examined VPP-model. This is mainly motivated by the time limit of the project.

- **System**

This study is delimited to a certain population of load profiles, why it should be considered as a case study. The investigated population of load profiles consists of 45 load profiles of different sizes, each connected to a BESS, a PV plant and an Energy Management System as communication unit, why the study is delimited to this specific size and form of population of load profiles, although more general patterns and conclusions will also be discussed.

1.5 Disposition

The report will continue with Chapter 2: *Background* and Chapter 3: *Previous Research*, in which relevant background information respectively previous studies within the area will be presented in order to provide the reader with the given context and relevant concepts and facts. Further on, the report will continue with Chapter 4: *Methodology* which will regard the methodology that has been used to execute the study and which will involve a literature study and a numerical study. The theory relevant for the calculations in the numerical part of the study will also be presented in Chapter 4. Chapter 5: *Data* will then follow, in which the data that was used in the simulations of the studied case system will be presented. Further on, the results of the simulations will be presented in Chapter 6: *Results* followed by a discussion in Chapter 7: *Discussion.* Finally, the report will be closed by the conclusions, which will be presented in Chapter 8: *Conclusions.*

2. Background

In order for the reader to understand the main purpose of this thesis, and further on being able to follow the report and understand the choice of methodology, necessary background information will be presented in this chapter. The chapter aims to clarify relevant concepts, structures and facts regarding the Swedish energy system overall, but also more specific areas connected to the subject of the thesis, such as frequency reserves, distributed energy resources, virtual power plants and peak shaving. Readers familiar with the Swedish energy system and electricity market can focus on section 2.5 and further. All figures, except Figure 1 and Figure 2, are self-made and marked with the source of where they are adapted from if that is the case. In Figure 1 and Figure 2 only the labels are translated compared to the original figures and the figures are published with the permission from the marked reference.

2.1 The Swedish Electricity Mix and Climate Goals

The electricity production in Sweden has been undergoing changes during the past 50 years. The composition of the annual electricity production during this time and the division of its different kinds of sources can further be seen in Figure 1. From Figure 1, a trend of an increasing annual production of electricity in Sweden since the 1980s can be distinguished and in 2018, the total electricity production in Sweden was 160 TWh of which 17 TWh was exported. It can also be seen from the figure that since the 1980s, the energy generation mainly comes from hydropower and nuclear power (Energimyndigheten, 2020).

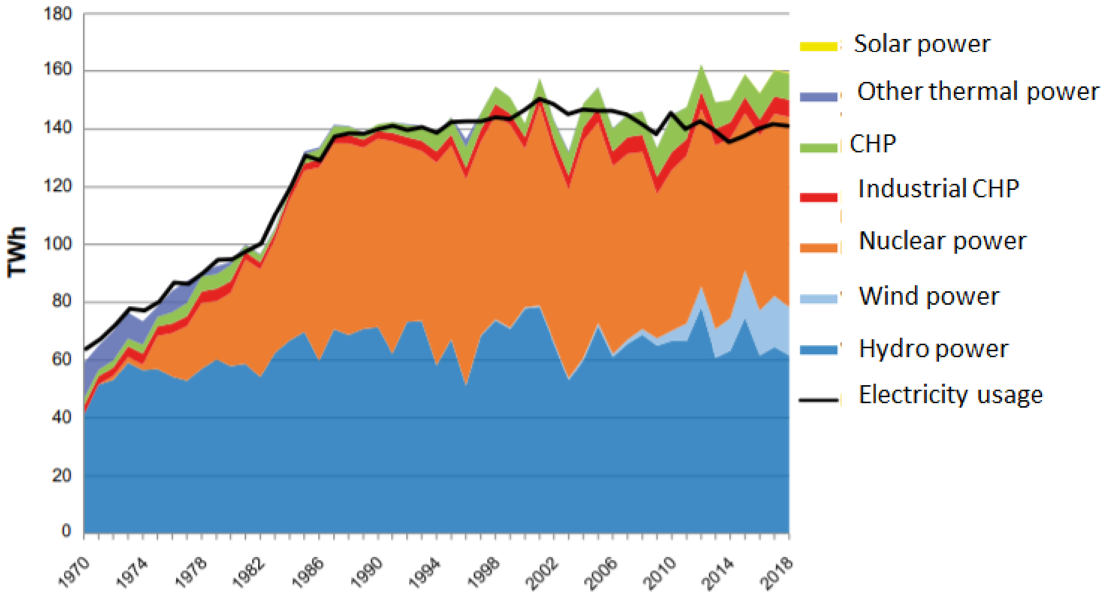

Figure 1. The electricity production [TWh] in Sweden divided by type of power source and the total electricity use in 1970–2018 (Energimyndigheten, 2020).

Furthermore, the electricity production from renewable sources accounted for approximately 90 TWh in 2018 and has increased since 1990, which can be seen in Figure 2 where the electricity from renewable sources from 1990 to 2018 can be found. The production from renewable sources further corresponded to 57 percent of the total electricity produced in 2018 (Energimyndigheten, 2020).

As can be further seen in Figure 2, the capacity for wind power has expanded every year since 1990 and by the end of 2018. Although electricity produced with photovoltaics (PVs) accounts for a very small share of the total electricity production, the installation of it is growing rapidly, as seen in Figure 2. The market of PVs consists of both grid-connected systems, which account for most of the capacity, as well as stand-alone systems. By the end of 2018, the installed PV capacity was 411 MW, which was an increase from the capacity of 231 MW in 2017. The total capacity produced further was approximately 391 GWh in 2018, which was 70 percent more than in 2017. The rapid increase of photovoltaic power capacity can further be explained by favourable support that further provides financial incentives for investments, an increased environmental awareness among private individuals as well as that the price of PVs has decreased during the recent years (Energimyndigheten, 2020).

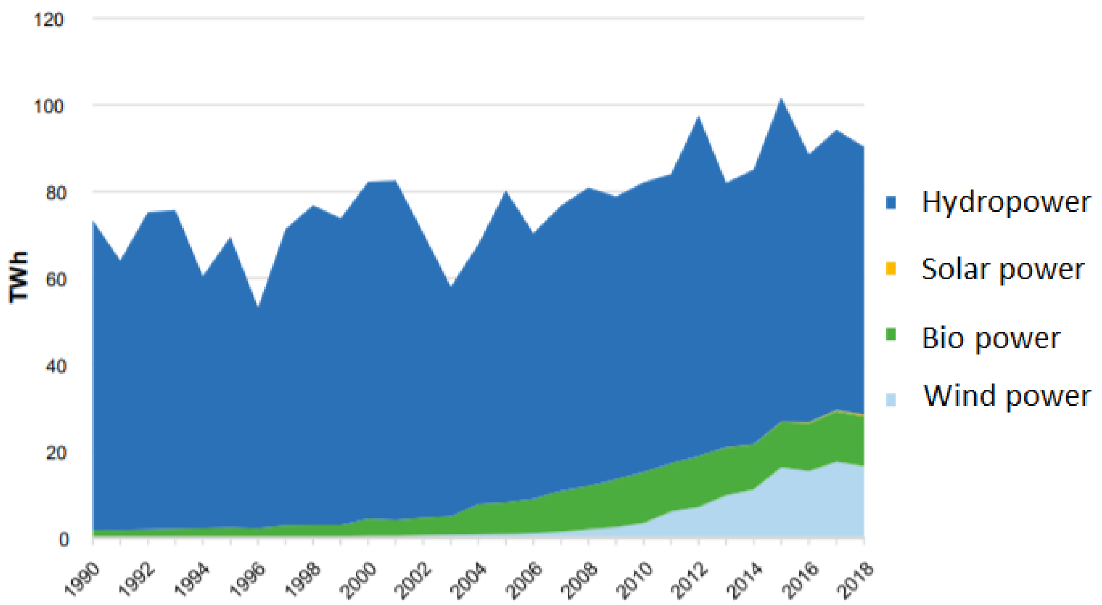

Figure 2. The electricity production [TWh] from renewable energy sources in 1990–2018 (Energimyndigheten, 2020a).

For an ecological sustainability regarding competitiveness and security of supply to take place, several energy and climate goals has further been set in Sweden accordingly to EU legislation. A selection of the Swedish energy and climate goals for 2030 and beyond is as follows (Energimyndigheten, 2020b):

- Greenhouse gas (GHG) emissions shall be 63 percent lower in 2030 compared to 1990.

- The electricity production shall be 100 percent renewable by 2040.
- The usage of energy shall be 50 percent more effective in 2030 compared to 2005.

Due to the Swedish energy and climate goals for 2030 and beyond, further changes within the current composition of the electricity generation as well as development within the energetic system must take place for these goals to be achieved (Energimyndigheten, 2014).

2.2 The Swedish Electricity System

2.2.1 Overview

Sweden is divided into four electricity market bidding areas, SE1-SE4, which are numbered from the most northern to the most southern area. In the two most northern areas, SE1 and SE2, there is a surplus of electricity, while in the two most southern areas, SE3 and SE4, there is a deficit of electricity. This means that large amounts of electricity are transported from northern to southern Sweden. The purpose of the division of the country into four areas is to make it more profitable to produce electricity where there is a deficit of electricity and further reduce the need to transport electricity, this due to the difference in price in the different areas (Konsumenternas energimarknadsbyrå, 2021).

The Swedish power grid is divided into three levels: the national transmission grid, the regional distribution grid and the local distribution grid. The national grid is owned by the Swedish TSO Svenska Kraftnät, the regional grid is mainly owned by three large companies: Vattenfall, E.on and Fortum, while the local grid is runned by approximately 170 different companies (Stockholm Environment Institute, 2015).

2.2.2 Relevant Actors

In order to further ease the understanding of the following parts regarding electricity trading, a brief overview of different affected actors is being done.

An *electricity consumer* is a user who withdraws electricity from the grid for usage, which occurs at a withdrawal point. The user could be a trader, such as an industry or a company, or a consumer, such as a household. The two can be defined according to Ellagen (Ellag, 1997). A trader is a user which uses electricity mainly in activities associated with business or other similar activities, such as an industry or a company. A consumer, on the other hand, is a physical person to whom electricity is transferred mainly for purposes outside of activities associated with business. This user could be a household, for example (Svenska kraftnät et al., 2020).

The financial responsibility for the energy balance is delegated to actors called *balance responsible parties* (BRPs), who must plan their customers' electricity use and or electricity production, and trade or sell electricity so that they end up in balance, which is often done via the electricity exchange Nord Pool. There are approximately 30 BRPs in Sweden and all electricity generators and electricity consumers are linked to one of them (Svenska kraftnät et al., 2020).

An *electricity generator* produces electricity and transfers it into the grid. The electricity generator is regarded as an owner of a production plant that sells the produced electricity to an *electricity retailer*. This company, further on, can act both as a trader that resells the electricity to the electricity consumers and as a BRP which means that it has a responsibility for the balance between the production and the consumption of electricity among its customers. The electricity retailer can either buy electricity from another electricity retailer in for example the Nordic electricity exchange Nord Pool, or directly from an electricity generator. The electricity retailer sells electricity on the free electricity market in competition with other electricity trading companies. The electricity price is set within an agreement between the buyer and the seller (Svenska kraftnät et al., 2020).

Furthermore, *electricity grid companies* provide the electricity grid and are responsible for ensuring that the electricity is transported from the electricity generators' production facilities to the electricity users. This is feasible due to main grids, regional grids as well as local grids, which further are owned by various electricity grid companies (Svenska kraftnät et al., 2020).

Lastly, the *transmission system operator (TSO)* is the authority responsible for security of electricity supply and bears the ultimate responsibility for imbalance settlement according to the national laws. In Sweden, the TSO is Svenska kraftnät (eSett, 2021). A brief overview of the Swedish electricity system and relevant actors is presented in Figure 3 below.

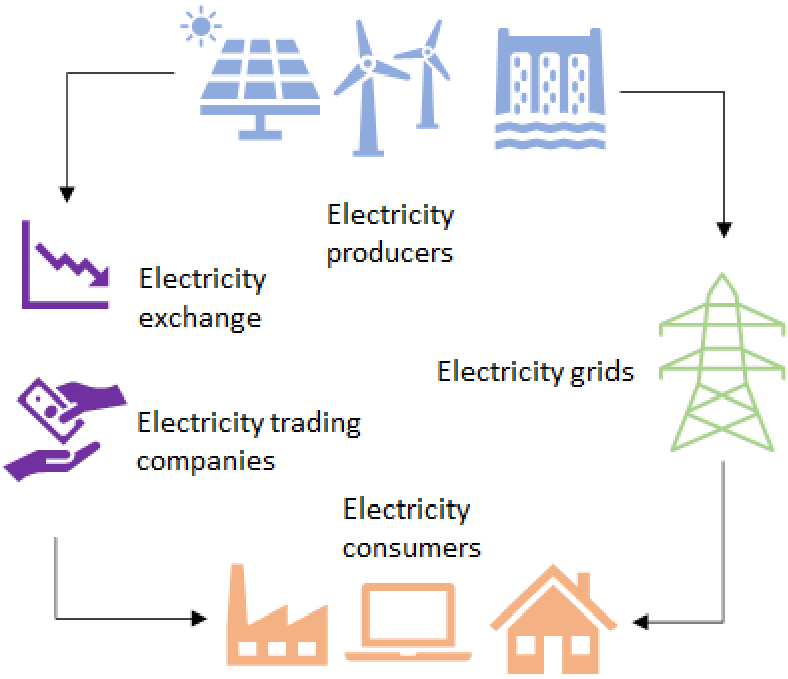

Figure 3. An overview of the Swedish electricity system [Adapted from Svenska kraftnät, (2015)].

2.2.3 Frequency Balance

The Swedish TSO, Svenska kraftnät, has an overall responsibility to maintain the short-term balance between the production and the consumption of electricity in Sweden. Without balance between the two, the electrical system will not work (Svenska kraftnät, 2020g). The production and the consumption is further in balance when the frequency is stable and the Swedish power system is, due to technical reasons, designed for an optimal frequency of 50.00 Hz (Svenska kraftnät, 2020a). An illustration of the frequency balance can be seen in Figure 4 below.

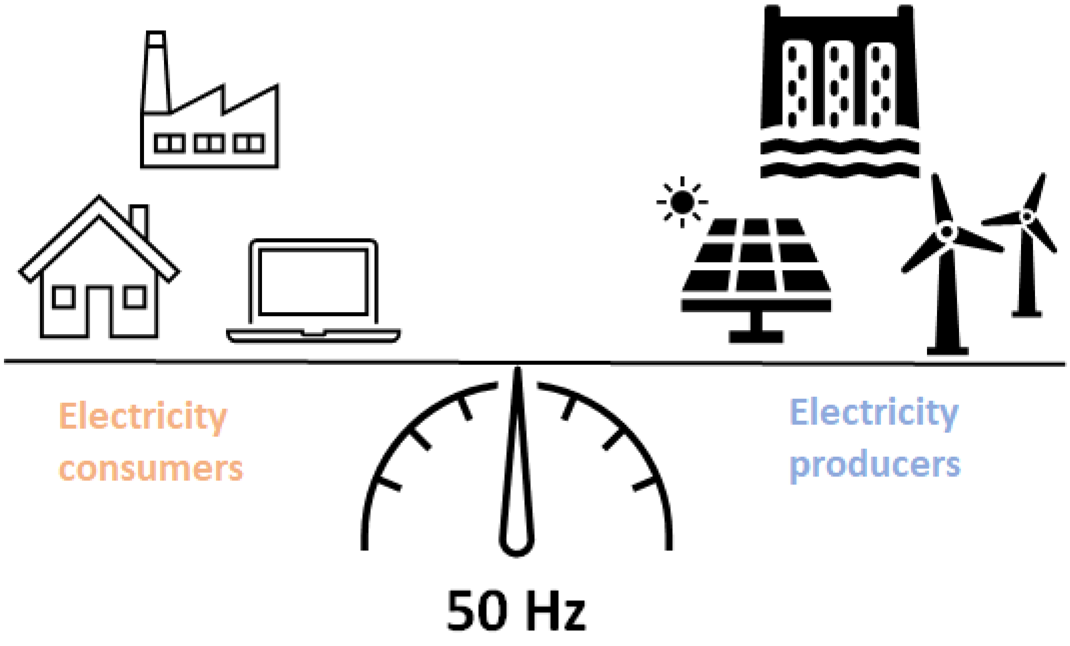

Figure 4 - The balance between electricity usage and electricity production in order to maintain the correct frequency on the grid [Adapted from Svenska kraftnät (2020a)].

The first way of regulating the frequency of the grid is through rotation energy maintained from large turbines, mainly in hydro- and nuclear power plants. The turbines create inertia, which can manage to handle small fluctuations and immediate frequency changes will thereby be smaller (Svenska Kraftnät, 2020e). Due to a growing share of intermittent energy, which does not provide inertia to the grid, the total inertia of the system can be expected to decrease. For this reason, complementary solutions are needed in order to retain system strength (IEA, 2021).

In addition to inertia, BRP trades electricity and Svenska kraftnät uses and procures ancillary services in order to maintain the balance and operational reliability of the power system (Svenska kraftnät, 2020b). These services and tradings are being introduced further in the following part of the background.

2.3 The Swedish Electricity Market

The trading of electricity takes place in a complex market where many factors determine the final electricity price (Energiföretagen, 2020a). Almost all electricity trade within the Nordic region goes through the electricity exchange Nord Pool and approximately 90 percent of the annual electricity production in Sweden is sold directly through Nord Pool. At Nord Pool, electricity generators can sell their produced electricity to electricity traders, and further on the electricity price is set hourly every day of the year. Through market connection, the Nordic electricity market is further connected to the Baltic countries, the Netherlands, Germany, Poland and Russia (Energiföretagen, 2020b).

Nord Pool includes two markets, namely elspot and elbas. Elspot is Nord Pool's day-ahead market. Elbas, on the other hand, is the intraday market of Nord Pool and is a physical adjustment market where a continuous trading of hourly contracts takes place (Energiföretagen, 2020b). In addition to Nord Pool's elspot and elbas, there is a market segment called the Swedish reserve market, which is used during the operation period in order to adjust sudden frequency changes (Power Circle, 2019). This market will be described further later in this chapter. The different submarkets are summarized in Figure 5 below.

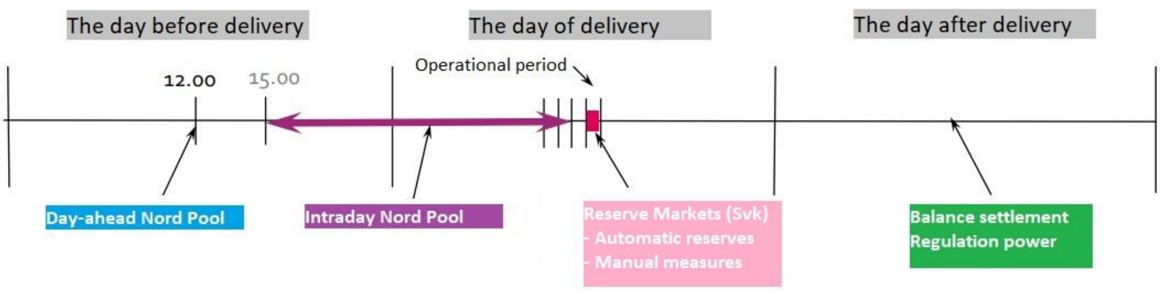

Figure 5. A summary of the various submarkets in the Swedish electricity trading [adapted from Power Circle (2019)].

Each BRP shall, in accordance with their forecast and ability, firstly trade so that they end up in balance in the day-ahead market. If the forecast change after the day-ahead market closes, the BRP can adjust its balance by buying and selling electricity in the intraday market. During the actual operation period, the TSO Svenska kraftnät is responsible for keeping the right frequency of the grid (Power Circle, 2019). This can be done by using the reserve markets. The available capacity that can be activated through the reserve markets during the operation period are procured by Svenska kraftnät one and two days before the day of delivery, which will be explained further in Section 2.4: *The Swedish Frequency Reserves.*

Further on, the day after the delivery of electricity, a balance settlement is made where the BRPs who were not in balance during the operating period together must pay the costs that the TSO Svenska kraftnät has had for all reserves corresponding to the electricity that were not delivered according to agreement (Power Circle, 2019). This period corresponds to the last period of the timeline in Figure 5.

2.4 The Swedish Frequency Reserves

There are several types of frequency reserves with related markets in Sweden, each of them with different requirements. In this section, these ancillary services will be presented followed by a short summarize of the current requirements and further presented in Figure 8.

2.4.1 Frequency Maintenance Reserves

One of the ancillary services that can be obtained as frequency reserve is maintenance reserves, which are called frequency containment reserves (FCR). The reserve is divided into two products: normal (FCR-N) and disturbance (FCR-D). FCR-N is used during normal operation and has the task of preventing imbalances by automatically steering the frequency down if it increases or automatically steering it up if the frequency decreases, until the system has found a new stable frequency mode. FCR-N is a symmetrical product, which means that it must be able to be adjusted equally up and down, while FCR-D only is requested to be available for upward regulation (Power Circle, 2019).

When frequency deviations from the grid's optimal frequency 50.00 Hz in the range of 49.90 Hz to 50.10 Hz appear, the activation of FCR-N must take place (Svenska kraftnät, 2020c). FCR-D is used in the event of an interrupted operation and must be activated to 50 percent within 5 seconds and 100 percent within 30 seconds as soon as the frequency falls below 49.90 Hz. The resources that are part of the FCR-N must be activated to 63 percent within 5 seconds and 100 percent within 3 minutes (Power Circle, 2019).

Svenska kraftnät procures FCR capacity two times before a delivery day. The first one is the D-2 trading, which implies that Svenska kraftnät procures part of the capacity two days before the actual delivery. The second one is the D-1 trading which implies that Svenska kraftnät procures the remaining capacity during the evening before the day of delivery. The procured FCR-N bids are paid in two steps. The first step is a payment according to pay-as-bid of the capacity bid that was put to the market. The other step is a payment for the energy volume that was actually activated during the day of delivery (Svenska kraftnät, 2018).

A capacity bid is placed per hour and the capacity needs to be available for the whole period of time for when the bid is placed. A capacity bid must be placed within the same electricity area. The volume that Svenska kraftnät purchases before each operating period is today approximately 200 MW FCR-N and 400 MW FCR-D. The purchase mostly takes place two days before the actual operating hour, and today it is mostly only hydropower that enters the market. The minimum bid allowed is 0.1 MW (Power Circle, 2019).

2.4.2 Frequency Recovery Reserves and Fast Frequency Reserve

Another ancillary service being offered is frequency recovery reserves (FRR) and it consists of two products: automatic (aFRR) and manual (mFRR). aFRR resets the frequency to 50 Hz and is activated automatically by a signal from Svenska kraftnät. The resources for up- and down-regulation are procured separately for aFRR. Furthermore, mFRR is called on manually and replaces the reserves that have been activated previously (FCR and aFRR) to make them available if new disturbances occur. The reserves of mFRR are traded on a separate market called the regulatory power market (RKM) and bids are called manually in real time on this market (Power Circle, 2019).

In addition to the previously mentioned frequency reserves, the new ancillary service fast frequency reserve (FFR) was recently implemented in Sweden. Its purpose is to create conditions for the user of the service to be able to handle initially fast and transient frequency changes, which can emerge when a fault in the Nordic power system occurs due to a low level of rotational energy in the system (Svenska kraftnät, 2020d).

2.4.3 Summary of The Frequency Reserves

A summary of the frequency reserves and connected markets mentioned above can be found in Figure 6. This applies to the activation time, the minimal bid size and the type of activation for each of the reserve markets FCR-N, FCR-D, aFRR, mFRR and FFR. Figure 6 also shows the order of the reserve markets regarding their respective activation time, from the reserve market with the fastest activation time to the reserve market with the shortest activation time.

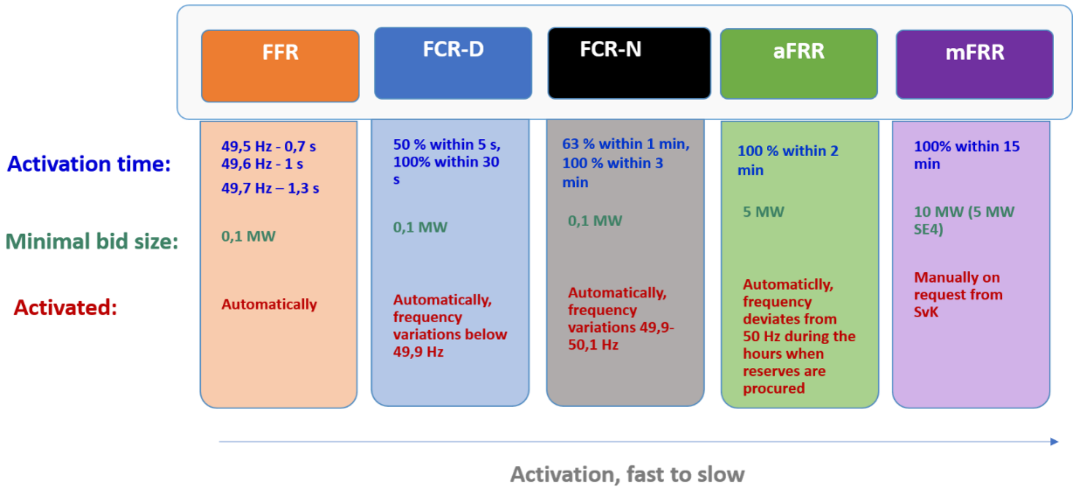

Figure 6. A summary of Swedish frequency reserves and market requirements [Adapted from Svenska kraftnät (2020a) & Svenska kraftnät (2017)].

2.5 Challenges in the Electricity System

Due to climate goals and an increasing electrification of the society, the electricity system is facing new challenges. The largest challenges according to the Swedish TSO Svenska kraftnät includes shutdown of large conventional power plants such as nuclear power plants in combination of a higher rate of renewable and intermittent power within the system and further also reduced inertia. These challenges require new solutions in order to secure a constant and stable electricity supply, why the Nordic electricity system faces the largest changes in 20 years with a new power system as a desired result (Sandborgh, 2020). The new power system is expected to include a common European market, technical and digital development within the area and a more ecological sustainable electricity system. A higher electrification of the society and consequently an increased electricity consumption in combination with less inertia and a higher rate of intermittent power requires, for instance, implementation of increased energy storage possibilities and increased demand flexibility which could be used as for example frequency regulation (Wolf & Andersson , 2018).

2.6 Distributed Energy Resources

Distributed energy resources (DER) are defined as small scale power sources. DER have the ability to combine various distributed generation (DG) technologies, distributed energy storage (DES) technologies and monitoring of energy. DER also control facilities in order to be able to provide potential improvement alternatives of the conventional power system (Adefarati et al., 2019). By using DER in a strategically smart manner, the resources can provide the electricity grid with flexibility and added value (SWECO, 2015).

DER can be divided into DG-technologies and DES-technologies (Akorede et al., 2010). Demand response (DR) can also be considered as a DER, why DR will be included in this section. The different DERs are further illustrated in Figure 7 below.

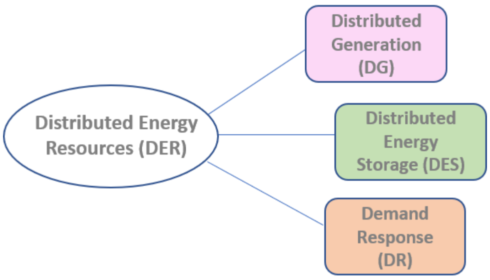

Figure 7. Schematic figure of the categories of DER.

2.6.1 Distributed Generation

The DG can be defined as any kind of electric power originating from a source of limited capacity, which further is being directly connected to the power system distribution network where its produced electricity is being used by electricity users. The DG can further be found on a local and an end-point level. At the local level, the DG could consist of site-specific renewable energy technologies such as PV, wind turbines and hydro-thermal plants whereas at the end-point level, the electricity user is able to apply a number of these DGs (Akorede et al., 2010).

2.6.2 Distributed Energy Storage

Furthermore, a conversion of the energy into electricity is required in order to go through with the power generation of DER. There are two main factors behind the need of DES. First, due to implementation of intermittent energy resources, some sort of energy storage capability is required in the power system. This in order to overcome the fluctuation in the energy supply. Another area of use for DES is when the ability to harness the excessed energy production is needed, which can occur during periods with lower demand of energy. Normally, the process of DES consists of electrical energy converted into another form of energy (Akorede et al., 2010).

2.6.3 Demand Response

DR can be defined as the changes in electricity usage by the end customers, compared to the normal pattern. The change can be due to electricity prices over time, frequency regulation or local power peaks. DR includes all modifications in electricity consumption patterns that are done in order to change the timing, total electricity consumption and level of momentary demand (El Saadany & Albadi, 2008).

DR can for example include actions where the end consumer reduces their electrical usage due to high load on the electricity grid or increases the consumption when the electricity price is low (Energimarknadsinspektionen, 2016). In general, DR can be divided into three actions. Firstly, the end consumer can change their electricity usage during peak hours, but not change the usage pattern during other periods. Secondly, the consumer can move their usage to periods when load of the grid is lower. Lastly, the consumer can use an on-site generator, a DG, which can be used during peak hours. Further on, one type of DR can be defined as peak shaving, which will be presented in the next section (El Saadany & Albadi, 2008).

2.7 Peak Shaving

As mentioned, an example of DR is peak shaving, where load power peaks are reduced in different ways. In order to ease the understanding of peak shaving, hence follows a brief overview of concepts like power tariff, load and demand which all are connected to the area. It is further followed by the presentation of peak shaving.

A power tariff is the amount of money which an electricity grid company can charge an electricity user for consuming the electrical power. In Sweden, a power tariff commonly includes a fixed fee and a transmission fee for electricity. In addition to these, some electricity grid companies also include demand tariffs which amount to what the electricity user is paying in accordance to their usage of power. The demand tariff therefore increases with the amount of electricity appliances that are being used simultaneously. The electricity user’s highest load, also called peak load, is further determining the demand tariff, which is commonly based on the hourly average power (Pyrko, 2005). Power tariffs based on the actual power usage for specific time does in comparison to many other fees and tariffs connected to this create incitements for the end consumer to move the electricity usage to times when the total power outlet of the grid is lower. Such a pattern could imply a more stable local grid with decreased power shortage as a consequence, why this kind of power tariffs is of interest not only for the end consumer but also for the DSO's , TSO's and society as whole (Energimarknadsinspektionen, 2012). Further on, power tariffs could create different incitements depending if they are implemented on local distribution, regional distribution, or national transmission level of the grid. For example, studies show that local power tariffs could possibly affect localisation of electrical intensive industry (Thema consulting group, 2019).

The cycle of the demand, also called load, over time can further be described by a load profile. In a graph, the load profile can be visualized throughout a certain time period as the ups and downs of the demand. The consumption of electricity is represented by the area under the demand line in the graph (Kadri et. Al., 2016).

An effective way of managing utility costs for electricity users with demand tariffs is load peak shaving. There are plenty of ways to perform peak shaving and depending on the load profile and the electricity need, the most optimal peak shaving method can be identified. Peak shaving amounts to lower and smooth out the highest loads, also called peak loads, in a load profile so that the short-term demand peaks that underlie the high demand tariffs are being reduced or eliminated (Uddin et.al., 2018).

The peak loads are a result of a common uneven load profile among electricity users. The power system therefore must be dimensioned for peak loads as well as lower loads throughout a certain time period. In order for the power system to be able to meet the peak loads and keep up with the peak demand, extra costs for the maximum peak load are being distributed to the electricity users in form of power fees, such as demand tariffs (Oudalov et al., 2006).

One way to peak shave is by using DG, for instance PV, in combination with a DES, for example a smartly controlled storage unit. An example of such a storage unit is a battery energy storage system (BESS), which will be described further in the next section, Section 2.7: *Virtual Power Plant (VPP)*. The concept of peak shaving is illustrated in Figure 8 below (Lawder et al., 2014).

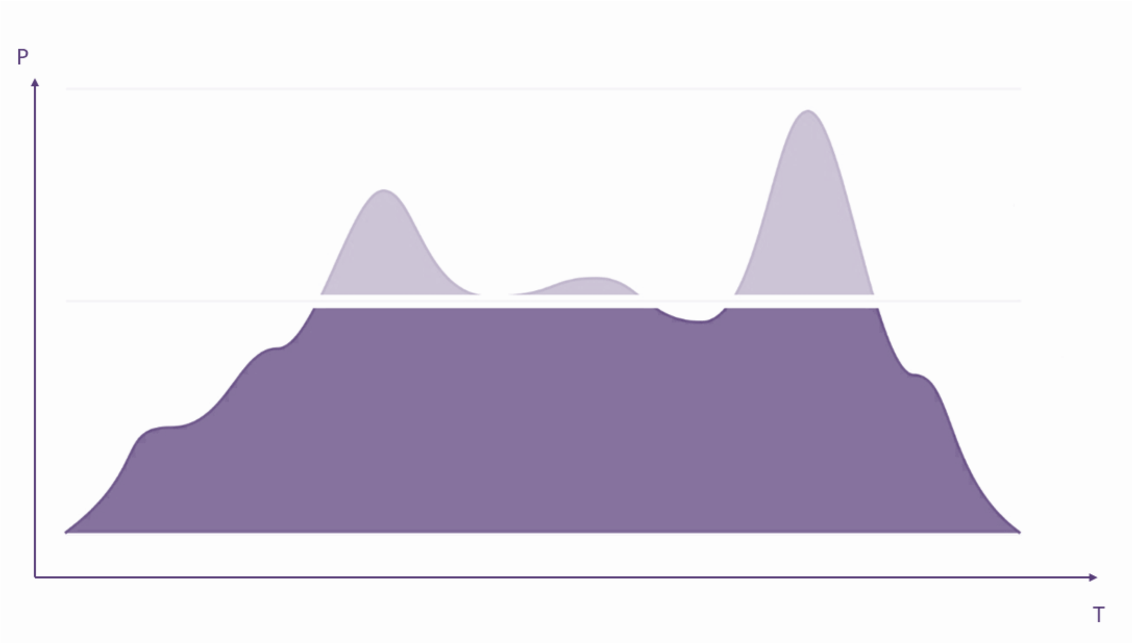

Figure 8. Conceptual graph of peak shaving, showing how power peaks can be reduced (light purple area) by using for example a battery as a complement during power peak hours. The x-axis represents time and the y-axis represents the load [Adapted from (Ideal Energy, 2020)].

2.8 Virtual Power Plant

2.8.1 Definition and Concept

Due to the previously mentioned challenges within the electrical system and an ongoing process of changing the electricity market from a monopoly system structure into a competitive market structure, it is inevitable to run a great amount of DERs units under market conditions. This, on the other hand, may bring some challenges. These include taking part in the market due to regulations, taking an intermittent nature into account regarding DERs and the fact that DERs units commonly stand-alone due to the ambition of satisfying the local needs rather than the whole grid. One way of acting regarding these challenges is to aggregate a number of DERs units which together form a VPP, acting as a collecting resource on the market. The different DERs can be coordinated by a common unit which is often referred to as the aggregator of the system. Although, an aggregator is not a necessity of a VPP. The aggregator could be run by the electricity grid company or, for instance, by a third party (Saboori et al., 2011).

The definition of a VPP further is, according to the European Flexible Electricity Network to Integrate the Expected Energy Evolution (FENIX) project:

> *"A VPP aggregates the capacity of many diverse DER. It creates a single operating profile from a composite of parameters characterizing each DER unit and can incorporate the impact of the network on*

aggregated DER output. A VPP is a flexible representation of a portfolio of DER that can be used to make contracts in the wholesale market and to offer services to the system operator" (FENIX, 2009).

The definition of a VPP mentioned above will further be used as a base in this thesis. The VPP can be operated by aggregated dispersed generator units, controllable loads and storage systems. The generators are capable of using both fossil and renewable energy sources (Saboori et al., 2011). However, the focus of this thesis will be a generator using a renewable energy source. A conceptual illustration of different DERs forming a VPP, which through the aggregator can offer uniform products to the different electricity markets, is shown in Figure 9 below.

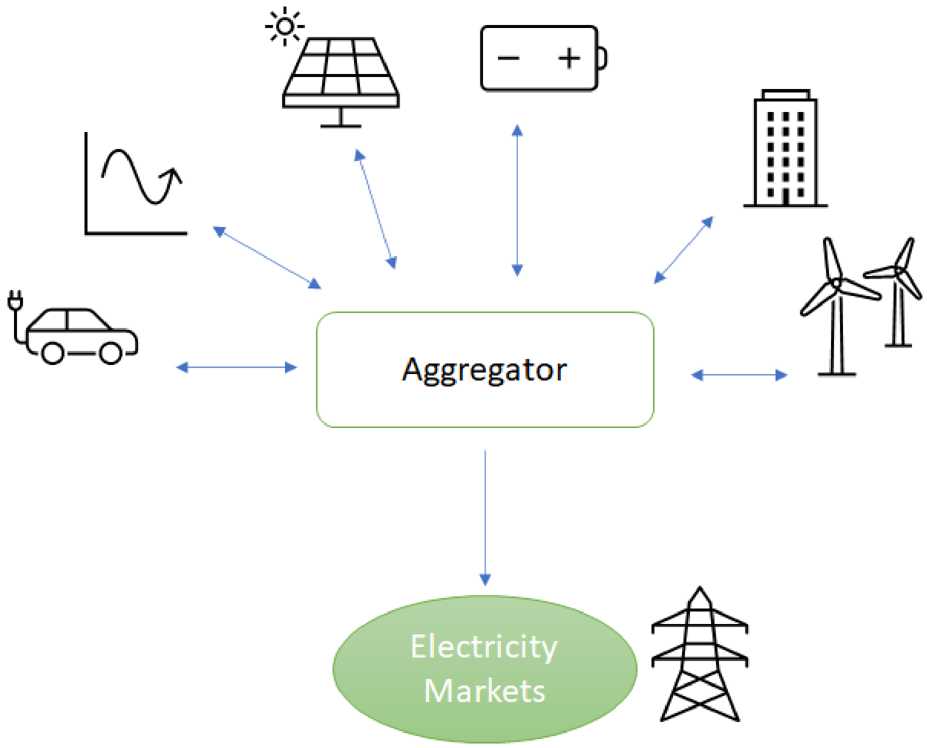

Figure 9. Illustration of a conceptual VPP where different DERs can act as a unitary market player.

2.8.2 Components

The VPP generally consists of three key units; generation units, energy storage units and information communication technology (ICT) units (Saboori et al., 2011).

Generation Units

Regarding the generation units, there are various technologies capable of specifying the DG for integration in the VPP, some of the considered alternatives for integration in the VPP are (Saboori et al., 2011):

- Combined heat and power
- Biomass and biogas
- Small power plants such as gas turbines, diesels, etc.
- Small hydro-plants
- Wind based energy generation
- Photovoltaics (PV)
- Flexible consumption (controllable/dispatchable loads)

Energy Storage Units

Furthermore, the energy storage systems (ESSs) are a complement that is able to adapt variations of the power demand to a given level of power generation. Regarding the generation of renewables, ESSs are also available for usage as additional sources or as energy buffers in situations of non-dispatchable generation or stochastic generation such as PV. The considered alternatives of ESSs for integration in the VPP are (Saboori et al., 2011):

- Hydraulic Pumped Energy Storage (HPES)
- Compressed air energy storage (CAES)
- Flywheel Energy Storage (FWES)
- Super conductor magnetic energy storage (SMES)
- Battery energy storage system (BESS)
- Supercapacitor energy storage (SCES)
- Hydrogen along with fuel cell (FC)

One of the most common ESS is BESS. The BESS differs from regular batteries due to its control software with learning algorithms, which anticipates the peak demand based on the electricity user's load profile. Furthermore, the BESS switches from the grid to batteries instead when the need occurs. In accordance with a predetermined limit, the BESS can control whether power should be maintained from the grid or the battery. If the power usage is exceeding the predetermined limit, the algorithms of BESS are able to detect this and the BESS further switches from the grid to the batteries during necessary periods of time when there is an additional demand. When the demand decreases, the batteries are being recharged (Lawder & Suthar, 2014)

Characteristics of importance regarding BESS which will be recurring throughout the study are its C-rate, maximum and minimum charging limits as well as charging and discharging efficiency.

The variable C-rate is a measure of at which current a battery is charged or discharged. The capacity of a battery is generally measured to 1C, which implies that a fully charged battery with a capacity of 5 Ah should be able to provide 5 Amps for one hour (MIT Electric Vehicle Team, 2008). According to manufacturers of batteries, the charging limits of 100 percent and 0 percent of the battery are actually representing 90 percent respectively 10-15 percent in order to increase the lifetime of the battery. 100

percent of the battery is therefore not utilised and charging limits are further set in order to take this into account (Wikner & Thiringer, 2018). Due to losses of energy in the form of heat due to internal impedances, a 100 percent efficiency is not possible to be obtained by a battery. According to Valøen and Shoesmith (2007), lithium batteries charge with an efficiency at 80-90 percent.

Information Communication Technology (ICT) Units

Finally, the ICT unit is of importance for the VPP. The units have an essential role including steering and communication within and between the different units connected in the VPP. There are different types of ICT units that could be used for VPP, considered alternatives could be for example (Saboori et al., 2011):

- Energy management systems (EMS)
- Supervisory control and data acquisition (SCADA)
- Distribution dispatching center (DDC)

This thesis is as mentioned in section 1.4: *Delimitations* delimited to a system with where EMSs are used. EMS is a commonly used ICT unit. It communicates with the generators, controllable loads and storages and further coordinates the power flows coming from these aggregated parts and therefore, the EMS is the central part of the VPP. This is being done both by generating information about the current status of each unit and by sending controlling signals to the aggregated parts. The EMS is further able to operate in accordance with a number of aims. These include a minimization of the generation costs, a minimization of the production of GHGs and a maximization of the profits of a VPP (Saboori et al., 2011).

2.8.3 Offered Services

The VPP is a source of control of distribution and transmission networks. The following services can be offered by the VPP to distribution service operators (DSOs) and TSOs in order to support the system operation (Saboori et al., 2011):

- Frequency control (TSO)
- Voltage control (TSO and DSO)
- Flow control (TSO and DSO)
- Stability enhancement (TSO)
- Security and reliability enhancement (TSO and DSO)

2.9 The Company CheckWatt AB

As mentioned in the introduction, this study is executed on behalf of CheckWatt AB, which is a small sized company based in Sweden. CheckWatt AB offers their customers measurement and control of their own sustainable energy and through information, measurement and visualization, CheckWatt AB wants to contribute to resource efficiency. The company wants to enable a 100 percent renewable energy system through intelligent data analysis and automatic control of loads and generators for their customers. Their customers include both private customers as well as companies (CheckWatt AB, 2021).

3. Previous Research

The following chapter regarding previous research aims to assist the reader with relevant research connected to the aim. In contrast to Chapter 2: Background, this chapter focuses on specific research studies with close connection to the subject, which together with the information presented in Chapter 2: Background will form the theoretical framework of the thesis. The research results and concepts that will be presented are of relevance to the choice of methodology, why the following chapter should be read as whole in order to enable a better understanding of the study.

3.1 Previous Work Done at CheckWatt AB

Previous work has been done at CheckWatt AB regarding the subject of this thesis. Wingstedt & Nilsson (2019) performed a study regarding the Swedish energy market and the potential of distributed energy resources (DER) and virtual power plants (VPPs). In the study, the authors conclude that the most attractive way of acting on the Swedish reserve market for the company is through the frequency containment reserve - normal (FCR-N).

Based on Wingstedt and Nilsson's (2019) results, Shafique (2020) performed a new study on behalf of CheckWatt AB which aimed to develop an algorithm to be used for distribution of a single battery energy storage system (BESS) resource between peak shaving of a local load and FCR-N service. The hypothesis of the study was that by designing an energy management system (EMS) that intelligently can manage the BESS resource, an added value would be generated through the already present resources.

The suggested EMS includes two main parts: a prognosis module and a real time operation module. The prognosis module makes recommendations for the hourly service of BESS and creates a schedule for BESS to follow. The real time operation module further dispatches the services based on the recommendations while simultaneously correcting the uncertainties from the prognosis module (Shafique, 2020). Lastly, the study concluded that an added value can be gained when managing the BESS resource with the suggested EMS (Shafique, 2020).

3.2 Peak Shaving

There are, as mentioned in Chapter 2*: Background* different approaches to performing peak shaving. In Levron et al.s (2012) study a method of optimal peak shaving is described, where a threshold level is introduced. The threshold is described as a level value which is able to be set to different values depending on the purpose of the optimization, which for instance could be cost minimization. The study states that the method reveals the lowest possible power peak given the load's profile and the storage capacity. The threshold level therefore decides under which value of power peaks peak shaving should take place.

Oudalov et al. (2007) suggest an optimal BESS capacity and power in order to minimize the energy costs by using dynamic programming in their study. The model takes energy losses of the BESS into account and proves a reduction of the annual electricity bill by four percent compared to when no BESS is being used to perform peak shaving.

3.3 Combining BESS, Frequency Regulation and Peak Shaving

Previous work has been done regarding how to use BESSs in order to provide either frequency regulation or peak shaving. However, few studies regard a combination of both services and how such a combination could imply an added value. Engels et.al. (2020) attempts to fill this gap by introducing a stochastic optimisation and control framework in order to optimally combine both frequency regulation and peak shaving. The result of the study shows that a combination of the suggested services increases the value compared to when BESS only is used separately for the suggested services. When combining the two services, the profit increases with 10 percent compared to when only performing frequency control and 100 percent compared to when only performing peak shaving.

Shi et al. (2017) investigates a combination of both services as well with the aim to reduce the energy bills of large commercial companies. The study is limited to the U.S energy market and fast frequency reserve (FFR) is chosen as the reserve market. The authors use a stochastic joint optimization framework which captures battery degradation, operational constraints and uncertainties regarding customer load and regulation signals. Further on, the result of the study shows a super linear pattern where the cost savings gained when using the BESSs with the joint optimization algorithm is larger than the sum of the individual cost savings gained when the services are used in certain cases.

3.4 Virtual Power Plant

3.4.1 FENIX

A typical research implementation of VPPs is the European Flexible Electricity Network to Integrate the Expected Energy Evolution (FENIX). The project was founded and initiated by the European Union and took place during the years 2005-2010. The objective of the project was:

> *"To boost DER (distributed energy resources) by maximizing their contribution to the electric power system, through aggregation into Large Scale Virtual Power Plants (LSVPP) and decentralized management"* (FENIX, 2009).

The project involved multiple actors from different disciplines, for example universities, research centers, transmission and distribution utilities and representatives from the business community (FENIX, 2009). The conditions enabled real large-scale tests of VPPs in practice.

Two scenarios were included in the project: a northern one in the UK and a southern one in Spain. The result showed that implementation of VVPs, in this case in a system with combined heat and power, enables higher flexibility in the electricity system, which further enables a higher integration of intermittent renewable energy sources such as PV and wind. As a result, this often leads to a reduce the emission of GHG and in this case, lower the gas consumption (Van Der Velle et al., 2009).

3.4.2 Aggregation of Several BESSs

In order to maintain an added value when using BESSs for ancillary services, studies have been performed where multiple BESSs are aggregated. Zhang et al. (2017) proposes a Hierarchical Energy Management System (HiEMS) aggregation strategy to achieve multimarket business operations where the BESSs are able to participate both at the energy market and the regulation market. The model coordinates the BESSs, manages their state of charge (SOC) values and optimizes market bids. The authors offer two main motivations why aggregation of BESSs is necessary for the given purpose. Firstly, a constant schedule for one BESS will not be able to utilize the BESS capacity fully due to energy margins. Secondly, multiple BESSs need to be aggregated in order to meet the minimum capacity requirement set by the market regulator. The model consists of a scheduler level and a dynamic dispatch level. The scheduler level includes a schedule optimizer, a prediction module, a regulation assessment module and a cost estimation module. The prediction module consists of photovoltaics (PV), load and market predictions. The dynamic dispatch level is responsible for distribution of real time charge and discharge of the different BESSs with the information gained from the scheduler level. The authors conclude that the HiEMS boosts the cost effectiveness for the system compared to only providing energy arbitrage by 40.17 percent.

In Engels et al.s (2020) study regarding combined frequency regulation and peak shaving, a framework where multiple BESSs can be aggregated in order to compensate for local forecast deviations is being suggested. The authors suggest that each site should have their own recharging controller and also explain that since power tariffs are charged for each site locally, the peak shaving objective is simply the sum of the peak shaving at the individual sites. Regarding the FCR, Engels et al. explain that the individual FCR has to be summed up to a total FCR capacity at every time step to be able to compensate for each other's forecast deviations. These conclusions are useful for the numerical model in this study as well. The suggested model in the study is able to aggregate frequency control for several BESSs in different locations. However, it does not investigate how this aggregation affects the result in comparison to when the units are not aggregated.

4. Methodology

This chapter contains descriptions and motivations regarding the methodology used to perform the study of this thesis. The methodology is divided into two parts. The first part is the literature study which aims to clarify through which methodology the information presented in Chapter 2: Background and Chapter 3. Previous Research was received. The second part consists of the design of a numerical model and the methodology used to perform the numerical study of the thesis. The part regarding the numerical study introduces the most relevant relations and equations, a section regarding how the simulations have been performed and closes with information regarding a sensibility analysis of the numerical study. The figure presented in the chapter is self-made.

4.1 Hypothesis

The hypothesis that will be tested in this thesis is that a specific system of aggregated battery energy storage systems (BESSs), providing local peak shaving and frequency containment resource - normal (FCR-N) to the grid, can imply an added value compared to when working alone. The hypothesis is further that reduced safety margins can be obtained within the system due to possibilities to compensate for each other's forecast deviations, compared to when the units are working alone.

4.2 Literature Study

Although this thesis mainly consists of a numerical study, a literature study is essential in order for the numerical study to take place. Through a review of the concerned field of the study, previous similar work as well as previous work regarding the subject at CheckWatt AB has been reviewed. Assumptions and decisions that can occur during the process of the study can further be supported by a thorough literature study. Most importantly, a literature study is essential for the research questions to be answered and for the aim of the study to be fulfilled.

To start with, a collection of material for the literature study was being done. By first distinguishing consistent keywords to use as search attributes, a list of articles and background material based on their abstracts and titles was then created. The initial keywords that were used when reading previous research were *Virtual Power Plant*, *Aggregator*, *Energy Management Systems*, *Battery Energy Storage System*, *Frequency Regulation* and *Peak Shaving.* By walking through the list and reading the material more carefully, articles and background material containing a significance for the understanding of the area as well as the formation of the study was selected. This procedure was being done repeatedly until the material needed was considered to have been retrieved and is inspired by Fribergs (2006) method regarding collecting material for degree projects. By using this methodology, the research work could be done in a structured and objective manner.

When the needed material had been collected, the review of the material could take place and a thorough completion of the most important and relevant facts concerning this study could be formulated in Chapter 2: *Background*. Moreover, a similar section considering general previous work, including previous work at CheckWatt AB, can be found in Chapter 3: *Previous Research.*

4.3 Numerical Study

The main part of the thesis is based on a numerical study, where a general numerical model was formulated in order to be used for simulations and calculations of the studied case system and further to fulfil the aim of the study. The model is inspired by the background information and previous studies presented in Chapter 2*: Background* respectively Chapter 3: *Previous Research*, and furthermore partly based on the previous work done by Shafique (2020) in his master thesis *"On Development and Optimization of Energy Management System (EMS) for Battery Energy Storage System (BESS) - Providing Ancillary Services"*. As mentioned in the introduction, the study by Shafique (2020) was performed on behalf of CheckWatt AB, as the study performed in this thesis. The study of Shafique (2020) focused on creating an algorithm and architecture for an energy management system (EMS) in order to be able to use a single BESS for both peak shaving and frequency regulation services. The numerical model in this study, compared to the algorithm created by Shafique (2020), focuses on aggregation of many BESSs, but is still based on the same algorithm for the local EMSs. By performing simulations of the given case system with the numerical model in this study, information regarding forecast accuracy, peak shaving and delivery of FCR-N can be obtained.

The model was coded with the Python programming language, and the data was used was provided by CheckWatt AB and Fingrid and is further presented in Chapter 5: *Data*. The time resolution of the available data regarding load and photovoltaics (PV) electricity production was hour by hour, why the model construction was adapted accordingly. The result of the model consists of a one-week simulation with different amounts of load units, with a minimum of one unit and a maximum of 45 units. The results connected to the populations of different sizes within this range were furthermore compared with a case where the load profiles of the same amount of units were not being aggregated.

4.3.1 Overview and Model Structure

The numerical study was based on a simple model of a virtual power plant (VPP) where several BESSs are smartly controlled in order to be used for both local peak shaving and as common providers of the frequency reserve FCR-N. As mentioned before, the result of the simulation of the VPP model was later on compared with the same data but for the non-aggregated case in order to find differences between the cases. The choice of characteristics and components were made depending on previous work, requests from CheckWatt AB, access to data and the given time limit. The model structure was, as mentioned before, based on the numerical model structure of an EMS developed by Shafique (2020), but with an added aggregation layer. The initial model structure was provided by CheckWatt AB. The added layer further enabled the different local units to compensate for each other's local deviations and to place common bids on the frequency reserve market.

To be able to develop the full model structure and to motivate the choices of the model structure, the components of the VPP had to be set according to the theoretical framework. The components and characteristics of relevance that were found in the theoretical framework are presented in Table 1 below, together with the choice of respective component for the numerical model used in this study. These choices were made due to available data, requests from CheckWatt AB and they were further done according to the system delimitations mentioned in *section 1.4 Delimitations.* Although the components of the system already were done according to the delimitations, short motivations of the choices will follow in order to increase the anchorage and the understanding of the delimited system.

Table 1. Summary of the choice of characteristics and components of the VPP used for the numerical model.

Generation Unit	Energy Storage Unit	ICT Unit	Offered Services
Photovoltaics (PV)	Battery Energy Storage System (BESS)	Energy Management System (EMS)	Frequency Regulation Peak Shaving

The choice of generation unit was, as seen in Table 1, set to PV. This choice was requested from CheckWatt AB and adds an interesting layer for the discussion regarding the role of a VPP in an energy system with a higher proportion of intermittent energy sources. The choice of generation unit was not of relevance for the investigation of the benefits of aggregated BESSs compared to BESSs working alone since it is not expected to affect the difference between the results of the two cases of aggregation and non-aggregation of the BESSs.

To use BESS as the energy storage unit of the system as a complement to the other components is motivated by the fact that the component adds more flexibility to the system. It is further in the interest of CheckWatt AB to be able to combine PV systems with BESS, why this was considered a reasonable choice.

It is further on also in CheckWatt AB’s interest to use EMSs as the choice of information communication technology (ICT) units, why the EMS architecture developed by Shafique (2020) was chosen. This algorithm was used as the base for the numerical model, but as mentioned before, with an extra aggregator layer which enables controlling of many BESSs. Shafique (2020) proved in his study that the EMS algorithm worked properly for controlling a single BESS, why it was of interest to use the same algorithm in this study where aggregation of many BESSs is investigated. The EMS structure was also suitable both in terms of time limit, access to data and to fulfil the aim of the study.

The offered services of the VPP were set to frequency regulation and local peak shaving according to the model of Shafique (2020). The fact that the VPP could offer both services added an extra value to the system, which is of interest for CheckWatt AB. The BESSs could be used for local peak shaving and as providers of reserve capacity to the grid in case of frequency deviations. The frequency regulation was in the model delivered as the frequency reserve FCR-N on the Swedish reserve market. This choice was made based on previous work done by CheckWatt AB (Wingstedt & Nilsson, 2019), and by the fact that the market is of interest for the company and therefore also of interest for the scope of this thesis. The choice of frequency reserve market implied some requirements, which is being presented in figure 6 in Chapter 2: *Background*. The requirements are summarized in Table 2 below.

Table 2. Summary of market requirements for FCR-N.

Activation Time	Minimal Bid Size	Activation
63 % within 1 minutes	0.1 MW	Automatically 49.9-50.1 Hz
100 % within 3 minutes		Symmetric

With the different choices of components, the VPP included three different categories of distributed energy resources (DER), namely distributed generation (DG) - PV, distributed energy storage (DES) - BESS, and demand response (DR) - peak shaving.

The VPP in the numerical model was delimited to a technical VPP where no economical optimizations were being executed regarding, for example, optimal bid sizes, optimal bid hours or optimal share of peak shaving respectively frequency regulation services. This choice was made based on the time frame of the study because of which, those kinds of optimization studies were not considered suitable. This was further explained in section 1.4: *Delimitations.*

The model structure was divided into two parts: the day ahead planning and the day of operation. This approach was based on the structure of Shafique's (2020) work and motivated by the fact that FCR-N bids must be placed at least a day before the actual service hour on the day ahead market. During the day ahead planning, an hourly schedule was done for each BESS, where one hour could be reserved for, for example, peak shaving and another hour reserved for delivery of FCR-N to the grid. The schedule is based on load and PV electricity production forecasts, which indicates, for example, when peak shaving is needed. During the day of the operation, FCR-N bids are placed on the frequency reserve market and the planned services are performed according to the BESS schedule.

The aggregator in the model aims to collect FCR-N bids from each local unit into one total bid which is placed on the reserve market. It also aims to smartly control the different local BESSs together and, if needed, allow them to compensate for each other if forecast deviations would occur by, for example, changing service from frequency regulation to peak shaving for an hour within specific limits. This will be presented later in this chapter. The different components of the model will also be explained more in detail in the following sections of this chapter. An overview flow chart of the model structure is furthermore presented in Figure 10 below.

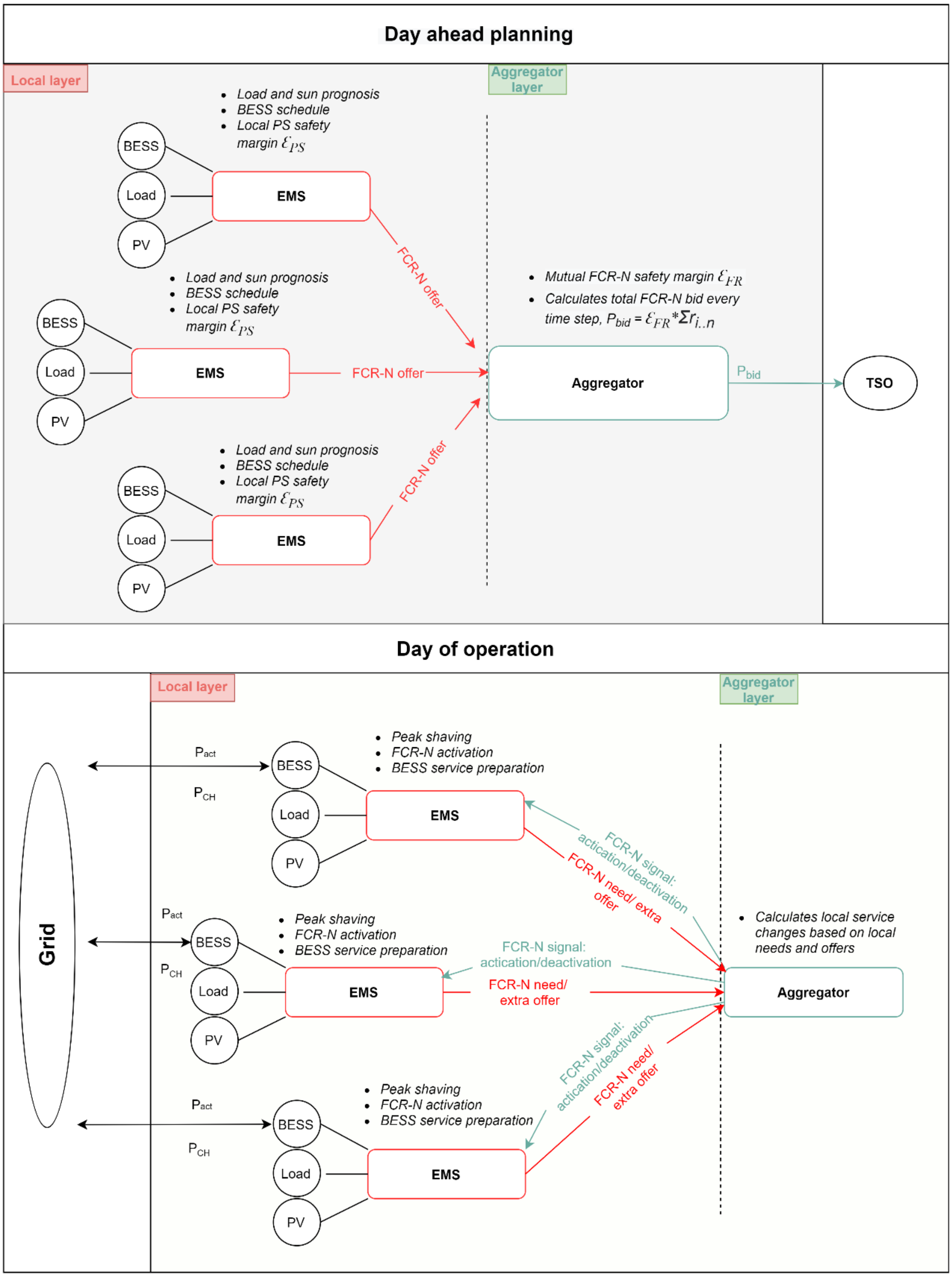

Figure 10. An overview flow chart of the model structure used for the numerical study.

4.3.2 Power Balance

For a local system as the model described above, the power balance of the system can be described by

$$P_L(t) = P_g(t) + P_{PV}(t) + P_{BESS}(t), \tag{1}$$

where $P_L(t)$ is the local load, $P_g(t)$ is the power supplied from the grid, $P_{PV}(t)$ is the power from the PV and $P_{BESS}(t)$ is the power supplied from the BESS. The equation was notably crucial for all calculations in the numerical model.

4.3.3 Peak Shaving

There are different approaches for calculating the need for peak shaving for a certain period of time. Shafique (2020) used an approach where a monthly threshold was set based on the load profile, which was inspired by the study by Levron and Shmilovitz (2012) presented in Chapter 2: *Background*. This approach was, in this study as well, motivated by the fact that it is a simple and suitable way of calculating the need for peak shaving in order, for example, to minimize the cost of power tariffs for a certain load unit or for the electricity system to handle capacity shortage.

If the hourly average power taken from the grid, Hourly Average Power (HAP), from a local unit and a certain hour exceeds the monthly threshold, the threshold will be set to the new value. This can be described as if the constraint

$$HAP > P_{th} , \tag{2}$$

is true for a certain hour, the new monthly threshold is set according to

$$P_{th} = HAP. \tag{3}$$

when the power taken from the grid is higher than the monthly threshold, the BESS will be used in order to try to compensate enough for the power taken from the grid to not exceed the monthly threshold and to avoid a raised value of the monthly threshold and further extra monthly power tariffs. The threshold is set to a new initial value every month, since power tariffs are based on the highest HAP of every month.

For a local system with a monthly threshold P_{th}, the following constraint,

$$P_L(t) - P_{PV}(t) > P_{th} , \tag{4}$$

describes when the connected BESS needs to operate in order to not exceed the monthly threshold P_{th}. The electricity needed to peak shave during a certain hour can further on be described by

$$W_{PS} = (HAP - P_{th}) \times t\,[h] , \; HAP \geq P_{th} , \tag{5}$$

where W_{PS} is the electricity needed to peak shave. If the opposite occurs where the hourly average power is less than the value of the monthly threshold, the BESS can be charged by

$$W_{CH} = (P_{th} - HAP) \times t\,[h] , \; HAP \leq P_{th}, \tag{6}$$

instead. If the constraint,

$$W_{PS} \leq W_{BESS,c} , \tag{7}$$

is true, the whole peak can be reduced, and the monthly threshold does not need to be raised. $W_{BESS,c}$ in the equation represents the energy that is currently stored in the BESS. When using the BESS to perform services in real time, the C-rate of the BESS has to be considered and implemented by

$$P_{PS} = W_{PS} \times C_{rate}, \tag{8}$$

and

$$P_{CH} = W_{CH} \times C_{rate}. \tag{9}$$

The variable C_{rate} [h^{-1}] is a measure of at which current a battery is charged or discharged, which was described in Section 2.7.2: *Components*.

4.3.4 Frequency Regulation

In order to perform simulations with the numerical model, calculations regarding the frequency regulation service of the grid had to be implemented. As mentioned earlier on, FCR-N was used as the choice of frequency reserve. One of the requirements in order to be able to participate in the FCR-N market regards the symmetry of the bid. The requirement implies that a capacity bid for a certain period of time must be able to be used for both upward and downward regulation of the frequency of the grid. When using a BESS for the purpose of regulating the frequency, it implies that the BESS can never be fully charged or fully discharged since it has to be ready to discharge in case of a needed upward regulation and to charge in case of downward regulation. According to this fact, a constraint,

$$SOC_{min} \leq SOC_c \pm \frac{P_{bid} \times t_{bid}}{W_{BESS\,size}} \leq SOC_{max}, \tag{10}$$

can be formulated. $SOC_c$is the current state of charge (SOC) for the BESS, SOC_{min} and SOC_{max} is the minimum respectively maximum SOC, P_{bid} is the local power bid placed to the FCR-N market or to the aggregator and $W_{BESS\,size}$ is the maximum energy that could be stored in BESS within safe limits in this equation.

In the simulation, the bid size was set to the value of the maximum bid size, which according to equation (10) would be half of the usable BESS size capacity. If the bid would have been larger for instance, the SOC would have exceeded SOC_{max} in case of full activation of downward regulation. The choice of FCR-N bid size can be motivated by the fact that the study, as mentioned before, does not include any bid optimizations which could have motivated a larger bid for a certain hour than for another hour of the day. The FCR-N bids are, for the same reason, assumed to be placed as hourly bids.

To be able to simulate the activation level of the FCR-N bid, P_{bid} during the day of operation, and further the charge or discharge of the BESS, data regarding frequency deviations was used. The data was provided by Fingrid and is described in more detail later in Chapter 5: *Data*. According to the Swedish transmission system operator (TSO), The Swedish National Grid (Svenska kraftnät, 2018), the actual power that is charged or discharged to or from the local BESS can be described by

$$P_{act} = (50 - f_{mean}) \times 10 \times P_{bid}, \quad (11)$$

during a linear activation and a frequency f in the frequency span from 49.9 to 50.1 Hz for a certain period of time. To summarize this equation, the actual power that is dispatched of the BESS during the day of operation is based on two variables, namely the size of the FCR-N bid, P_{bid}, and the frequency deviation.

4.3.5 Prognosis

In order to forecast the load curves and the PV electricity production during the day ahead planning, a prognosis methodology was implemented in the model.

For the prognosis of the load data, forecasting with moving average was executed according to the framework of Mattson (2004). The quantitative forecasting method implies that an average of the previous demand over a certain period of time is calculated and which result is further used as the forecast value. For a quantitative forecasting method to actually be as simple as possible, the next demand of the next period is assumed to be as large as the demand of the last period. Although, such a method risks becoming too sensitive to variations, and the chosen method in this study instead implies that the mean value of demand over a number of periods can be assumed to be the forecasted value. This method meets greater requirements for stability than the aforementioned. The choice of forecasting method is motivated by the fact that it is quite simple but still considered stable enough for the aim of this study. However, the moving average method to forecast the load might not fully catch rapid load changes, and should be considered as a simplified forecast method.

In this study, the moving average was based on the load data from the same weekday during the four previous weeks. For instance, a forecast of the load of a Monday for a certain site, is based on the average load of the four previous Mondays.

In order to get a valid load forecast, a compensation factor has been considered to compensate for certain variations. One of the factors that has been considered is whether the date of the obtained data is or is not a holiday. According to Svenska Kraftnät (2017b), the electricity consumption changes during public holidays in Sweden. Due to a change in electricity consumption on holidays compared to weekdays, a condition was implemented when the average value for the load was calculated. If any of the previous days being accounted for in the prognosed value would turn out to be a holiday, the data for this day was then not being accounted for. Instead, the data of the next represented weekday would replace the data of that particular day. If the day that is being forecasted turns out to be a holiday on the other hand, the load forecast of this day is based on the load of the same holiday during the year before.

For the prognosis of the PV production data, a mean value of the two previous days for each hour is being used as the prognosis data for the upcoming day. The outcome of this method is not completely accurate, but was considered reasonable due to the time frame of the study as well as due to the fact that the same differences based on the simulations could be seen between the actual and prognosed load for the aggregated and the non-aggregated case. Other alternatives that were considered to this method includes for example the autoregressive moving average model (ARMA) (Mills, 2019). Although, it was determined that the ARMA-model was not suitable for this thesis regarding the time frame. For instance, it was considered to be too resource intensive to collect historical weather data for all sites that were included in the case study which would have been needed in order to forecast the production one day ahead. Thus, the used approach represents a less complicated course of action regarding the PV prognosis than other alternatives. If using the numerical model for a larger study, the PV prognosis could be updated to a more advanced forecast method.

4.3.6 BESS Schedule

As mentioned in Section 4.2.1: *Overview and Model Structure*, a local BESS schedule was performed locally for each BESS during the day ahead planning. A schedule is necessary in the numerical model to ensure that the requested and promised services will be available during the right hour during the day of operation. For example, if a FCR-N bid, P_{bid}, was placed for a certain hour during the day ahead planning, the corresponding capacity of the BESS has to be available during that specific hour. The scheduling was based on Shafique's (2020) algorithm, which was requested by CheckWatt AB in order to be able to perform a comparison between the case when the BESSs were aggregated and when they were working alone locally. Shafique's (2020) model was further based on scientific studies, which will not be described further in this thesis, but which is available to read about in Shafique's (2020) study. However, the construction and motivation of the formation will be described below.

The scheme was made binary, which implies that one hour was allocated to one service. If the model would have aimed to optimize the distribution between the two offered services in order to maximize the profits, it could have been reasonable to use one hour for both peak shaving and frequency regulation.

Since no optimization was performed and the scheme was made binary, the schedule procedure started by marking the hours which, according to the prognosis and equation (4) presented in Section 4.2.3: *Peak Shaving,* would need to be used for peak shaving. To ensure that the BESS would have enough power to perform the requested peak shaving, some hours before the actual peak shaving could therefore be marked as preparation intervals. The need and allocation of peak shaving preparation interval hours was based on forecasted load and PV data and equations (6) and (9) presented in Section 4.2.3*: Peak Shaving*. Peak shaving hours were flagged as "PS" in the schedule, while peak shaving preparation interval hours were marked as "PIPS".

When hours needed to perform and prepare the BESS for peak shaving were marked in the schedule, the remaining hours of the day could be used for frequency regulation, although within certain limits. The limits were formulated in the condition presented in equation (8) presented in Section 4.2.4: *Frequency Regulation*. As in the case for the peak shaving, the schedule had to ensure that the BESS would be charged enough accordingly to these limits so that the capacity according to the local FCR-N bid size, P_{bid} , would be available at the hour when the bid was placed. For this reason, if needed, the hours before frequency regulation service was marked with frequency preparation interval according to equations (6) and (9) presented in Section 4.2.3: *Peak Shaving* in combination with the forecasted load data for the next day. The hours reserved for FCR-N service were marked as “FR”, while the hours reserved for frequency regulation preparation intervals were marked as “PIFR”.

In some cases, a gap could occur between the services why BESS was not reserved for any service during those hours. For example, this could occur when there were not enough hours to prepare the BESS for a new service. The no service hours were marked as “NOSE”. For visualization, a fictional example of what part of a BESS schedule could look like is presented in Table 3 below.

Table 3. An example of how the BESS schedule is constructed. During the hours flagged as PIFR and PIPS, the BESS is charging. During the FR- and PS-hours, peak shaving and frequency regulation services are being executed.

Hour	Flag	Forecast load [kW]	Monthly threshold [kW]
00	PIFR	1	1,5
01	FR	1	1,5
02	NOSE	1,2	1,5
03	PIPS	0,9	1,5
04	PS	1,7	1,5

4.3.7 Aggregator

The aggregation layer was added to the numerical model in order to be able to aggregate offers from connected BESSs into a mutual FCR-N bid to be placed on the reserve market and to allow the local units to compensate for each other’s forecast deviations. The aggregator was inspired by previous studies but adjusted as a simplified version since no optimizations were performed in this study compared to the suggested models found in the literature study and presented in Chapter 3: *Previous Research*, as mentioned before. Engels et.al. (2020) concluded that the local sites were not able to compensate for each other regarding peak shaving but were able to compensate regarding the frequency control. He suggested that the local site's FCR-N bid should be summed up to a total bid in the aggregator in order to be able to compensate for local forecast deviations. These conclusions were useful for the development of the aggregator in this study as well and could further be used as motivation regarding the formation of the aggregator. As presented in Chapter 3*: Previous Research,* Zhang et al. (2017) suggested two main motivations why aggregation of BESSs are necessary. It was stated that it is difficult for a single BESS to on its own meet the minimum bid size requirements stated by the TSO, which further motivates a total summed up FCR-N bid as well. The authors also stated that a constant schedule for one BESS is not able to utilize the BESS capacity fully, which motivates an aggregator that enables change of services for the local sites and furthermore flexible schedules during the day of operation. Based on the previous studies, the aggregation part of the numerical model was formulated.

On the day of operation, the aggregator is able to send and respond to signals from the different EMSs and based on that, if necessary, change the service for certain BESSs compared to the BESSs schedule, in order for each BESS to be able to deliver according to the initial bid. The aggregation initiates that BESSs can compensate for each other in the event of either forecast deviations or unexpected peaks or valleys in the local load curves. Further on, the aggregation has been set to be binary according to the rest of the numerical model. This implies that only one service at a time can be performed by a unit during a service hour and no further optimizations between different services within an hour is therefore being executed during the aggregation.

The different BESSs in this study's simulations are able to compensate each other regarding the frequency regulation since they have placed a joint bid. This differs from peak shaving. Since peak shaving can only happen locally, no other unit can compensate directly for another unit's peak shaving, as mentioned before. Based on the theory of an aggregator that enables change of services for the local sites and more flexible schedules previously mentioned in Section 3.4.2: *Aggregation of Several BESSs,* the different needs and offers that can occur as signals from the BESSs to the aggregator are stated below.

Needs

In the aggregator, a need from a local EMS can occur due to two different reasons. One of those reasons is when the available capacity of a local BESS during a FR-hour is less than the amount it was supposed to be according to the capacity bid, P_{bid} , that was initially being placed for that particular hour by the local unit. The need for capacity in this case, where the capacity bid is set to the maximum bid size being half of the BESS's capacity, is the absolute difference in SOC between the forecasted, $SOC_{C,prog}$, and the real, SOC_C , multiplied by the usable energy size of the BESS, $W_{BESS\ size}$ according to

$$P_{need} = \left|SOC_{C,prog} - SOC_C\right| \times \frac{W_{BESS\,size}}{t}. \quad (15)$$

Equation (15) can be derived from equation (10) presented in section 4.2.4: *Frequency Regulation*, which implies that the BESS has to be ready for both upward and downward regulation of the grid, according to requirements of the product FCR-N presented earlier.

The other reason for a need for capacity to occur from an EMS is when the particular hour initially has been flagged as a FR-hour, but the hour in real time turns out to be needed for local peak shaving instead. When such an event occurs for a binary solution of the case, the EMS completely focuses on peak shaving instead of frequency regulation. Therefore, the need for capacity becomes the initial bid at that particular hour. The binary calculation is represented by

$$P_{need} = P_{bid}\ , \quad (16)$$

where P_{bid} is the FCR-N bid from the local unit to the aggregator's total bid, $P_{bid\ total}$.

Further on, in the event of an hour being flagged as anything other than frequency regulation, no supposed need would be able to be met. If an hour is flagged as a PS-hour for instance, the peak shaving cannot be compensated due to it being a local service and the fact that the BESSs are not physically connected. An EMS with an hour reserved for peak shaving that however needs more peak shaving than planned cannot be compensated by another unit's capacity.

If the scope of the thesis would have been economical, the model could have been updated with an optimization between the two services for a certain hour.

Offers

During the day of operation, situations could occur when the capacity of the BESS is larger than what is needed for the given hour according to the local BESS schedule. In these situations, the local EMS can place a capacity offer to the aggregator as a way of compensating for other's forecast deviations. These offers could be used to meet the needs that were presented in the previous section. For example, if an hour is flagged as a PS-hour according to the BESS schedule, but no peak occurs, the capacity that was supposed to be used for peak shaving can be offered to the aggregator instead. Consequently, if the total capacity needs and the total capacity offers placed to the aggregator are of the same size, the total bid would be the same size corresponding to the bid size, $P_{bid\ total}$, placed during the day ahead planning, but possibly with other BESSs operating this service. The offers placed to the aggregator are therefore frequency regulation bids that can compensate for needs of frequency regulation capacity that has been placed by other BESS, and not for local peak shaving or service preparation.

The offers can only be placed to the aggregator in a way so that the local services that are planned for the forthcoming hours can be performed according to the local BESS schedule. This implies that after the frequency regulation services that are offered to the aggregator are performed, the BESS's SOC has to be within some conditions. The SOC_c either has to be larger or equal to the SOC_{prog} or the condition in equation (10) presented in Section 4.2.4: *Frequency Regulation* has to be fulfilled. The last-mentioned condition has to be fulfilled if frequency regulation is planned during the oncoming hours, so that the BESS is ready for both upward and downward regulation according to the bid size, P_{bid}.

Aggregator in the Numerical Model

If the numerical model were to be a real system, the offers and needs could have been updated, for example, minute by minute and further be matched more frequently. In the numerical model used in this study, the data was obtained in hour by hour resolution. Due to this, net calculations were performed every hour and the offers and needs were calculated and passed on to the aggregator accordingly. For example, it was assumed that a need for peak shaving would be discovered in the beginning of the hour, why the service was changed for the whole hour. This is not always accurate when a comparison to a system in reality is being done, where the need of peak shaving for example could be discovered in the middle of the hour. However, this should still be considered as a reasonable way of calculating since the total peak shaving that is needed for a specific hour is the same value numerically.

Further, if the size of the total needs and the total offers sent to the aggregator are not of the same size, the offers will be activated locally in scale with the needs in order to avoid a total activation higher than according to the bid placed during the day ahead planning, $P_{bid\ total}$. If the need is higher than the offer on the other hand, the system will consequently fail to deliver the promised power.

4.3.8 Safety Margins and Measurements of Accuracy

Due to the fact that a forecast can never be done without deviations compared to reality, the system had to include some safety margins. Since the system includes two different services, two different main safety margins could be identified. One of the safety margins is connected to peak shaving and the other one is connected to frequency regulation. Since peak shaving is being performed locally for each unit, the safety margin regarding peak shaving had to be applied locally accordingly. When scheduling the PS-hours in the BESS schedule, the estimated need of peak shaving is further on consequently dependent on how well the forecast is considered to be. In reality, the safety margin could be applied in different ways, for example included in the monthly threshold, the amount of electricity needed to charge BESS or the expected need of BESS capacity to perform the wanted peak shaving.

In the case where the BESSs are aggregated, the aggregator will place a mutual bid, $P_{bid\ total}$, on the FCR-N market. Therefore, the safety margin connected to the frequency regulation could be applied either locally in the FCR-N bid sent to the aggregator, or for the total FCR-N bid sent from the aggregator. In an aggregated portfolio of BESSs, the forecast deviations can occur in different directions for different load profiles, which can imply that the total forecast deviation is smaller than compared to the absolute value of each individual unit totally. In order to distinguish this benefit, the safety margin regarding frequency regulation for the aggregated case was applied for the total bid in the aggregator, and furthermore locally applied in the non-aggregated case.

The relations

$$P_{safe\ PS} = P_{PS} \times \epsilon_{PS}, \tag{12}$$

and

$$P_{safe\ bid} = P_{bid} \times \epsilon_{FR} , \tag{13}$$

$$P_{safe\ bid\ ,total} = P_{bid\ total} \times \epsilon_{FR}$$

describes the size of the FCR-N bid, P_{bid} , or for the aggregated case, $P_{bid\ total}$, and the peak shaving power, P_{PS}, when including safety margins in the calculations . $P_{safe\ PS}$ is the expected need of peak shaving power when including a safety margin. Equation (13) is divided into two constraints depending on if the safety margin is applied within the local FCR-N bids according to the first constraint or to the total FCR-N bid in the aggregator according to the second constraint. $P_{safe\ bid}$ is the bid placed from the local units to the FCR-N market in the non-aggregated case and $P_{safe\ bid\ ,total}$ is the safe bid placed from the aggregator to the FCR-N market, when including a safety margin. ϵ_{FR} is the frequency regulation safety factor and ϵ_{PS} is the local peak shaving safety factor.

There are different quantitative measurements of accuracy which can be used to validate and analyse the correctness of the prognosis. To be able to perform the study within the given period of time, a simple methodology which could be used to analyse patterns where requested. There are some simple and commonly used methods that could be used for the purpose, such as mean average percentage error (MAPE), mean absolute deviation (MAD), mean deviation (MD), mean error (ME), mean absolute error (MAE) and mean squared error (MSE). To avoid division by zero and to be able to distinguish if the deviations were positive or negative, ME was considered as the most suitable method to use for the purpose of measuring the accuracy of the prognosis (Prestwich et al. 2014). The ME values were used to analyse how the safety margins could be changed in the aggregated case compared to the case where the BESS are working non-aggregated. ME is defined by

$$ME = \frac{\sum(E(t) - P(t))}{n}, \quad (14)$$

where $E(t)$ is the real value, in this case bid size or load for the peak shaving safety factor, $P(t)$ is the forecasted value of the same quantity and n is the number of time periods which in this case represents the number of hours. Further, values of MAE were calculated for the load forecast deviations, where MAE only differs compared to Equation (14) by the fact that the absolute value of the numerator is calculated within the equation.

4.3.9 Simulations

Simulations of the case system over 24 hours a day for one week, which is equated with 168 hours, was done. The simulations were being done both for when the units were aggregated and also when they were not, in order to see differences and potential advantages. The simulations ran first for one BESS whereupon one by one, the other BESSs were added to the portfolio with the maximum number of 45 BESSs. In each case, both the aggregated and the non-aggregated, the information regarding for example delivered FCR-N capacity and shaved peaks were submitted. In the non-aggregated case, the BESSs were working alone according to the numerical model developed by Shafique (2020), which was mentioned earlier on in this chapter.

The data was obtained between the dates 01-01-2020 and 31-03-2021, whereas the simulated week extends over 25-03-2021 and 31-03-2021. The range of 168 hours was chosen based on available historical load data, time limits and since the results were considered approved based on the purpose of the study. Regarding data during days that include change to summertime, data of one hour was missing. In order to replace the missing data, a mean value of the data for the hour before and after the missing hour was further submitted in order for the prognosis to be implemented.

The safety margins presented in Section 4.2.8: *Safety Margins and Measurements of Accuracy* were both set to one. This is motivated by the fact that it is of interest to examine how the safety margins are able to change within the aggregated case compared to the non-aggregated case. However it is of interest to understand how the safety factors can be placed in the system and further affected, why the theory behind them where presented earlier.

Further on, according to Section 4.2.3: *Peak Shaving,* the model had to be fed with a monthly threshold, P_{th}, in order to be able to perform the simulations. Since the simulations were done only during a one-week period of time and not during a whole month, the monthly threshold was based on recommendations and experience from CheckWatt AB and the load profile of the first day of the simulations. This resulted in a monthly threshold, P_{th}, that was set to approximately 90 percent of the highest power peak during the same month the year before. If the load profile during the month of the simulation would be exactly the same as the year before, the chosen value of P_{th} would imply that 10 percent of the power peak would be preferable shaved if the simulations were to be done during a whole month. Since CheckWatt AB obtains a great experience regarding the subject, it can be considered reasonable to base the value of P_{th} on their recommendations and experience. It is also of interest to perform a study which results can be used by CheckWatt AB, which motivates this choice further.

CheckWatt AB determines recommendations regarding the BESS size to their customers, which affects the possibilities to perform peak shaving and further initial monthly threshold, which further motivates the choice of BESS size and monthly threshold in the range based on the recommendations.

Parameters of BESS

Due to the data being gained from 45 different load units and since each BESS is assumed to be unique in terms of size and dispatchable energy, significant parameters were set equally according to Table 4 below.

Table 4. Parameters of BESS and its respective values.

BESS parameter	Value of parameter
Maximum charging limit for SOC	0.9
Minimum charging limit for SOC	0.1
Initial SOC	0.5
Charging and discharging efficiency	1.0
Battery C-rate	1C

The size and dispatchable energy of each individual BESS was being set according to

$$BESS\ size\ = \frac{1}{3} \times Peak\ load \times \frac{3}{2}, \tag{17}$$

which is a guideline provided by CheckWatt AB. The rule is considered reasonable to use since it is of interest for CheckWatt AB that the simulations includes the same $BESS\ size$ [Wh] that is recommended for their customers. Through various simulations, a third of the peak load during the year has been arbitrarily obtained by CheckWatt AB. It has also been noted that a greater value for this factor is further equal to less efficiency in peak shaving. Further, the factor of 1.5 in equation (15) is also a value obtained by CheckWatt AB. According to the demands from SvK regarding FCR-N, there must be at least one hour of endurance at full power. By further adding 0.5 to that hour results in a margin. It has also been noted that a greater value for the storage is further equal to more costs without generating that much more revenue from frequency control.

As mentioned earlier on and presented in Table 2 in Section 4.2.4: *Frequency Regulation*, the market requirements for FCR-N are for each battery concerned with a bid to be able to charge 63 percent of its full capacity within 60 seconds and 100 percent in 3 minutes. The batteries used in this study are therefore set to meet these requirements. According to the requirements, the FCR-N bids have to be placed so that the BESSs are able to perform 100 percent during the entire period of time for when the bid is placed.

As for the maximum and minimum charging limits, the results of Wikner and Thiringer (2018), found in Section 2.5.2: *Components,* are being taken into account and maximum and minimum SOC are further set to 90 percent and 10 percent respectively. The initial SOC is set to 0.5 to ensure that each BESS is ready to perform any kind of service.

Although it according to Valøen and Shoesmith's (2007) results, found in Section 3.7.2: *Components,* is not possible to obtain a 100 percent efficiency, in this study, the efficiency of both charging and discharging has been set to 100 percent in order to enable the usage of the individual BESSs at full charging and discharging capacity. This is motivated by the fact that the charge and discharge efficiencies are the same for the aggregated case and the non-aggregated case, why it does not affect the differences and is not of importance for the scope of this study. Due to the same reason, the C-rates of the batteries were set to 1C.

4.3.10 Sensitivity Analysis

In order to examine how sensible the system is, a sensibility analysis was executed. The parameters that were considered to affect the results of the numerical study principally was the storage size of the BESS and the monthly threshold level. The two parameters do affect each other, since a higher monthly threshold requires a larger storage size of the BESS. For this reason, the storage size of BESS was set constant according to previously used values, while the initial monthly threshold for all load profiles was changed with $\pm$ 10 percent of the original values. A greater change of the threshold value was not considered necessary since it would have affected the ratio to an extent that was considered unreasonable. The sensitivity analysis aimed to examine if the monthly threshold was set to a reasonable level in relation to the storage size of BESS in the original case, and also to examine how the results were changed by a changed ratio between the two factors e.g. how sensitive the system was.

5. Data

The following chapter contains information regarding the data used for the simulations done in the numerical study. The data is divided into three sets, one containing load data from the different sites, one containing data regarding PV electricity production from the different sites, and one containing frequency data. The chapter should be read as whole if it is of interest to understand how the data was received and which data that was used in the numerical study.

5.1 Load and Production Data

The data that was used as input for the forecast of the load and PV production, and to simulate the load curves for the day of operation, has been obtained using an internet-based control panel provided by CheckWatt AB. The control panel includes available data regarding the customers of CheckWatt AB and their electricity from their photovoltaics (PVs), data which has been obtained by a number of different types of meters. The electricity production is referred to as PV data in this study and the consumption is referred to as load data. The datasets were obtained in hour by hour resolution and for a further better understanding of the magnitude of the various load units, the maximum and minimum values as well as the median and average of the obtained load withdrawn the production respectively PV data on an hourly basis among all 45 sites has been compiled in Table 5 below.

The time range regarding the calculated values stated in the table further is 24 hours a day for 15 months, a period which was set in order to enable the usage of holiday compensation factors and further in order to base the calculations of monthly thresholds on load values from the year before. It was further described in Section 4.2.9: *Simulations*. The significant values being described in Table 5 concern each individual unit per hour, and not the whole population.

Table 5. Significant values amongst the obtained load respectively PV data on an hourly basis among all 45 energy load profiles.

Load data	Value [kW]
Maximum	248.46
Minimum	0.00
Median	7.86
Average	3.36
PV data	**Value [kW]**
Maximum	202.10

Minimum	0.00
Median	4.18
Average	0.010

A further summary of the load profiles is shown in Figure 11 below. In this graph, the total hourly mean load for the period of 15 months, is shown for different sizes of the populations.

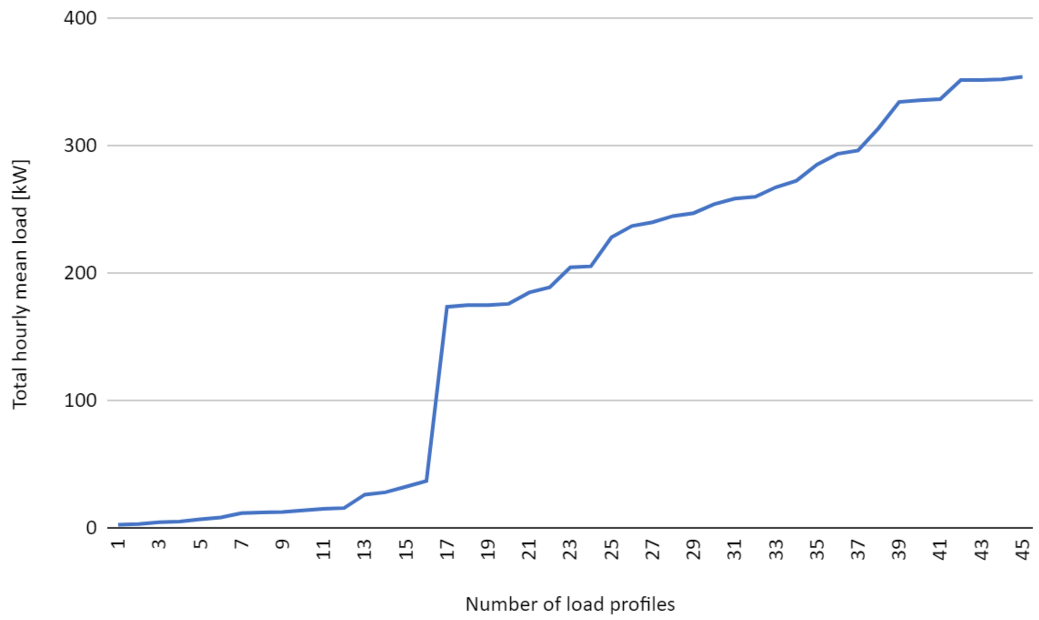

Figure 11. Total hourly mean load of the different population sizes for the period of which the data was collected.

The data obtained from customers has been chosen according to a demand of possessing at least one each of the meters that measures electricity production, sold electricity and purchased electricity. The data has been selected with the aim of obtaining diversity amongst the different data regarding type of residence, total consumption as well as size of residence and consumption. Three different types of residences can be found amongst the data: apartment buildings, houses and different types of stores or office buildings.

A limitation regarding the selected data was further done regarding electrical area, mentioned in section 1.4: *Delimitations.* This entails that all data originates from residences that subsist in the same electrical area, namely SE3.

5.2 Frequency Data

As has been mentioned before, data regarding the grid frequency was needed in order to execute the simulation of grid frequency control. The data was obtained from Fingrid, which is the Finnish transmission system operator (TSO), and the data was further considered to be valid. The data set that was used was “*Frequency - real time data"*, which can be obtained with a three minutes resolution from Fingrid’s website. Since the load and PV data was obtained in an hour by hour resolution, an hourly mean was calculated for the grid frequency as well. The fact that the frequency can change more often than every third minute implies that hourly average values could have been slightly different compared to reality. However, this was considered as insignificant for the results. The data was collected for the period of time for which the simulation is performed, i.e. between 25-03-2021 and 31-03-2021.

The particular data being chosen to be used in the study could have an impact on the outcoming results. For example, the data obtained during the chosen months could vary from data obtained during other periods of time, why a seasonal compensation factor which will be further described in section 7.1: *Prognosis* is of importance.

6. Results

In this chapter, the results of the simulation of the study are presented. Starting off with the results of the real and forecasted load, the results of real and forecasted frequency containment reserve - normal (FCR-N) capacity as well as real and forecasted peak shaving follow. Furthermore, the results regarding accepted FCR-N bids are being presented. Lastly, a sensitivity analysis is being executed in order to investigate the sensibility of the case model.

6.1 Real and Forecasted Load

In order to investigate to what extent the impact of the prognosis is having on the results of the simulations and to further enable a discussion regarding the subject, observations regarding the load and the prognosis of the load were being done. The load values were plotted against the prognosed values for populations consisting of up to 15, 30 respectively 45 battery energy storage systems (BESSs) in order to enable a distinction of the difference in the prognosis between populations. This was being done for every value during all simulated hours, being 168 hours, and the three different amounts of populations were selected due to being considered to represent three sufficiently different ranges of populations. Figure 12, Figure 13 and Figure 14 are representing these plots and are in order of magnitude of the selected populations. The difference between the real and prognosis of the load can be distinguished as the distance between the blue and green curves in each of the three figures. As seen in Figure 12, there is a discernible difference between the prognosis and real load when populations of 15 load profiles were used in the simulations. A reduction of the deviation can be discerned when instead populations of 30 load profiles were used in the simulations, seen in Figure 13. Further, when populations of 45 load profiles were used in the simulations as seen in Figure 14, the deviation is decreasing slightly more.

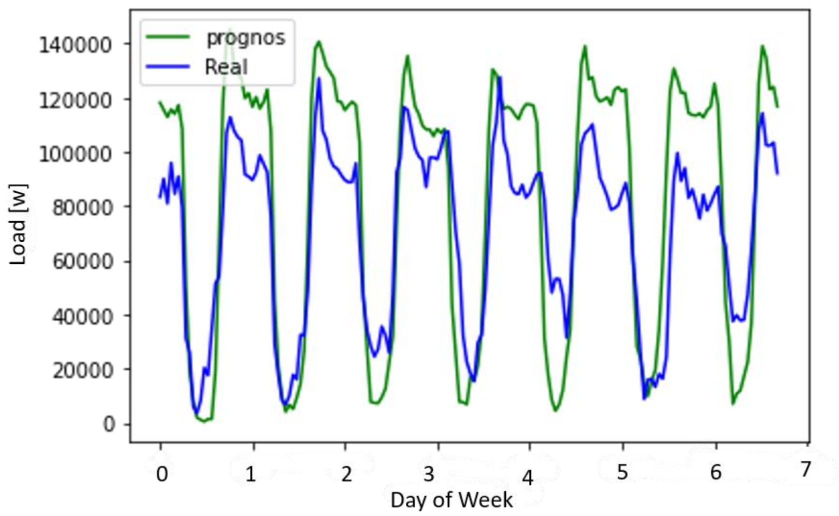

Figure 12. A graph of the real load and the prognosed load in a population of 15 load profiles.

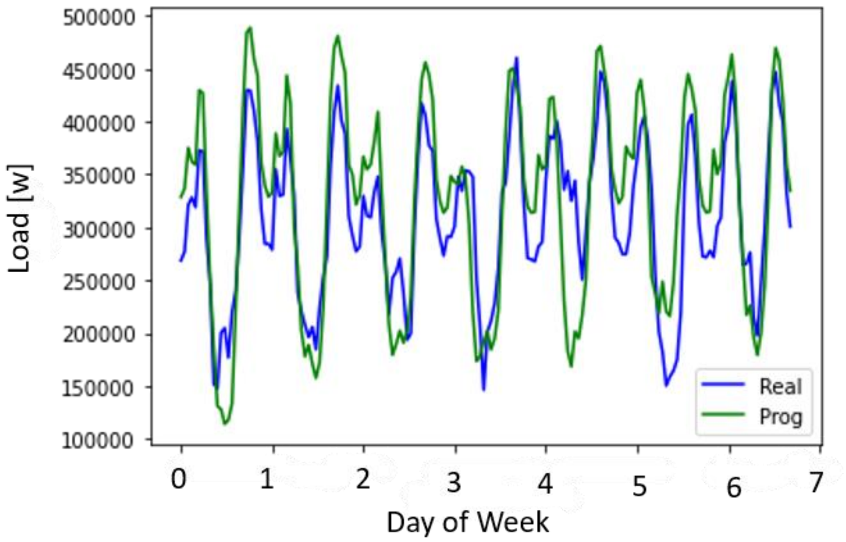

Figure 13. A graph of the real load and the prognosed load in a population of 30 load profiles.

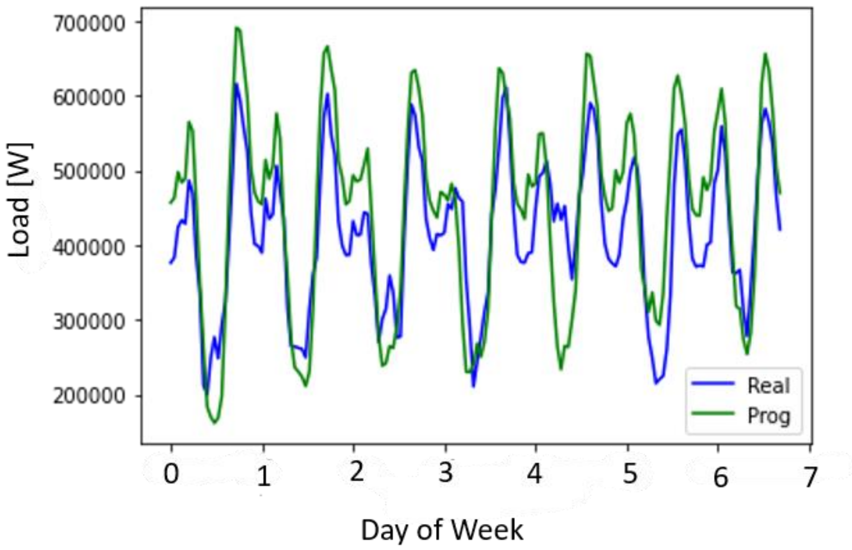

Figure 14. A graph of the real load and the prognosed load in a population of 45 load profiles.

In order to obtain an even more clear picture of the results of the simulations regarding the deviation between the load taken from the grid and the prognosis of the load taken from the grid, the hourly average absolute load prognosis deviation for each load profile was plotted. Each deviation was obtained by plotting the average difference between the load and the prognosis of the load for all simulated hours. The total result of the deviations is presented in Figure 15. As can be seen in the figure, the average mean deviation is quite consistent for the load profiles with a greater exception of four load profiles standing out from the rest of the profiles. The mean absolute error (MAE) for the total population regarding the hourly average load error compared to the prognosis was calculated to 2.50 kW/unit. This value could further be used in order to allow comparison for future studies.

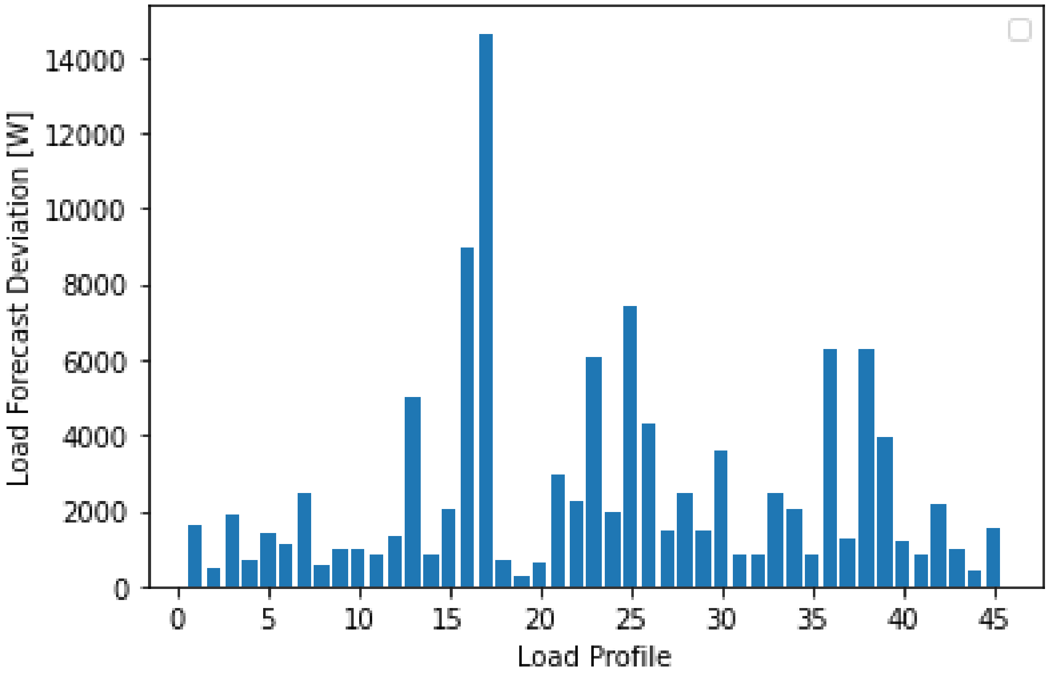

Figure 15. A graph of the hourly average absolute load forecast deviation for each load profile, numbered from 1 to 45.

6.2 Real and Forecasted FCR-N Capacity

Results regarding the FCR-N capacity bid and real FCR-N capacities for aggregated and non-aggregated populations of up to 45 BESSs have furthermore been obtained. A plot of the three different cases of hourly FCR-N capacity for the different populations of BESSs have been plotted. The plot is further presented in Figure 16. In the figure, it can be seen that the FCR-N capacity bid is slightly larger than the real FCR-N capacity for the aggregated populations, which further on is slightly larger than the real FCR-N capacity for the non-aggregated populations.

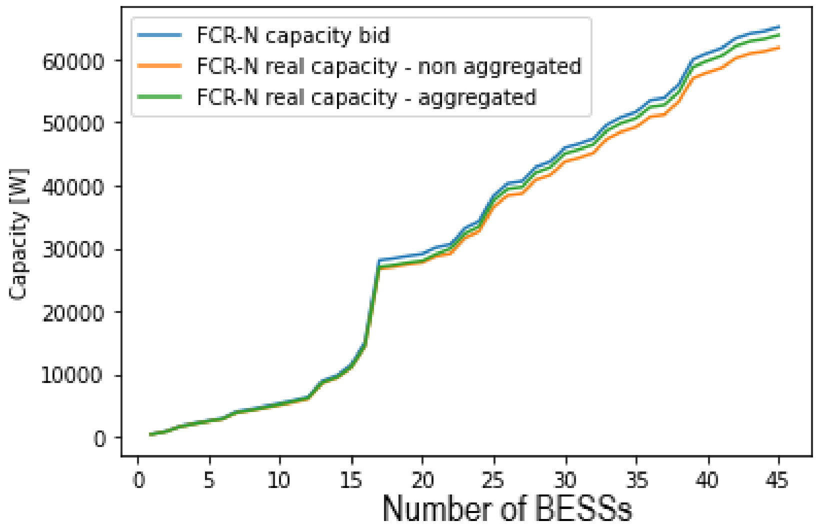

Figure 16. A graph of the hourly FCR-N capacity bid, the real hourly FCR-N capacity for aggregated populations of up to 45 BESSs and the real hourly FCR-N capacity for non-aggregated populations of up to 45 BESSs. Extra FCR-N capacity higher than the value of the placed bid are not included.

A result regarding hourly real average extra FCR-N capacity for aggregated populations of up to 45 BESSs has further been obtained. The total result is presented in Figure 17 and shows that the hourly real average extra FCR-N capacity for aggregated populations of up to 45 BESSs increases accordingly to the increased number of BESSs in the simulated populations. This represents capacity that is higher than the bid that was placed during the day ahead planning, and furthermore could not be used. The total capacity presented in Figure 16 could further be less than the total bid although extra capacity can be observed in Figure 17. This is since the extra capacity is useless if it were not being bidded during the day ahead for a certain hour, and due to the fact that the hourly average values are showed in Figure 16 only include the capacity that actually could be used for a certain hour. For example, one hour might have plenty of extra capacity offered to the aggregator, but which could not be used anyway. If the capacities would have been plotted per hour instead, it would have become clearer.

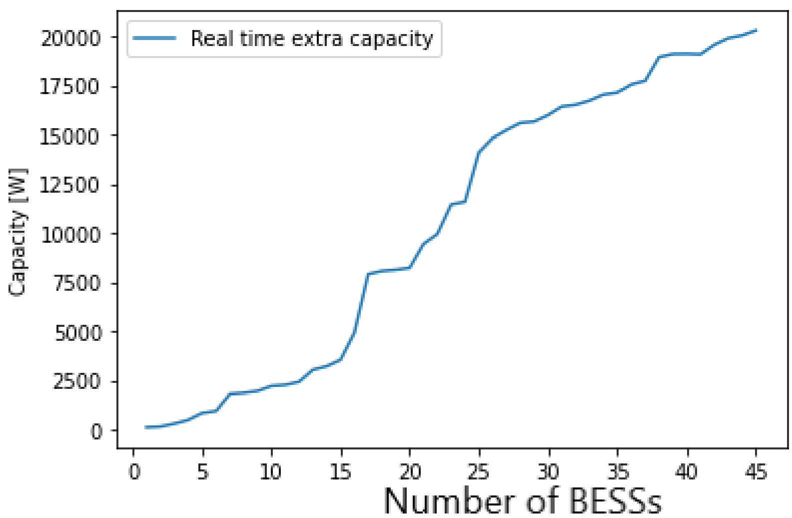

Figure 17. A graph of the hourly real average extra FCR-N capacity for aggregated populations of up to 45 BESSs.

Further on, the simulations of the study also resulted in an hourly average prognosis deviation regarding the frequency containment reserve - normal (FCR-N) capacity for the aggregated populations of up to 45 BESSs, respectively non-aggregated populations. The average deviation for each case are presented in Figure 18. If the difference is zero, it implies that the available capacity is the same as the bidded value during the day ahead planning, since no useless extra capacity offered to the aggregator is included. The average result does, besides all simulated hours, also regard the number of units of the concerned population. The presented deviations in Figure 18 therefore each regard the hourly average result per unit concerned. As can be seen in the part of the figure including populations of a greater amount of BESSs, the hourly average FCR-N capacity prognosis deviations is decreasing when the units are being aggregated and consistent when the units are not being aggregated. A deviating increase of the difference in the graph can further be seen around load profile 15, an exception that could be explained by a deviating load profile.

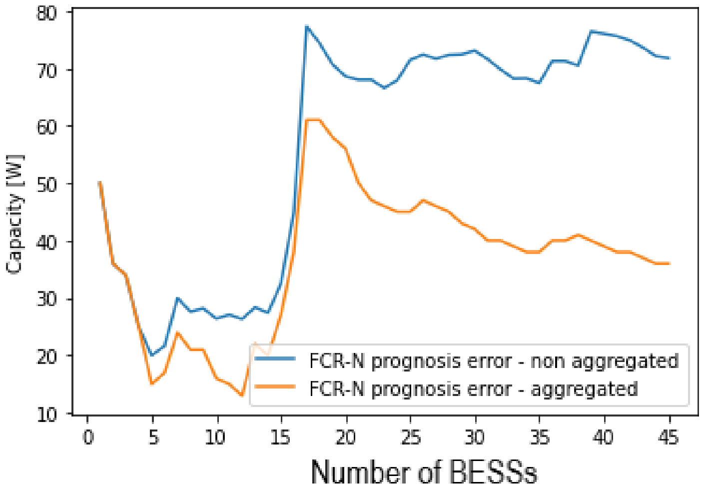

Figure 18. A graph of the hourly average FCR-N bid capacity deviation per unit for an aggregated population of up to 45 BESSs, respectively non-aggregated population of up to 45 BESSs compared to the actual bid that was place during the day ahead planning. FCR-N capacity higher than the value of the placed bid are not included.

Following the result presented in Figure 18, a compilation regarding the hourly average prognosis difference regarding the FCR-N capacity for the aggregated populations of up to 45 BESSs respectively non-aggregated populations was obtained. The obtained result regarded the difference between the aggregated populations of up to 45 BESSs and non-aggregated populations regarding the percentage difference between the actual capacity and the prognosed capacity in each case. The difference between the aggregated and non-aggregated cases which was observed in Figure 18 could further be plotted regarding the percentage reduction for the aggregated case and is further presented in Figure 19. With an exception of the load profiles around 15 BESSs, the FCR-N prognosis deviation difference is decreasing accordingly to the increased amount of BESSs in the simulated populations. The exception is based on the recurring exception of the load profile with up to 15 BESSs.

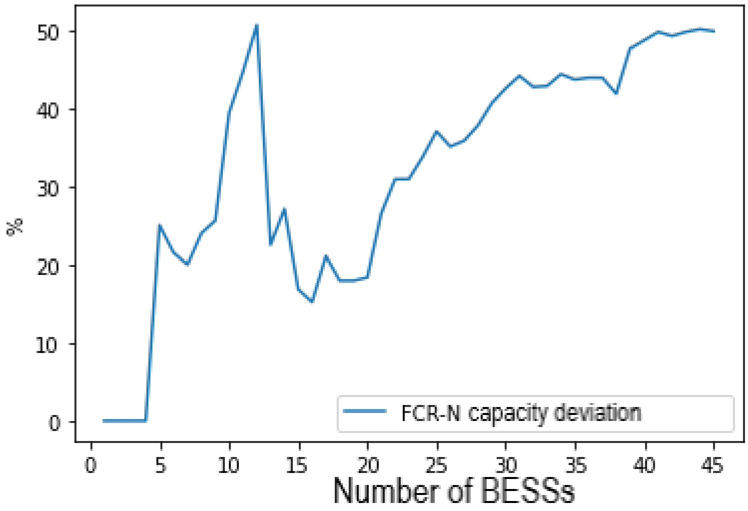

Figure 19. A graph of the reduction of the hourly average FCR-N capacity deviation compared to the actual bid - when aggregating the BESSs compared to when not aggregating the BESSs in populations of up to 45 BESSs. Extra FCR-N capacity higher than the value of the placed bid are not included.

6.3 Real and Forecasted Peak Shaving

Results regarding the total shaved load of each simulation for aggregated and non-aggregated populations of up to 45 BESSs have been obtained. A graph of the two different cases of total shaved load for the different populations of BESSs has been plotted. The plot is further presented in Figure 20. In the figure, an increment can be seen of the peak, which follows due to the shaved load for the aggregated, respectively non-aggregated populations of up to 45 BESSs. For a further deeper understanding of how the aggregated and non-aggregated populations differ and their ranges, their respective maximum, minimum, mean and summary of all hourly increases of the peak is presented in Table 6. The table shows that the significant values of the aggregated cases are larger than for the no-aggregated cases, emphasizing that a larger amount of peak shaving is able to take place when the units of the populations are being aggregated in the simulations.

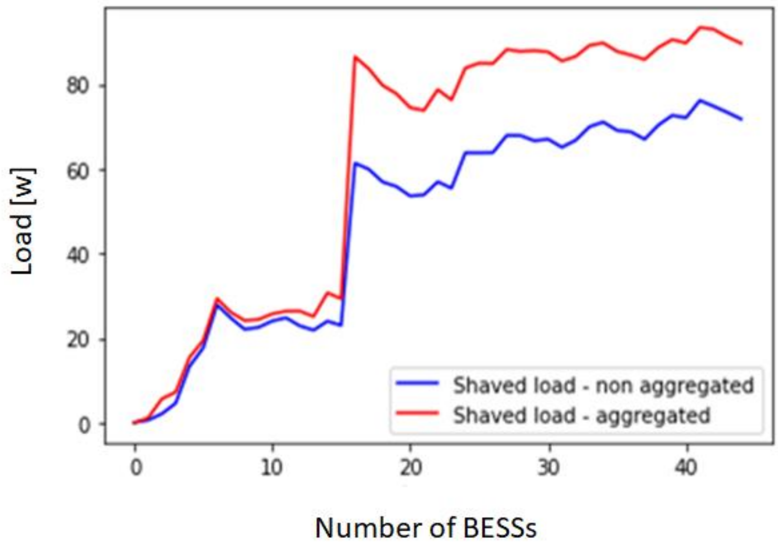

Figure 20. A graph of the hourly average shaved load per unit for aggregated and non-aggregated populations of up to 45 BESSs.

Table 6. Significant values regarding the decrease of the peak for the aggregated and non-aggregated populations of 45 BESSs.

	Min [kW]	Max [kW]	Mean [kW]	Sum [kW]
Aggregated	70.0	29.672	3.438	154.696
Non-aggregated	0.0	19.800	2.568	115.552

Furthermore, with the results presented in Figure 20 and Table 6 in mind, another result regarding the total shaved load of each simulation could be obtained. The result presents the difference between the aggregated populations of up to 45 BESSs and non-aggregated populations regarding the total hourly average shaved load per unit of each simulation, e.g. the difference between the red curve and the blue curve in Figure 20. This is presented in Figure 21 below.

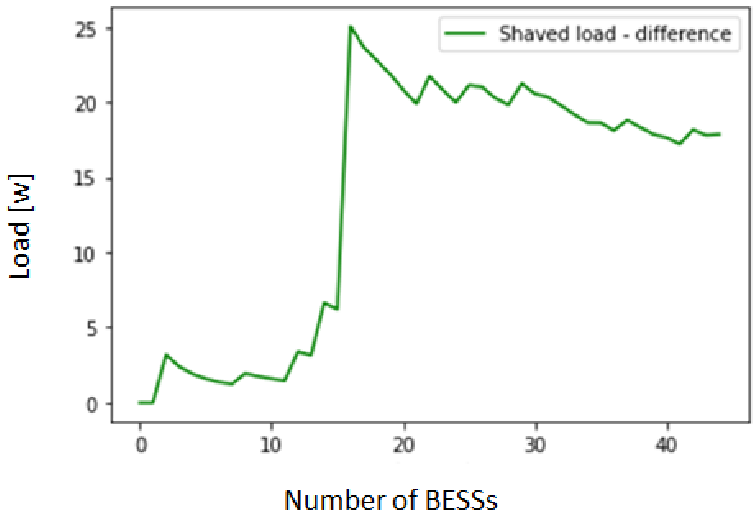

Figure 21. A graph of the average hourly shaved load difference per unit between the aggregated and non-aggregated populations of up to 45 BESSs.

6.4 Accepted FCR-N Bids

The study resulted in results regarding accepted and non-accepted FCR-N bids according to bid size, that being bids with a value higher than 0.1 MW, which can be found in Figure 22. The figure consists of the plotted values of which part of the total amount of bids that were later on being accepted for the aggregated, respectively non-aggregated populations of up to BESSs. As can be seen in the figure, non-bids originated from the non-aggregated cases of the simulation were accepted, while an increasing amount of the bids originating from the aggregated cases of the simulation were accepted starting from around load profile 15. This could be explained by the fact that the minimum size of an accepted bid is 0.1 MW, implying that the size of the individual battery energy storage systems (BESSs) of each population were too small to be able to put an accepted bid by themselves, whilst when being aggregated, they are able to gain the requested size of an accepted bid by compiling the individual bids into a joint bid.

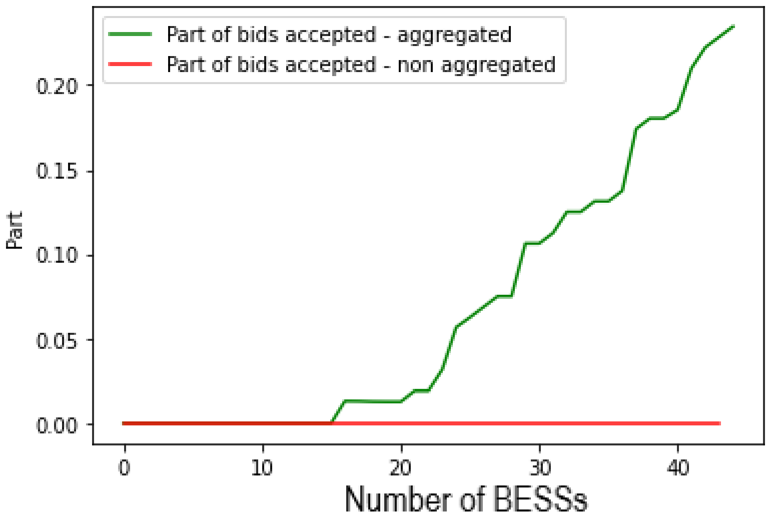

Figure 22. A graph of the total amount of bids being accepted for the aggregated, respectively non-aggregated populations of up to BESSs.

6.5 Shares of Peak Shaving and Frequency Regulation

A result regarding the share of hours of which is being allocated for peak shaving respectively frequency regulation for the simulated week has been obtained and further compiled in Table 7. The allocated services and their respective share compared to the total amount of hours of the week regards to the simulation of both the aggregation and non-aggregation of the units of each population, since the eventual aggregation part takes place afterwards the initial flagging of the hours.

Table 7. The shares of PS- and FR-hours compared to the total amount of hours of the simulated week.

Allocated service	PS	FR	Other
Share of total hours	16%	25%	59%

6.6 Sensitivity Analysis

A sensitivity analysis has further been done in order to investigate the sensibility of the model. The analysis regards the chosen values of thresholds and investigates the outcome of all simulations when the thresholds are decreased and increased by 10 percent, respectively.

The sensitivity analysis showed that the general patterns regarding frequency regulation and peak shaving remained when increasing and decreasing the monthly threshold by 10 percent compared to the original case, although the actual values of course changed. This implies that the system is quite stable regarding this kind of changes. As mentioned in the methodology, the ratio between the BESS sizes and monthly threshold was the parameters that was considered most important to investigate regarding sensibility.

6.6.1 FCR-N Capacity

When increasing and decreasing the initial monthly threshold by 10 percent, it could be observed that the pattern regarding the deviation from the bid placed during the day ahead planning and the actual FCR-N capacity of the non aggregated and aggregated case remained quite the same. The pattern was similar regarding shape, initial value and the top of the graph. The quite linear decrease of difference occurred around when load profile number 16 was added to the system, according to the pattern that could be observed in Figure 19, for the original case. The actual percentage difference was around 10 percent lower for the largest population of the case with an increased threshold by 10 percent. The case with a decreased threshold had approximately the same value as the original case, 50 percent for the largest population.

The FCR-N bid placed during the day ahead planning and the actual value of the FCR-N capacity available during the day of operation changed as a natural consequence of the changed threshold, but the patterns remained for both the increase and decrease of threshold here as well. A changed threshold changes the amount of peak shaving hours, why the FCR-N capacity also is affected as a naturally result. The graphs connected to this part of the sensitivity analysis can be found in Appendix A.

6.6.2 Shaved Load

The results of the sensitivity analysis connected to peak shaving showed that the observed patterns observed in the original cased remained quite stable. The result of the total shaved load of each simulation for aggregated and non-aggregated populations of up to 45 BESSs with decreased thresholds respectively increased thresholds has been plotted in Figure 23 respectively Figure 24. When comparing Figure 23 with Figure 20 where initial thresholds have been used, it can be observed that the shaved load is larger when a decreased threshold is being used and the shaved load does also get larger for each simulation. When comparing Figure 24 with Figure 20 where initial thresholds have been used it can be observed that throughout the simulations, the total shaved load is larger when the initial thresholds are being used in the simulations.

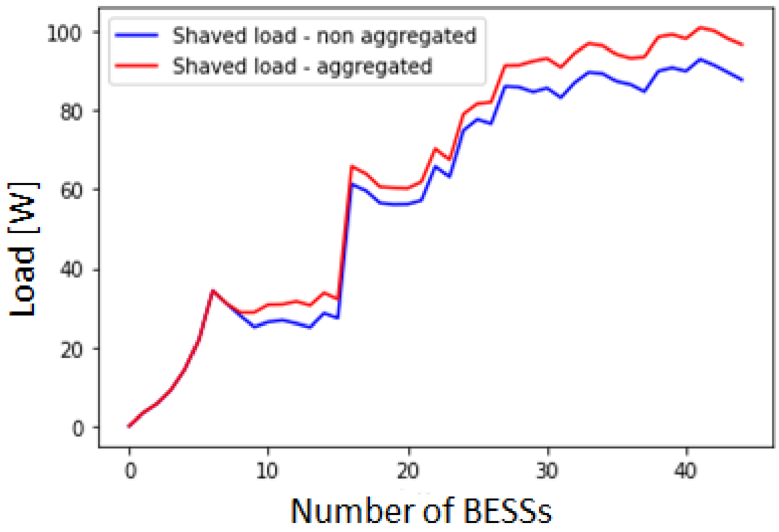

Figure 23. A graph of the hourly average shaved peak load per unit for aggregated and non-aggregated populations of up to 45 BESSs when the individual threshold of each unit is decreased by 10 percent.

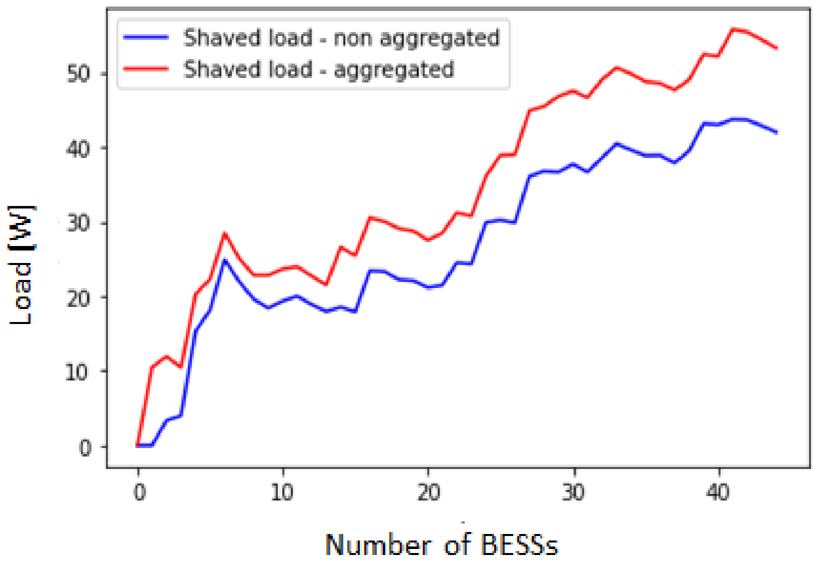

Figure 24. A graph of the hourly average shaved peak load per unit for aggregated and non-aggregated populations of up to 45 BESSs when the individual threshold of each unit is increased by 10 percent.

Furthermore, the respective maximum, minimum, mean and summary of all hourly peak shaving of the aggregated and non-aggregated cases when the individual threshold of each unit is decreased by 10 percent respectively increased by 10 percent are presented in Table 8 respectively Table 9. These tables shows that the total reduction of the monthly power peak decreased compared to the original case, both when increasing and decreasing the initial monthly threshold. This implies that the ratio between the threshold and the BESS size that was set in the original case was reasonable.

Table 8. Significant values regarding the decrease of the peak for the aggregated and non-aggregated populations of 45 BESSs *when the individual threshold of each unit is decreased by 10 percent.*

	Min [kW]	Max [kW]	Mean [kW]	Sum [kW]
Aggregated	0.0	17.500	2.831	127.414
Non-aggregated	0.0	17.500	2.485	111.826

Table 9. Significant values regarding the decrease of the peak for the aggregated and non-aggregated populations of 45 BESSs when the individual threshold of each unit is increased by 10 percent.

	Min [kW]	Max [kW]	Mean [kW]	Sum [kW]
Aggregated	0.0	12.540	23.270	104.695
Non-aggregated	0.0	12.540	18.770	83.797

7. Discussion

In the following chapter, the results of the numerical study are discussed within the given context and in relation to the results from the literature study which were presented in Chapter 2: Background and Chapter 3: Previous Research. The text discusses the observed patterns connected to peak shaving, regulation of the frequency and the safety margins of the system. Further, the chapter consists of a discussion regarding the numerical model structure, the aggregator's role in the future electricity system, possible future studies and the sensitivity analysis. The chapter should be read as whole in order to understand the conclusions better within the given context.

7.1 Prognosis

When observing Figure 12, 13 and 14 in Chapter 6: *Results*, it becomes clear that the accuracy of the load forecast increases when comparing a population of 15 energy BESSs with a population of 30 BESSs. However, when comparing the population of 30 BESSs with the largest population of 45 BESSs, the accuracy does not seem to change as significantly. This could be due to the fact that no seasonable compensation factor was implemented in the forecast methodology, why the deviations often occurred in the same direction and did not compensate for each other within the population. For example, if the positive deviations would have been the same size as the negative deviations, the total net deviation would result in zero. If the majority of the deviations instead would have been positive, the total difference would be greater. A seasonal compensation factor would therefore probably increase the correctness of the forecast when adding more units to the population. A seasonal compensation factor would be reasonable to implement in the forecast methodology since the electricity consumption changes due to for example outdoor temperature, which a rolling mean forecast might not fully pick up. However, the fact that the prognosis is improved by aggregating more units, indicates that the units are able to compensate for each other's local forecast deviations and why advantages connected to an upscaling of the population should be able to be obtained.

Another factor that affected the correctness of the prognosis was, as mentioned in Chapter 5: *Methodology*, the choice of methodology regarding the performance of the PV electricity production forecast. This methodology was simplified and did not take for example historical temperatures into account. However, the forecast accuracy is the same for both cases, and does not further affect the differences between the aggregated case and the non-aggregated case to any great extent. A possibility is that the aggregated system would be able to compensate for the deviations better, which however is one of the purposes of aggregating many battery energy storage systems (BESSs). A perfect forecast would not imply any need of compensation regarding each other's load and production deviations within a population.

7.2 Frequency Regulation

The most significant results were found in the frequency regulation part of the numerical study. Firstly, by observing Figure 16, which can be found in Chapter 6: *Results*, it becomes clear that the actual difference in delivered frequency containment reserve - normal (FCR-N) capacity is small. This is a natural consequence of the model structure, since it includes preparation intervals which are supposed to, based on the forecast, ensure that the BESSs are ready to deliver the promised capacity according to the bid and further avoid fines. However, the more interesting part is to investigate whether the difference increases or decreases when aggregating many BESSs. When observing Figure 18 a trend where the difference in delivered power compared to the promised bid decreases when around 16 or more BESSs are aggregated could be found. For the non-aggregated case on the other hand, the difference seems to remain on the approximately same level after this point. The trend becomes even more clear when observing Figure 19 in the same chapter, where the percentage reduction of the deviations of the bid can be found. An essential point to discuss is therefore why the first part of the graph does not follow the same pattern and further also the peak that can be observed around load profile 10. The main explanation why the first part of the graph does not follow the same gradient as the rest of the graph is probably the fact that the populations are too small to be able to compensate for each other's deviations, why the coincidence has a great impact on the result here. The aggregated cases were lucky and able to compensate for some deviations that occurred around 10 BESSs. Although the percentage difference is great in these sizes of populations, the actual differences are very small. This fact strengthens the reasoning regarding the coincidental impact of the results with small populations, and it can further be concluded that it is simply difficult to conclude anything from population sizes.

Between approximately load profile 16 and 45, a change of around 30 to 35 percent could be observed regarding the difference for the aggregated case compared to the non-aggregated case. This implies that by aggregating the population instead of letting the units work by themselves, the average delivered power per unit increases. In order to validate the results further, a study including a greater population size would be required to examine if the trend continues. However, according to the information presented in the literature study, it is reasonable to believe that the trend would continue in a greater population as well. For example, Shi et al. (2017) showed a super linear pattern with their suggested model. To investigate how the optimal population size would be formed in order to optimize the benefits of the aggregated system, a correlation analysis between the number of units and load size would be requested. For example, the linear pattern of the right part the graph in Figure 19 occurred when a large load profile, profile number 16, was added to the population. The correlation between the results and the sizes of the load profiles is further discussed later in Section 7.4.1: *FCR-N Bid Safety Margin.*

Another advantage of aggregating the BESSs that could be observed is the share of accepted bids, according to Figure 22 presented in Chapter 6: *Results*. In a real system, none of the bids placed by the individual units in the non-aggregated case would have been accepted in terms of bid size. In the aggregated case on the other hand, the share of accepted bids increased with a clear linear pattern when aggregating 16 or more BESSs. This should be considered as a great advantage which implies that aggregated BESSs are a stronger market player compared to when the BESSs are working alone. This further implies that by enabling more accepted FCR-N bids, the flexibility on the market increasing. This would further imply a development of the electrical system, something that further on is needed in order for the energy goal of a 50 percent more effective usage of energy in 2030 compared to 2005, which was mentioned in mentioned in Section 2.1: *The Swedish Electricity Mix and Climate Goals*, to be met.

Worth mentioning, though, is that if an aggregator would be implemented on the real market, an assumption regarding the actor taking on the aggregator role could be made that it would have been charged a fee or similar in order to be able to provide the aggregator services. This would further have reduced the profit for the individual units.

The last point to be discussed regarding the frequency regulation part is the unused overcapacity that could be observed according to Figure 19 presented in Chapter 6: *Results.* It becomes clear that the system includes a lot of extra capacity that could have been used to deliver FCR-N, but which were not bided during the day ahead planning. This extra capacity could have been used better, both in the aggregated case and in the non-aggregated case. In order to utilize this capacity better, either the safety margins need to be changed, or the forecast deviations needs to be reduced by for example implementing an improved forecast methodology. The overcapacity is a result of an hour that for example was flagged as a preparation interval according to the forecast, but where no preparation was needed. As seen in Table 7, 59 percent of the hours were allocated for preparation intervals and no service intervals, which apparently was too much. By using a better forecast, the preparation hours could probably be reduced and be more in line to what actually is needed during the day of operation.

7.3 Peak Shaving

In Section 6.5: *Shares of Peak Shaving and Frequency Regulation,* Table 7 can be found from which it can be observed that a reduction of peaks was being implemented during the simulations of the populations. By further comparing the results of Table 7 regarding the total reduction of the peak, observations regarding the difference in peak shaving between the aggregated and non-aggregated cases could be done. When the largest simulated population of 45 units were aggregated, the total reduction of the peak throughput the simulated week was 154.70 kW, whilst for the non-aggregated simulations the total reduction of the peak was 115.55 kW. A distinct difference by almost 40 kWh between the cases further on implies an advantage of aggregating the individual units due to the further reduction of the monthly peak, which as described in Section 3.2: *Peak Shaving* was something the simulations of the study aimed to obtain.

In Chapter 2: *Background,* it was stated that that the demand response (DR) peak shaving is used in order to change manage utility costs in the form of demand tariffs for electricity users by shaving the electricity user's peak load, which is determining the demand tariff. Peak shaving is furthermore executed by using a combination of the distributed energy resources (DERs) photovoltaics (PV) and BESS. By aggregating several DERs, a virtual power plant (VPP) is formed. This strategically smart manner of using DERs further provides the electricity grid with flexibility and an added value, why the results of a larger reduction of the peak throughput the simulations when the individual units were being aggregated is proving this. By providing the grid with more flexibility through aggregation of units, the goal of a more effective energy usage mentioned in Section 2.1: *The Swedish Electricity Mix and Climate Goals* would be more likely to be met. It furthermore implies how a VPP could be used as a sustainable and flexible solution for balancing the electrical grid in the transition to a sustainable energetic system, which was part of the aim of this study. Beside the advantaged connected to the grid, the reduction of monthly power peaks and ability to sell flexibility as FCR-N implies an economical advantage for the end consumer being a part of the VPP.

In Chapter 6: *Results,* the results regarding peak shaving for aggregated and non-aggregated populations of up 45 BESSs can be seen in Figure 19, Figure 18 and Table 6. As can be seen from the results, no excessive difference can be distinguished between the hourly average shaved load per unit for the aggregated and non-aggregated cases of simulations. The main reason behind this is the prognosis since it is not entirely correct, which is an issue being further described in section 7.1: *Prognosis*. Due to the lack of reliability of the prognosis, several hours were initially being flagged as PS-hours when in reality there was no actual need for peak shaving. This further resulted in a small total amount of actual peak shaving, which led to a difficulty regarding the observation of improvements in the ability of peak shaving between the aggregated and non-aggregated cases of simulations.

Although, an improvement of the flagging of PS-hours in order to ease the observation of improvements would be difficult to implement. As being described in section 4.2.6*: BESS Schedule*, the schedule is binary meaning only one of the services can occur during an hour. Therefore, if the monthly threshold was to be decreased in order for the enabling of a larger number of PS-hours, the share of FR-hours would be less and furthermore, the amount of peak shaving would still not be correct according to reality since the initial amount of hours already was too large. A decrease of the monthly threshold would only imply more flagged PS-hours but not necessarily a larger size of power that was peak shaved. It could also have resulted in a situation where the monthly threshold was set to a very low level compared to the size of the BESSs, why the BESSs would not be able charge enough to peak shave. Therefore, there is a need for a better prognosis in order for the accuracy of the improvements to be more according to reality. Another solution could perhaps be to allocate more hours for peak shaving but not raise the threshold level by introducing complementary conditions. This could however, as mentioned before, result in less FR-hours.

A reason for the improvement of peak shaving not being as distinct between the aggregated and non-aggregated cases as the improvement of frequency regulation is further that the units are able to compensate for each other to a larger extent regarding frequency regulation than peak shaving. This is since frequency regulation is a service able to be performed over all units, whilst the service of peak shaving is only able to be performed locally for each unit. The possibilities for the BESSs units to compensate for each other is further lower for peak shaving compared to frequency regulation, why the advantages connected to peak shaving consequently are smaller compared to frequency regulation. However, both services are part of the same system and the peak shaving could be compensated by letting another unit perform frequency regulation if needed. The possibilities of compensating for each other in the different cases is further described in Section 4.2.1: *Overview and Model Structure.* To sum up, the total power that was peak shaved increased and the monthly power peaks were reduced when aggregating the units compare to when not aggregating the units. This implies advantages both connected to flexibility to the grid and to the private economy for the consumer taking part of a VPP of this kind.

7.4 Safety Margins

As mentioned in Chapter 4: *Methodology*, the system consists of two main safety margins, one connected to peak shaving and one connected to frequency regulation. The two safety margins could be analysed separately since they are of different characters in the context. According to the methodology, the one connected to peak shaving must be applied locally for each unit, while the safety factor connected to frequency regulation can be applied for the total bid in the aggregated case.

7.4.1 FCR-N Bid Safety Margin

As observed in Figure 14 presented in Chapter 6: *Results*, the forecast accuracy connected to the FCR-N bids could be increased to a greater extent when the BESSs were aggregated, compared to when the BESSs worked alone. When observing the largest population of 45 load profiles with hourly mean load of 350 kWh for the period when the data was collected, the safety margins could have been reduced by approximately 50 percent when aggregating the units since de reduction of difference between the bid and the actual delivered power was according to this size. With a deviation of 10 percent, this would imply a decrease between 40-60 percent, and with a deviation of 20 percent this would imply a decrease between 30-70 percent. When observing only the interval between a population size of 16 to 45 BESSs, which as according previous discussion is the interval from where conclusions could be drawn in this manner, the safety margins could be reduced by approximately 1-2 percent per added unit or corresponding approximately 0.2 - 0.3 percent per added hourly average kW load to the population.

While the population size increased between 16 and 45 BESSs, the hourly mean load increased from approximately 190 kWh to 350 kWh, which implies an increased load by 84 percent. Although it is out of the scope of this study to examine the reason for possible reduction of safety margins, it is of interest to discuss if the number of BESSs or the total load size has the greatest impact on the reduction of safety limits. From the results it can be concluded that the discovered pattern where the safety limits could have been decreased, occurred after a heavy load increase by load unit number 16, which can be observed in Figure 9, Chapter 5: *Data*. It is further reasonable to assume that the total load size due to this does have an impact of the reduction of safety limits. However, the same load size divided on for example only two load units, would not imply a population with the same possibilities for compensation of each other as if the load is divided of 45 load units. To examine the ratio between the load size impact on the safety factor and the number of unit's impact of the safety factor, a regression analysis can be performed.

For small populations, with less than 15 units and an hourly mean load for the observed period less than 20 kWh, the safety margins could not be proved to be reduced at all due to the uncertainties discussed in section 7.2: *Frequency Regulation*.

In addition to the reduction of safety margins that could be applied to the aggregated population compared to when the population worked alone, the safety margins in both cases could be reduced due to the extra capacity presented in Figure 19. The extra capacity increased according to a quite linear pattern by an hourly average of approximately 400-500 W per added unit to the population. However, this reduction of safety margin is, as mentioned before, mutual for both cases why it is not analysed further. A better prognosis model could possibly have reduced these extra values, since it could have been calculated into the original FCR-bids instead of during the day ahead planning. However it would be of interest to use this capacity in a more effective manner in order to avoid waste of capacity. Some preparation intervals and no service hours are necessary for the system to work, but a minimization study regarding these hours would be an interesting continue of this work.

7.4.2 Peak Shaving Safety Margins

According to what has been stated in the methodology, the peak saving safety margin has to be applied locally for each unit. However, they are affected by the compensation possibilities from other units in the aggregation population. Therefore, as mentioned in Chapter 4: *Methodology,* it should be calculated depending on the whole population. The peak shaving margins are not able to be decreased to the same extent as the FCR-N bid safety margins and there are two main reasons for this.

The first reason is that peak shaving did not occur to a great extent. As can be seen by the result stated in Section 6.5: *Shares of Peak Shaving and Frequency Regulation,* only 16 percent of the total amount of the hours during the simulated week was flagged as PS-hours. Due to this, there is only a certain amount of hours being able to take into account regarding the safety margins, whilst for the FCR-N bid safety margins it can be seen that 25 percent of all hours can be taken into account. Therefore, there is less data regarding peak shaving forecast deviation and performed peak shaving, and further harder to draw any conclusions regarding reduction of safety margins in this case. If all PS-hours actually would have been used for peak shaving according to the flagging, a larger difference might have been able to be observed. The fact that only a part of the flagged PS-hours actually performed peak shaving increases the differences in observed executed services between frequency regulation and peak shaving further, and therefore also the possibilities of reduction of safety margins.

The other reason for the peak shaving safety margins not to be able to be decreased to the same extent was brought up in the earlier section, Section 7.3: *Peak Shaving.* Since the service of peak shaving is a locally occurring service, the units are not able to compensate each other to the same extent as they are regarding aggregated services, such as frequency regulation. Due to this, the only possibility of compensating for each other is for a unit that was supposed to perform peak shaving according to the schedule but actually is able to perform frequency regulation, instead performs peak shaving in order to compensate for another unit's peak shaving. This causes less opportunities for compensating for each other using this service compared to when using another service, like frequency regulation. Because of this, the benefits of the aggregation are reduced which further on also reduces the possibilities of reducing the peak shaving safety margins.

As seen in Figure 19 in the Section 6.3 *Real and Forecasted Peak Shaving*, the shaved peaks are slightly higher for the aggregated cases than for the non-aggregated cases. It also increases after the critical point of when around load profile 15 but after that point, the difference between the aggregated and non-aggregated cases is continuous and the graph is slightly negative. Because of this, it is hard to say if the sudden change of the slope is due to the added load profile causing the sudden increment or if it is a general pattern throughout the simulations of the system. Because of the indefinite reason behind the appearance of the graph at this specific stage, no further analysis regarding a possible prognosis deviation leading to the emergence of this part of the graph has been executed. This also since the peak shaving safety margins are not imaginable to be decreased in this specific case.

Due to named reasons, the peak shaving safety margins would be easier to investigate if the prognosis were to be more precise, and larger populations were to be simulated due to the then increasing possibility of actual executed peak shaving. The peak shaving safety margins would then be explored further in a way more closely connected to the forecast accuracy and mean deviation (MD) than are able to be formulated as in this study.

7.5 Model Structure and Methodological Strengths and Weaknesses

Since the numerical model could be formed in slightly different ways and the fact that it is based on an already existing model, it is of interest to discuss the model structure. Firstly, the model structure is formed according to a binary approach, which implies, as described in Chapter 4: *Methodology,* that the BESSs only can perform one service at the time. If the model would have been formulated according to a non-binary structure, both peak shaving and frequency regulation could possibly have been performed at the same time. For example, a possibility could perhaps be that when performing peak shaving of the local load, the EMS could also perform downward regulation of the frequency as a bonus. However, these kinds of combined services would have required other analysis than the ones in the scope of this thesis. Another possibility with a non-binary model structure is the fact that the BESS capacity could be reserved, for example, half for FCR-N bid and half for peak shaving. This could imply a more effective use of the BESS resources, both for the aggregated case and the non-aggregated case. However, this kind of combination would have required more advanced calculations since the BESSs has to be ready for both downward and upward regulation of the frequency as well as for peak shaving. Further on, this kind of combination would have been of larger interest if optimization between the services were performed, which this study is delimited from. However, a disadvantage of the used model structure is the fact that a FR need sent to the aggregator could be greater than the peak shaving that was performed in case of change of service, which could be considered as waste of BESS resources. Consequently, of all these factors, a non-binary model structure could possibly have resulted in even more advantages for the aggregated case compared to the non-aggregated case.

Secondly, it is of interest to discuss the extra capacity that was found and the fact previously mentioned, that less than half of the hours were reserved to actual profitable flexibility services. The other hours were reserved for preparation intervals or no service intervals. Although these hours are necessary for the system, the extra capacity that was found indicates that these preparation intervals could have been reduced if using a better prognosis model. Another possibility could have been to introduce some kind of factor, which could be connected to the forecast accuracy. If it for example were known that a inaccurate prognosis was used, a factor that adjusted the preparation intervals according to this could have been implemented for the next simulation.

In general, the methodology’s strengths include the fact that the model is able to simulate a system that works close as it could work in the reality. The numerical model is quite simple compared to what it is doing, and the different parts and parameters are flexible and easy to change in order to try different parameters or sizes of populations. The numerical model does further show trends and more interesting results could be gained except the ones presented in this study. The methodology also included use of a large amount of real data, which should be considered an aspect that creates credible results.

The prognosis part of the model is the weakest part of the methodology, and an updated forecast model should be implemented in order to require more clear results. The methodology is further based on a numerical model constructed by CheckWatt AB, which somehow could be considered as subjective. The choice of numerical model was a desire for CheckWatt AB since it is of their interest to execute results according to their model. Further, no other model suitable structures were found in the previous research which implemented both peak shaving and FCR-N, and usage of the model further allowed a fair comparative with a non-aggregated case. However, the choices within the model are based on mathematical relationships and given system limits which has been motivated by and in previous research, why another model structure of the system probably would have achieved similar results. Further, the main choices of the numerical model were motivated in the methodology in this thesis as well.

7.6 Possibilities of the Aggregator in the Future Electricity System

The result of this study showed that advantages connected to total increased flexibility within the system could be found. These results are in line with what the FENIX project (2009) showed, but then by aggregating combined heat and power. The results are also in line with Zhang et al. (2017) conclusions regarding the fact that BESSs need to be flexible in their services in order to provide more flexibility and to meet the minimum bid sizes of the market. Aggregation of BESSs and VPP as concept thus seems to be solutions with potential.

A future electricity system with higher penetration of intermittent energy requires new solutions in order to balance the frequency and to avoid lack of power. Increased demand flexibility is, as mentioned in Chapter 3: *Background,* a possible solution for the problem. In order to deliver demand flexibility, profitable and effective solutions must be implemented in the electricity system and in the electricity markets. An aggregator could, according to the results found in this study and previous studies, reduce safety margins and increase the total delivered demand flexibility, compared to when individual units are acting alone. An aggregator would also allow small units to act as a stronger market player, which probably would create circumstances for a higher rate of DER in the electricity system. An aggregator and a VPP would further enable a more stable electricity production where different intermittent units could compensate for each other’s production deviations. A VPP consisting of smartly controlled BESSs units would be able to combine different services and possibly increase the profitability and effectiveness further. An electricity system that enables a high rate of aggregators, would likely enable a higher rate of renewable energy resources and consequently reduce the emissions of greenhouse gases (GHG). A part of the aim of the study, being examining how a VPP could be used as a sustainable and flexible solution on the electricity grid, was therefore fulfilled and the results of the study could also contribute to the pursuing of meeting the Swedish climate goals. Further on, an integration of aggregators would allow small electricity consumers and producers to affect their electricity usage, monthly power fees and market repositions. DER that previously only been used locally could become a more active part toward a stable electricity system. According to previous studies mentioned in Chapter 2: *Background*, it is of interest whether which level power tariffs are implemented, which further also could be of interest for the implementation of aggregators including different kind of local DER.

7.7 Sensitivity Analysis

The sensitivity analysis, being presented in Section 6.6*: Sensitivity Analysis*, analyses the sensibility of the system by examining the outcome of the system when the individual thresholds of the units are increased respectively decreased by 10 percent. By observing Figure 23 and Figure 24, an increased shaved load due to decreased thresholds as well as a decreased shaved load due to increased monthly thresholds can be seen. This indicates a rather insensitive stable system that changes its values of the shaved load to the same extent in both directions of changed monthly thresholds. When analysing the results related to the frequency regulation in the sensitivity analysis, it can be concluded that the previous observed patterns remain although the actual values of course changes. This implies that the system in this matter is rather insensitive as well since the patterns regarding the shaved load remain although the monthly thresholds are changed.

The analysis also shows a change in the total value of the shaved peaks when the threshold is being changed. When Table 6, Table 8 and Table 9 are compared, it can be observed that if the threshold is changed, regardless if increased or decreased, the total value of the shaved monthly, or in this case weekly, peaks decreases. This can be explained by the fact that the size of the individual batteries are not suited for a change of the monthly threshold: increased monthly thresholds result in an amount of PS-hours that is unnecessary small compared to what is actually possible to peak shave and a decreased thresholds result in an increased monthly threshold either way due to the battery not being capable of shaving all peaks accordingly to a too small monthly threshold, which is being described in Section 4.2.3: *Peak Shaving.* For example, a too low initial level of the monthly threshold might imply a very high level of the power peaks are shaved in the beginning of the period. In a later stage of the period the BESSs might on the other hand fail to perform a full peak shaving due to a too small BESS size, why the monthly threshold is increased, and the total decrease of the monthly power peak is reduced. For this reason, it is possible that the total power peak shaving is higher, but the reduction of the monthly power peak is lower compared to another case. Consequently, the total reduction of the monthly power peaks decreases when the thresholds are being changed in either direction. This further implies that the initial ratio between the monthly thresholds and the BESSs sizes seem to be on a reasonable level in order for the system to be operated at its full potential in this aspect.

7.8 Requests and Impact of The Enterprise

Due to the fact that this study has been done on behalf of CheckWatt AB, an enterprise, it is of interest to note that although the study was conducted on the request of an enterprise, there has been no attempts from the enterprise to control the outcoming results of the study, attempts such as controlling what particular data that has been used in the study. Although the study is on behalf of an enterprise, both the numerical and literature parts of the study are scientifically based. However, as mentioned in Chapter 4*: Methodology* the reader should be aware of the fact that some choices of parameters or structures have been done according to the company's interests.

7.9 Future Studies

Through the report, some interesting future studies have been exemplified. For instance, optimization studies with an economical focus would have been interesting to understand how profitable an aggregated system could be compared to a non-aggregated system. This kind of optimization study could for example take price data into account when constructing the BESS schedule, instead of prioritizing peak shaving of the local system. Different economical optimization models could be implemented and compared with each other.

Further, a model structure with a non-binary approach would have been of interest to compare with the results of this study, in order to examine if there are any additional benefits of the aggregated case compared with the non-aggregated case. It would also be of interest to perform a larger study with a high number of units, and to examine different compositions of load profiles.

A study regarding the ratio between the monthly threshold and the size of BESS would be of interest to optimize the system further. Lastly, a minimization study regarding the need of preparation interval hours and no service hours of the system would be of interest in order to use the BESSs resources in a more effective manner.

8. Conclusions

In this study the advantages of aggregating several battery energy storage systems (BESSs) to provide ancillary services to the electricity system were investigated. This was done by simulating a system with different population sizes of, namely up to 45, BESSs with differences in between the individual units and which performed ancillary services in terms of peak shaving of the local load and providing frequency containments reserve - normal (FCR-N). The hypothesis was that an added value could be obtained by aggregating many BESSs compared to when they are working alone. The hypothesis was further that reduced safety margins could be obtained within the system.

The study proved some advantages connected to aggregation of several BESSs, in general the aggregation enabled an added value and a higher level of flexibility within the system. The study also concluded that an even higher level of flexibility probably can be obtained by using a better load and PV electricity production forecast than the one used in this study.

The main advantages of the aggregation of several BESSs for providing the ancillary services peak shaving and frequency regulation that were found were the following. Firstly, the monthly power peak for a simulated week could be reduced by 39,15 kW for the studied system, compared to when not aggregating the units. Secondly, when aggregating many BESSs they could generally provide more FCR-N capacity. For a population of 16 or more BESSs with a total hourly average load of 190 kW or more, the deviations compared to the placed FCR-N bids could be reduced by approximately 1-2 percent per added BESS or corresponding approximately 0.2 - 0.3 per increased hourly average load added to the population, compared to when not aggregating the units. This decrease implies an added value to the system and a possibility to deliver a higher volume of FCR-N capacity when aggregating many BESSs compared to when not aggregating the same population of BESSs. Lastly, it was found that an aggregated population would have better circumstances to perform as a stronger actor on the FCR-N market compared to a non-aggregated population.

It was found that the load forecast became more accurate when aggregating many units since the forecast deviations complemented each other, which implicates that safety margins regarding promised effect should be able to be decreased when aggregating more units compared to when not aggregating them and that an increased flexibility can be obtained. The safety margins connected to a delivery of FCR-N capacity could, according to the study, be reduced to the same extent as the deviations connected capacity bid placed to the market mentioned above. A system consisting of an increased number of aggregated BESSs could consequently reduce the safety factors more and receive an added value to the system and further increased flexibility for the electricity system as whole. The safety margins connected to peak shaving could not be proved to be reduced to any greater extent when comparing an aggregated population with a non-aggregated population, why a more extensive study regarding this is requested.

By the added value found in this study, it was shown that a VPP consisting of different units implies economic benefits for the consumers and producers being part of a VPP and increased flexibility to the electricity system as whole. A VPP should further be considered as a suitable alternative in the future electricity system in order to allow a higher penetration of intermittent energy sources and distributed energy resources (DER), and should also be concerned as an instrument to reduce the emissions of greenhouse gases (GHG). This further implied that aggregators and VPPs can be used in the pursuing of meeting the Swedish climate goals.

9. References

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10. Appendix A

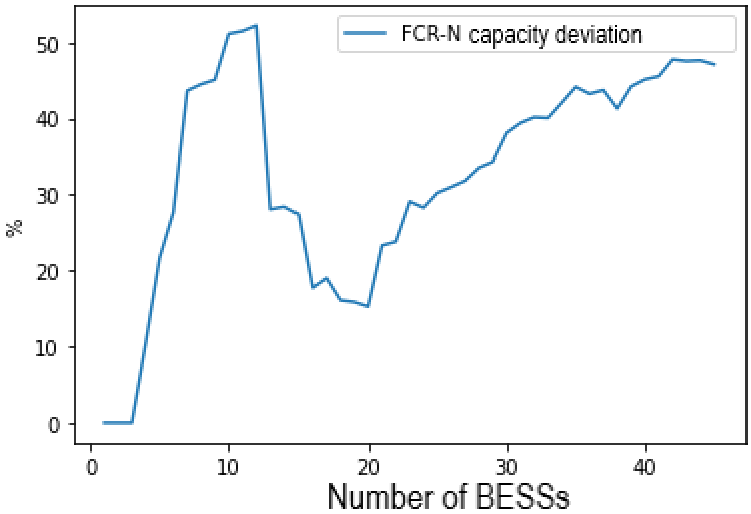

Figure 25. A graph of the reduction of hourly average FCR-N capacity deviation compared to the actual bid - when aggregating the BESSs compared to when not aggregating the BESSs in populations of up to 45 BESSs and the individual initial monthly threshold is decreased by 10 percent. Extra FCR-N capacity higher than the value of the placed bid are not included.

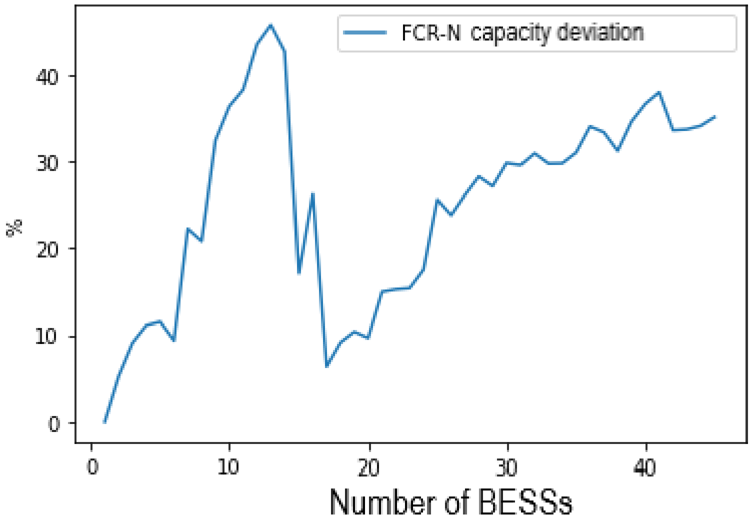

Figure 26. A graph of the reduction of hourly average FCR-N capacity deviation compared to the actual bid - when aggregating the BESSs compared to when not aggregating the BESSs in populations of up to 45 BESSs and the individual initial monthly threshold is increased by 10 percent. Extra FCR-N capacity higher than the value of the placed bid are not included.

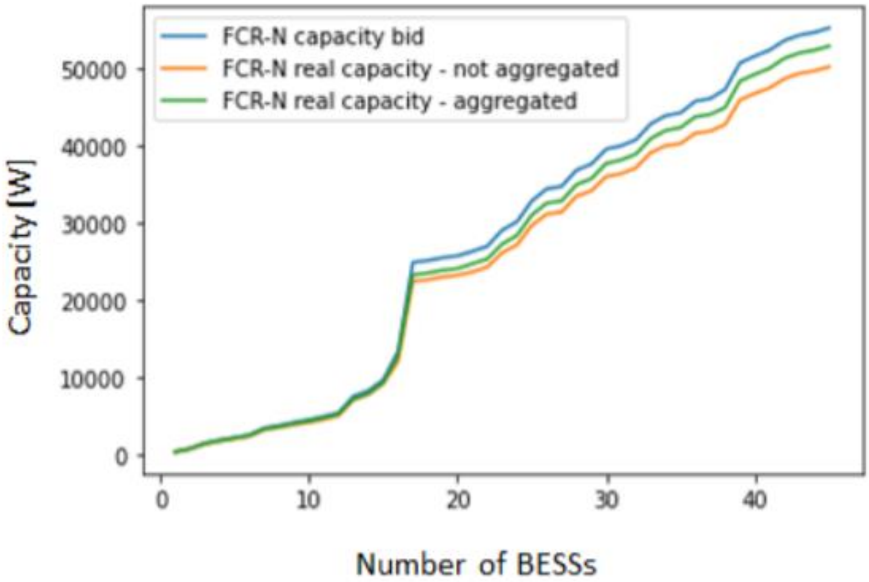

Figure 27. A graph of the hourly FCR-N capacity bid, the real hourly FCR-N capacity for aggregated populations of up to 45 BESSs and the real hourly FCR-N capacity for non-aggregated populations of up to 45 BESSs when the individual threshold of each unit is decreased by 10 percent. Extra FCR-N capacity higher than the value of the placed bid are not included.

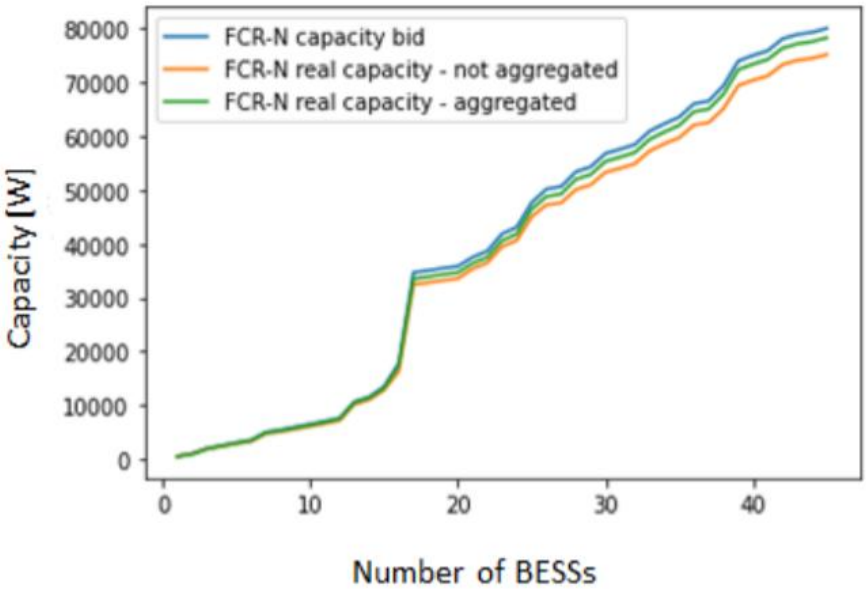

Figure 28. A graph of the hourly FCR-N capacity bid, the real hourly FCR-N capacity bid for aggregated populations of up to 45 BESSs and the real hourly FCR-N capacity for non-aggregated populations of up to 45 BESSs when the individual threshold of each unit is increased by 10 percent. FCR-N capacity higher than the value of the placed bid are not included