Batteries charging into the future?

Techno-economical analysis of BESS participation on the Swedish frequency regulation market using a mixed method approach

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Master thesis
June, 2023

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ISRN LUTFD2/TFEM—23/5196–SE52
ISSN 1102-3651

Printed by Media-Tryck, Lund University

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MADE IN SWEDEN

Abstract

As the penetration of variable renewable energy is increasing, the demand for flexibility in the electrical grid is on the rise. One way in which flexibility is needed is to provide frequency regulation. If electricity consumption and production momentarily are unbalanced there needs to. The Swedish TSO, Svenska Kraftnät, procures multiple different frequnecy regulation services to protect against these imbalances. As a result of falling costs, Battery Energy Storage Systems (BESS) are now a possible suppliers of frequency regulation. This thesis investigates the economic and technical feasibility for BESS on the Swedish frequency regulation market in its entirety, and which services are the most suitable for BESS.

A mixed method approach is employed in the thesis. After presenting background for central topics, both quantitative and qualitative data was gathered. Modelling of price and frequency data of 2022, as well as an interview study with 12 interviewees, was conducted. Cycling degradation and energy costs were included in the modelling. In a parallel manner the two data types are analysed, and integrated in the discussion and conclusion sections.

Through its result, the thesis shows that FCR-D and FFR are the most economically suitable frequency regulation services for BESS. With the price level of 2022, economic feasibility is high, with pay-back times of 1.6 years, and 64 % IRR. The thesis further points out that the general price level is expected to drop due to an increase in supply. Simultaneously, regulatory changes are making BESS operation more independent and allowing for more liberal bidding strategies, increasing revenues this way.

Keywords: Battery Energy Storage Systems, Frequency Regulation, FCR-D, FFR, economic feasibility, Sweden

Sammanfattning

I takt med att andelen förnybar el ökar så ökar även efterfrågan på flexibilitet i elnätet. Flexibilitet behövs bland annat för att tillhandahålla frekvensreglering. Om elförbrukningen och elproduktionen tillfälligt är i obalans kommer frekvensen i elnätet att avvika från sitt börvärde. För att skydda mot dessa obalanser upphandlar Svenska Kraftnät flera olika frekvensregleringstjänster. Som ett resultat av fallande produktionskostnader har batterilager (BESS) blivit en potentiell leverantör av frekvensreglering. Denna uppsats undersöker den ekonomiska och tekniska gångbarheten för BESS på den svenska frekvensregleringsmarknaden i sin helhet, och presenterar de tjänster som är mest lämpade för BESS.

Uppsatsen omfattar både kvantitativ och kvalitativ data. Först presenteras den relevanta bakgrunden. Sedan initieras metoderna för de olika datatyperna och resultaten presenteras för respektive typ. För den kvantitativa datan modelleras intäkter för år 2022. Pris- och frekvensdata ligger till grund för den kvantitativa analysen, och cycklingsslitage samt energikostnader är inkorporerade i modellen. Den kvalitativa datan består av en intervjustudie med 12 intervjuer. Efter att den kvantitativa och kvalitativa datans resultat har presenterats parallellt slås de samman i diskussion och slutsats.

Uppsatsens resultat visar att FCR-D och FFR är de ekonomiskt mest lämpliga frekvensregleringstjänsterna för BESS. Data från 2022 visar att den ekonomiska genomförbarheten är hög, med återbetalningstider på 1,6 år och med 64 % IRR. Uppsatsen pekar vidare på att den allmänna prisnivån förväntas sjunka på grund av ett ökat utbud. Samtidigt gör regeländringar BESS-verksamheten mer oberoende och möjliggör mer liberala budstrategier, vilket ökar intäkterna på detta sätt.

Acknowledgements

This thesis is the final part of my education in Industrial Engineering and Management at LTH in Lund, Sweden. The last five years has been a wonderful time in my life.

Firstly, I would like to thank my supervisors, Lars J Nilsson and Hannes Sonnsjö. Your guidance and expertise has been essential through the entire process of writing this thesis. I am very grateful for your support.

Also, I would like to thank Eolus Vind, and my supervisor Per Skålén, for being given the opportunity to write this thesis.

Finally, I would to thank my friends and family. Writing this thesis on my own wasn't half as tough as it would've been without you ever-present support. I am truly happy to have you by my side.

Theodor Rosengren
Lund, June 2023

Contents

Nomenclature

aFRR Automatic Frequency Restoration Reserve

BESS Battery Energy Storage System

DoD Depth of Discharge

DSO Distribution System Operator

ENTSO-E European Network of Transmission System Operators for Electricity

EV Electric Vehicle

FCR Frequency Containment Reserve

FFR Fast Frequency Response

LER Limited Energy Reservoir

MARI Manually Activated Reserves Initiative

mFRR Manual Frequency Restoration Reserve

NBM Nordic Balance Market

PICASSO Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation

SoC State of charge

SoH State of Health

SvK Svenska Kraftnät (Swedish TSO)

TSO Transmission System Operator

V2G Vehicle-to-grid

VRE Variable Renewable Energy

1 Introduction

In any well-functioning electrical grid, flexibility serves an important role. When consumption or production deviates from what they were predicted to be, additional power need to be added or removed in order to keep the balance. As the world turns its focus to solving the climate crisis, the penetration of variable energy production is increasing. The production of these sources, mostly wind and solar, varies throughout the day and can be hard to predict. As the grid encompasses a higher level of variable renewable energy, the need for flexibility to create balance in the grid also increases.

At any given moment how well the system is balanced can be measured by the frequency of the current, since grids have alternating current (AC). The nominal frequency, 50 Hz, is to be kept in order to ensure high quality electricity in the grid. But, if there is an momentary imbalance between consumption and production the frequency will deviate from 50 Hz. A unexpected peak in electricity consumption makes the frequency go below its nominal value. Higher production than what was predicted will drive the frequency up. The vice versa goes for consumption or production falling below their predictions.

As protection against sudden imbalances and frequency deviations, transmission system operators (TSO) procure frequency regulation services that act quickly to restore the frequency. Frequency regulation works by producing or consuming additional electrical power at the moment of the deviation. The frequency regulation services vary in response time, durability, and whether they push the frequency up or down, all in order to confidently protect against different kinds of deviations. A supplier of said services is on standby, ready to activate its resources for regulation when instructed to do so by the TSO.

The Swedish TSO, Svenska Kraftnät (SvK) has traditionally been procuring frequency regulation from hydro power. However, regulation prices has seen a strong increase in recent years. From 2021 to 2022, the costs nearly doubled [1]. Seeing the new price level, new parties are heading into the market. Battery Energy Storage Systems (BESS), systems which have seen a steep decrease in costs the last decades, are suddenly possible candidates to step into the market. Their technical capabilities make them a suitable provider of frequency regulation.

Since the possibility of providing frequency regulation are new options to BESS , the economic feasibility of the investment has to be examined. Without such an investigation, investment decisions are difficult to take. Simultaneously, technical requirements and market regulation need to be considered. The topic raises many interesting questions. Is BESS a suitable product for the frequency regulation market? What specific frequency regulating services should BESS be applied for? What return of investment could be expected for BESS on frequency regulating markets?

1.1 Problem formulation

As previously mentioned, there is a growing demand for flexibility as the penetration of variable renewable energy (VRE) increases [2]. The Swedish government has committed itself to provide 100 % renewable electricity production by 2040. During the same time, the Swedish demand for electricity is expected to see a strong increase [3]. Since BESS naturally can be a provider of flexibility, it has become a widely discussed tool in recent times.

The possibility for BESS participating on the frequency regulation markets is also a hot topic. As mentioned in the introduction, a decrease in costs combined with an increase in frequency regulation prices has suddenly created new opportunities for BESS.

The thesis initially decided upon focusing on BESS and the Swedish frequency regulation market. However, to further specify the research questions and the scope of the thesis, an initial literature study was conducted. In doing so, a suitable focus of the thesis became clear while simultaneously avoiding to choose research questions similar to what has already been researched. It is important to find a suitable research gap when initializing a thesis.

The way in which this part of the literature study was performed is discussed to a greater extent in Section 2. Here follows a quick summary of research done on the topics of BESS on the frequency regulation markets.

[4]–[8] investigate the economics of BESS on frequency regulation on the Nordic market. None of them, however, do so with Swedish prices or with Swedish market rules. [9] investigates the Swedish market, but only for a single month of 2022 and only for a single frequency regulation service. [10] investigates frequency regulation profitability in various European markets, again not including the Swedish.

The initial literature study reveals that there is a knowledge gap describing the economic feasibility of BESS on the Swedish frequency regulation market. There are similar analyses made in recent times for other markets. But, as markets rules differ in-between different markets, these results are not necessarily comparable with the Swedish market [10]. Furthermore, the initial study found no research analysing the possibility for BESS on all frequency regulating services together.

By the result of the initial literature study, a research gap for BESS on the Swedish regulation markets was discovered. There are, to the knowledge of this thesis, no recent study discussing the economic feasibility and technical viability of BESS on the Swedish frequency regulation market. And no research discussing the entire range of frequency regulation services, services - previous research seem to focus on one or perhaps two services.

It would be important to know how the different services compare to each other, and how economically feasible they are for BESS. Furthermore, to be able to make sound investment decisions for BESS on these markets, it is essential to know what the level of economic feasibility is, and how technically available the markets are for the BESS technology.

1.2 Research questions

This thesis investigates the economic feasibility of BESS on the Swedish frequency regulation markets. It does so for the frequency regulation market in its entirety. The thesis will aim to answer the following questions.

1. *What is the economic feasibility and technical viability of Battery Energy Storage Systems (BESS) participating in the Swedish frequency regulation market?*
2. *What frequency regulation services are the most suitable for BESS in the Swedish market?*

The research questions thus asks how economically feasible and technically viable an investment in BESS is, when connected to the Swedish grid and applied to the Swedish markets. Additionally, what specific services are appropriate for BESS is investigated.

Since batteries are investments that last for numerous years, the economic feasibility is dependent on future cash flows. And cash flows are set by future prices, which, in turn, are decided by supply and demand. Together with prices, regulation is one of the most important aspects of profitability for BESS [6].

All together, the impact of the future market state on the feasibility of BESS is palpable. Thus, a forward looking approach is inherently present in the research question; the economic feasibility of BESS is dependent on future revenue. The emphasis on future revenue is inherent in the research problem.

1.3 Delimitations

As hinted at in previous paragraphs, this thesis will only be applied to the Swedish markets. However, within the Swedish market, no delimitation is presented. The thesis aims to provide results for all four electrical areas in Sweden.

Furthermore, the application of the battery will be restricted to the frequency regulation markets. There are, of course, multiple other areas of application for BESS. Local flexibility, energy arbitrage and peak load-shaving to mention a few. These all lie outside the scope of this thesis.

Moreover, as prices of frequency regulation services and costs of batteries has changed drastically in recent years, delimitations regarding relevant literature were added. Studies regarding said areas had to have been published later than 2019 to be included in this thesis. The value and relevance of research on the subjects that was published before 2019 was deemed low. Areas beside the ones concerning batteries or frequency regulation were not affected by this restriction.

As for the battery itself, the thesis will be limited to investigating Lithium-ion (Li-ion) batteries. They are the most prominent type of batteries in the initial literature study. Moreover, this thesis will discuss the research question with regards to stand-alone BESS. There are numerous ways in which a BESS can be set up, for example in connection to production or consumption. However, in this thesis it will be the stand-alone BESS that is investigated.

1.4 Thesis outline

In Section 1 the thesis is introduced and its research questions presented. In Section 2 the relevant background is laid out, providing essential context to the relevant areas. Section 3 describes the chosen methodology of the thesis and the results is presented in Section 4. Lastly, the results are discussed in Section 5 and conclusions from the results are drawn in Section 6.

2 Background

In the background, the groundwork of the thesis is laid out. Topics central to the research questions are defined, and the relevant research of those areas is presented. The first part of the background has already been presented in Section 1, where an initial literature study was used to identify a research gap. The selection of papers brought up in this study was selected based on a set of key-words. For this part the key-words were *Battery Energy Storage System*, *Frequency regulation*, *Frequency control*, *Economic*, *Nordic* and *Sweden*. Choosing the key-words was made so that they were suitable for the scope of the thesis.

Throughout the thesis a number of search engines were used. The engines used in the selection process were primarly IEEE Xplore and ScienceDirect (Elsevier). At times, specific topics were discovered through additional searches on LUBsearch and Google Scholar. Additional research material, such as master's theses, was used too. Finding master's theses was done through searches on DiVA portal and LUP Student Papers. Information regarding the Swedish electricity system, especially regarding frequency regulation, was, in large, found through the Swedish TSO, Svenska Kratnät's, webpage.

The background initially describes the Swedish electrical system, to provide the reader with the context in which frequency regulation exists. Thereafter, the electrical markets are presented. Subsequently, the frequency regulation market and the individual frequency regulating services will be described and their properties presented. Finally, information regarding Li-ion batteries is presented. A good understanding of their properties is essential for further analysis of BESS possibilities on the frequency regulation market.

2.1 Electricity system

The Swedish electricity system is an intricate system that is built to provide reliable electricity from producers to customers. There are numerous levels and aspects to the system. The most obvious is the power grid. Svenska Kraftnät, are in charge of all main transmission lines in Sweden [11]. Main transmission lines (220 or 400 kV), act together with regional lines (130 kV) and local lines ($<$40 kV) to distribute the electricity from producer to consumer. Regional and local distribution lines are not owned by SvK, but rather by distribution system operators (DSO). Additionally Sweden has international AC lines to Finland, Norway and Denmark as well as high voltage direct current (HVDC) lines to Finland, Denmark, Germany, Poland, and Lithuania.

The transmission and distribution grid physically moves electricity through the country, and to countries with which Sweden is connected. But, to ensure that the electricity consumed can be supplied by the production, there exists multiple electricity markets on which consumption and production can be matched in beforehand.

Before deep-diving further into the markets in the electricity system, a note on some safety measures of the electricity systems that are not traded on commercial markets. Some of the important measures include voltage control and rotor angle stability, responsibilities of SvK [12]. The same goes for insuring against situations of power shortage. For this, power reserves (sv. Effektreserv) and disturbance reserves (sv. Störningsreserv) are procured to protect against persistent power imbalances [13]. Although the above mentioned measures are important for the operational reliability, neither of them are sold or bought on daily markets.

They all lie outside the scope of the thesis.

As mentioned before, the TSO is responsible for the over-all performance of the grid. The DSOs are in charge of regional and local distribution grids. Furthermore, there exists a third party that plays an important role in the electricity system, the Balance Responsible Party (BRP).

The BRP is accountable for balancing production and consumption in their area in which they are responsible [14]. The area in which a BRP is responsible is not to be confused with the four electrical areas in Sweden. There are numerous BRPs in Sweden that together share the full responsibility of providing the same amount of electricity that is consumed. When difference between production and consumption occurs in a given BRP's area, the BRP has to pay a penalty fee proportional to the difference to SvK [15]. BRPs are also the only parties that are allowed to bid on the frequency regulation markets, markets which are presented in-depth below. Any owner of a resource capable of contributing on the frequency regulating markets must go through a BRP to be able to participate on the markets. An owner of a reserve that provides frequency regulation are also known as Balancing Service Provider (BSP). SvK are currently re-writing the rules so that a BSP that wants to take part in frequency regulation not has to go through a BRP to do so. It is not known when the separation of BRP and BSP will take place. In this thesis *supplier* will regularly be used to describe BSP. Ultimately, the BSP supplies SvK with their frequency regulating resources. Now, a few words on the electricity market.

2.2 Electricity markets

The Swedish market can be divided into a set of submarkets. These are the forward market, the day-ahead market, the intraday market, the frequency regulation markets, and finally the market for imbalances [16]. These markets will be discussed further below. A summary of all markets can be seen in Figure 1.

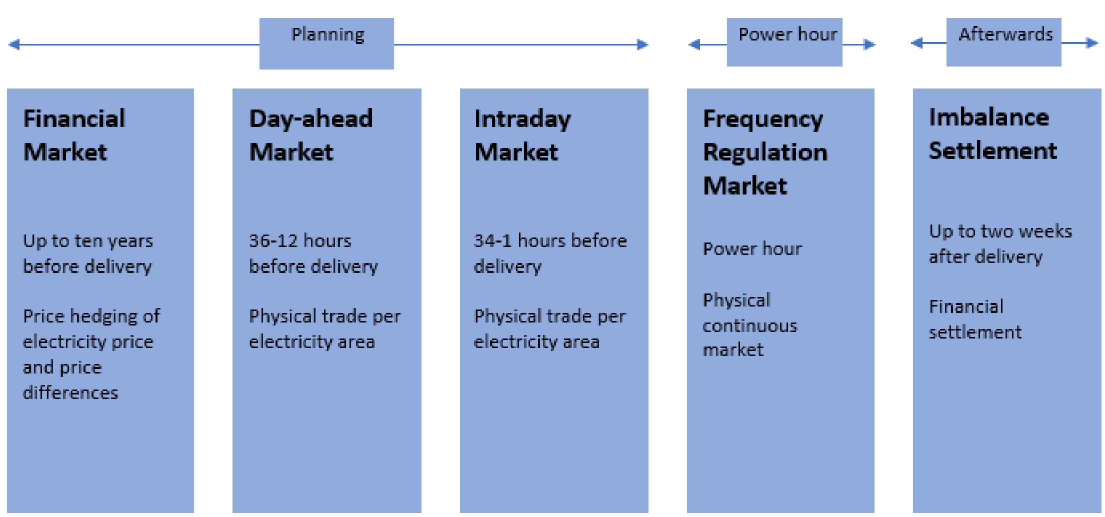


Figure 1: A summary of the Swedish electricity markets [17].

2.2.1 Forward market

The forward market is a financial market, where no physical transaction of electricity is made. Instead electricity derivatives are constructed and traded so that parties can mitigate their exposure towards risks regarding fluctuating electricity prices [17]. The forward market allows for contracts up 10 years before the delivery hour.

2.2.2 Day-ahead market

The day-ahead market is where most of the electricity is bought and sold [17]. The market takes in bids for every hour of the coming day. At 12.00, the day before delivery, the market closes. After matching the demand with the supply, the market price is set. At 13.30, prices for all hours the coming day are presented. In other words, prices are presented 12-36 hours in advance. The day-ahead market is using marginal pricing, or pay-as-cleared. At the same time as the market closes at 12.00, it opens for the next day. Thus, the market is open for 24 hours. The prices of electricity set on the day-ahead market are generally referred to as the *spot prices*. Prices set on the day-ahead market differ within Sweden. More specifically they differ between the four different electrical areas, shown in Figure 2. The Swedish electrical areas are SE1 (furthest north), SE2, SE3, and SE4 (furthest south). In Sweden, prices are generally lower in SE1 and SE2 due to the areas' large electricity production. Prices are generally higher in SE3 and SE4, due to the fact that consumption is higher here, and production lower.

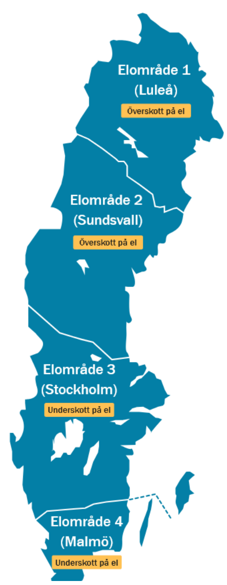


Figure 2: The four electrical areas of Sweden

In the last few years, Swedish spot prices has seen an increase [18]. The general price level has become higher and the volatility of the price has also grown. There are many factors that affect the spot price. One of the more apparent is the Russian invasion of Ukraine in 2021. As Europe's import of Russian gas has been diminishing, the prices of energy - and electricity - has been rising [19].

2.2.3 The intraday market

The intraday market is a market that enables market players to correct their positions after the day-ahead market has closed. There are many possible reasons that parties would wish to bid on the intraday market. Changed production predictions, increased electricity demand, and bids that were not accepted on the day-ahead market are all reasons to participate on the intraday market [17].

The intraday market is growing. One of the reasons being that the part of intermittent electricity production is increasing. Intermittent, or variable, electricity production renders uncertain predictions. This is simply due to the fact that variable electricity production is weather-dependent. The uncertainty of the production output diminishes as the hour of delivery approaches. Therefore, the intraday market is an important tool for to correct predictions for variable production.

The intraday market opens two hours after the day-ahead market closes, at 14.00, and closes one hour before delivery. [16] The intraday market is a continuous market. Bids are matched continuously throughout the day. 2.6 TWh were traded in Sweden in 2020, approximately 2 percent of the yearly production or consumption. From Q2 2023 the intraday market will start with 15 minute minimum bid, instead of the current 1 hour minimum [20].

2.2.4 Frequency regulation market

Frequency regulation markets are markets put in place to provide stability during the hour of delivery. On the frequency regulation market, a total of seven services are bought by SvK, and provided through the BRPs [21]. These services act to keep the frequency in the grid at its nominal value, 50 Hz. Whenever the frequency differs from 50 Hz, one, or multiple services are activated to correct the frequency. They have different properties to provide support in different situations. Svenska Kraftnät, the Swedish TSO, is the only buyer of frequency regulation services. It is quite a unique market in the sense that there is only a single buyer.

The Swedish electrical system is tightly connected to the other Nordic countries in the sense that they are synchronous [20]; the frequency in the Swedish grid is the same as the frequency in Finland. Since the Nordic grids are interconnected and synchronous, the TSOs of the Nordic countries have decided to share the responsibility of frequency regulation among themselves. All Nordic countries do not have the same share of the responsibility [22]. Sweden, more specifically SvK, has to procure 38 % of the total Nordic demand for the services FCR, for example.

The frequency regulating services in Sweden are FFR, FCR-N, FCR-D up/down, aFRR up/down, and mFRR. Their names, and how the differ from one another, will be explained in detail below. A service name that ends with up only performs *up regulation*. Up regulation refers to services that are activated to push the frequency upwards. Up regulating services act by adding power/energy to the grid. The opposite is true for *down regulation*. Henceforth, these expressions will be used in the thesis.

The terminology used to describe frequency regulating services varies between different markets and countries. In this thesis, their names are used as is. They are not put into any categories. However, another set of terms is primary and secondary reserves [10]. Primary reserves refer to the FFR and FCR services, and secondary reserve to the FRR services. Although not used in this thesis, the distinction between primary and secondary reserves is intuitive. Primary reserves acts as the primary tool to hinder a change in frequency and, at best, to restore it. Secondary reserves are activated as the primary reserves are depleting, and aims to restore the frequency to its nominal value.

The frequency services in Sweden are traded on different markets, all with varying supplierst and with different market rules. Suppliers of frequency regulating services can receive revenues in two ways: through *availability* and through *activation*. All services provide remuneration for availability, while some services provide remuneration for both availability and activation.

For availability the suppliers are paid to be available with their resources. Regardless of if a supplier's resource is activated or not, the supplier will be reimbursed either way. Frequency regulation is essentially a protection, it is not certain that the protection will be needed. It is, in short, the TSO buying insurance for unexpected imbalances. It is emphasized that SvK is the only buyer on all frequency regulation markets.

For the services that offer payments for activation, from this point on referred to as *activation remuneration*, an additional revenue is gained by the supplier in the case that their resource is actually activated for frequency regulation. In that case, the supplier can see two revenues: remuneration from availability and activation. Which services that offer activation remuneration too will be discussed in a moment.

In thesis thesis costs for SvK are discussed recurrently. The reader should keep in mind that SvK's costs of frequency regulation are the same as the revenues for the suppliers providing frequency regulation. This is evident when considering the fact that SvK is the sole buyer of frequency regulating services in Sweden.

SvK uses two different models to pricing models for their different services. These are called pay-as-bid and pay-as-cleared (marginal pricing). Same for both models is that bids with the lower prices are accepted first. This continues until SvK has filled the hourly quote for each frequency service. It should be emphasized that the prices the suppliers label their bids with is the price for availability. If their bid is accepted by SvK, the bid's price is what SvK will have to pay for availability, again, regardless of activation.

Pay-as-bid is a simple mechanism. Suppliers provide bids with the price for which they are willing to sell their capacity. SvK fills their needed capacity quote with the most affordable bids. The bids are paid according to their respective price. For pay-as-bid, bid prices are most profitable if they lie as close to the highest accepted bid as possible, but just below to ensure they are accepted. A simple model of pay-as-bid can be seen in Figure 3. Here, SvK will have to pay the sum of the staples to the left of the demand line.

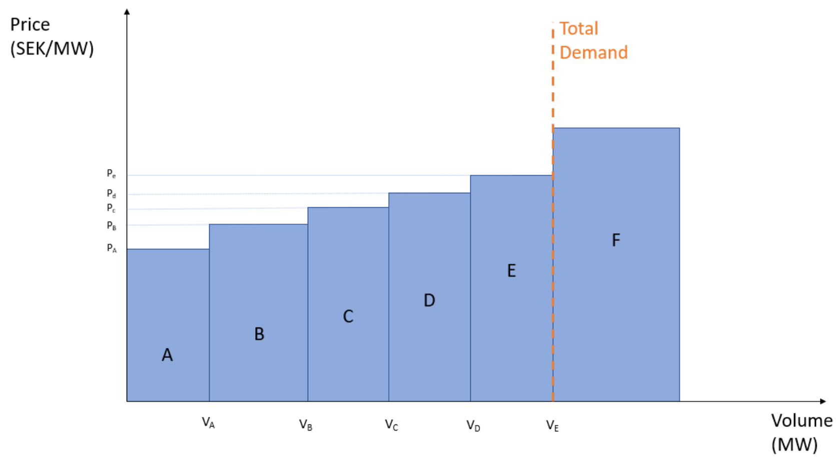


Figure 3

Pay-as-cleared, or marginal pricing, has a different mechanism. Still, the first part of the process is the same: suppliers submit their bids and corresponding prices to SvK. SvK sorts them in ascending order. The last bid to make SvK's capacity quote sets the *marginal price*. All bids that are included in the quote are priced with the same marginal price. Figure 4 aims to describe pay-as-cleared. All bids are paid according to the price of the highest bid, thus SvK has to pay the total demand multiplied with the price of the highest bid.

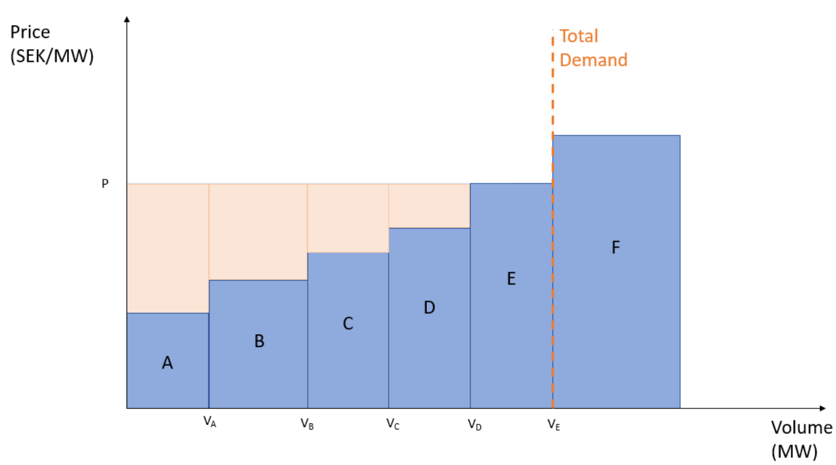


Figure 4

An important aspect to understanding the frequency regulation services is to know their respective volumes. Volume is the same as power on these markets, so the volume SvK procures for a given service is the same as the amount of power they procure. To provide an overview of the volumes each services encompasses, average hourly availability volumes are presented in Table 1.

Table 1: Average hourly availability capacity procured by SvK in 2022 (MW). FFR is only procured certain months, but the average was computed on the year for comparability. [1], [23]. FCR-D down is a new service for 2022, procured volumes was ramping throughout the year.

	FFR	FCR-N	FCR-D up	FCR-D down	aFRR up	aFRR down
Capacity	3*	249	529	135*	94	99

Moreover, in Table 2, the costs for SvK for the services are displayed. The costs here refer to the costs of purchasing availability. There will be additional costs for SvK, e.g. the costs for activation remuneration. To give the reader some perspective on the price development, costs for 2021 and 2022 are included in Table 2.

Table 2: Yearly costs for SvK of frequency regulating services (MSEK). FCR-D was introduced in 2022. [1], [23].

	FFR	FCR-N	FCR-D up	FCR-D down	aFRR up	aFRR down	Total
Costs 2021	81	893	2212	0*	314	298	3797
Costs 2022	57	1435	3086	451	666	520	6215

From Table 1 and Table 2 it can be seen that the FCR services are the largest, both in procured capacity volumes as well in costs for SvK. Moreover, availability costs for SvK almost doubled from 2021 to 2022. Before going on describing the individual services thoroughly, an overview of the services in the Swedish grid are presented in Table 3.

Table 3: Frequency regulating services. Activation speed for FFR depends on how large the frequency deviation is. FFR has to be ready again, after 15 min.[21], [24].

	FFR	FCR-N	FCR-D up/down	aFRR up/down	mFRR
Min. bid size	0.1 MW	0.1 MW	0.1 MW	1 MW	10 MW
Activation [100 %]	0.7-1.3 sec	3 min	30 sec	5 min	15 min
Min. durability	5/30 sec	1 h	20 min	1 h	1 h
Availability pricing	Marginal	Pay-as-bid	Pay-as-bid	Marginal	-
Activ. remuneration	No	Yes	No	Yes	Yes

The services' requirements above is a set of market rules to which a supplier has to abide. More in-depth technical specifications must also be met [25], for regarding the accuracy of a supplier's regulation. These are set by SvK to make certain that the regulating resources actually aid the grid when they are activated. The specifications presented in Table 3 together with the mentioned detailed technical requirements are the basis for pre-qualification. Any owner of a resource fit to provide frequency regulation must first be pre-qualified in order to be eligible to participate on the markets. Pre-qualification is performed by SvK. Since the grid is under continuous change, the rules for pre-qualification are changeable too [26]. Pre-qualified resources are to be re-examined for qualification every fifth year [27], [28]. If the requirements have been updated during that five year period, the supplier has to be examined again at the end of the period. If the new requirements are met, the supplier may continue to participate on that market. For example, in the case of FCR-N and FCR-D, there are a new set of requirements that has been presented for the market [26]. The rules are to be implemented during the fall of 2023. Resources that currently are qualified for FCR will have five years to adapt to the new rules from the time that they are put into place. Any new resources that wish to enter the market has to comply with the new rules. Thus, no later than the fall of 2028, all resources contributing on the FCR market, will be qualified according to the new technical requirements.

As previously mentioned, the Swedish hydro power holds a strong position on the frequency regulating markets. A more extensive summary of the currently pre-qualified capacities for the most common resources are presented in Table 4. Note that mFRR is not present in Table 4. SvK does not provide information of pre-qualified supply mFRR

Table 4: Pre-qualified resources per category, for frequency regulating services in Sweden (MW) [29].

	FFR	FCR-N	FCR-D up	FCR-D down	aFRR up	aFRR down
Hydro	0	1910	2410	1030	1800	1800
Wind	0	150	170	320	0	250
Flex consumption	100	<10	180	<10	0	0
Heat Power	0	40	40	20	50	50
Energy storage	50	<10	10	<10	0	0
Hydro & battery	0	<10	0	10	0	0

As can be seen from Table 4, hydro power is the dominant resource for almost all services, FFR being the exception. The energy storage category, in which BESS is included, has a significant market share in the FFR market, but not in the rest.

Below, a more technical explanation of the frequency regulation services is presented.

2.2.4.1 FFR Fast Frequency Response (FFR) is the fastest of the frequency regulating services. As mentioned in Table 3, the response time is between 0.7 and 1.3 seconds depending on what the frequency is. It is presented in detail in Table 5. The amount of FFR that is procured is dependent on amount of inertia in the grid [13]. Less inertia will require more FFR. FFR is only purchased by SvK during a certain months of the year. In 2022 FFR was traded May through November. However, in those months it was not traded at all hours or even all days. According to SvK no more than 100 MW FFR will be procured for a single hour. In 2022, the highest hourly volume was 71.5 MW [23]. FFR is priced with marginal pricing.

Table 5: FFR response time depending on different frequency deviations [23].

Grid frequency (Hz)	Response time (sec)
49.5	0.7
49.6	1.0
49.7	1.3

2.2.4.2 FCR-N Frequency Containment Reserve Normal (FCR-N) is a reserve that is activated when the frequency deviates from its nominal value 50.0 Hz [27]. It is linearly activated in the intervals 49.9 - 50.0 Hz and 50.0 - 50.1 Hz. It is a symmetrical reserve so it can provide both up and down regulation. If the frequency is outside the outer limits the reserve remains activated at 100 %. The degree of activation is presented in Equation 1 as a function of the frequency *f*. Negative activation is the same as down regulation. Positive activation means up regulation. Activation is on the interval [-1, 1] and is denoted A from this point on in this thesis. A positive activation value corresponds to adding electricity to the grid, and discharging the battery. A negative activation value corresponds to removing electricity from the grid, and charging the battery.

$$A_{FCR-N} = \begin{cases} 1 & \text{if f} \leq 49.9 \text{ Hz} \\ \frac{50.0-f}{0.1} & \text{if } 49.9 < \text{f} < 50.1 \text{ Hz} \\ -1 & \text{if f} \geq 50.1 \text{ Hz} \end{cases} \tag{1}$$

The demand for FCR-N is set to 231 MW for 2023 in Sweden [30]. Thus, it is in volume smaller than FCR-D up. The pricing mechanism for FCR-N is pay-as-bid.

For FCR-N, suppliers are remunerated for activation. I.e. whenever energy a supplier of FCR-N is active, it will be compensated for the amount of energy it supplies. The activation prices are the NordPool prices for up and down regulation. These prices are not necessarily the same for different electrical areas in Sweden.

Since the frequency almost never is precisely 50.0 Hz, resources supplying FCR-N are activated, to some degree, throughout the duration of the bid [31]. FCR-N requires one hour of durability.

2.2.4.3 FCR-D Frequency Containment Reserve Disturbance (FCR-D) is activated when the frequency goes below 49.9 or above 50.1 Hz. There are two different reserves of FCR-D: FCR-D up and FCR-D down. They provide up and down regulation respectively. FCR-D up is activated linearly in the interval 49.9 - 49.5 Hz and FCR-D down in the interval 50.1 - 50.5 Hz. [28] [32]. In Equations 2 and 3, the degree of activation is presented for FCR-D up and FCR-D down, as a function of the frequency *f*.

$$A_{FCR-Dup} = \begin{cases} \frac{49.9-f}{0.4} & \text{if } 49.5 \leq \text{f} < 49.9 \text{ Hz} \\ 1 & \text{if f} \leq 49.5 \text{ Hz} \\ 0 & \text{Otherwise} \end{cases} \tag{2}$$

$$A_{FCR-Ddown} = \begin{cases} \frac{50.1-f}{0.4} & \text{if } 50.1 \leq \text{f} < 50.5 \text{ Hz} \\ -1 & \text{if f} \geq 50.5 \text{ Hz} \\ 0 & \text{Otherwise} \end{cases} \tag{3}$$

The demanded volume of FCR is a set value, dependent on the largest producer and consumer in the Nordic grid. The biggest producer is currently Oskarshamn 3 (1450 MW) and the biggest possible consumers are currently the HVDC cables North Sea Link and Nordlink (1450 MW each). [22] Svenska Kraftnät is said to provide 38.45 % of the FCR needs in the Nordic grid. If the largest consumer or producer would change, for example during maintenance of Oskarshamn 3, so would the demand for FCR-D.

FCR-D down is a new services, introduced in the beginning of 2022. Its demanded volume has been increased by Svenska Kraftnät in a step wise manner. The rate of the increase is dependent on the amount of pre-qualified supply. The demand for Q2 2023 is 255 MW.

FCR-D is also priced with pay-as-bid. This will change however. No later than 1st February 2024, the FCR-D markets are to be priced with marginal pricing [33]. FCR-D bids are not reimbursed for activated bids.

Regarding durability, FCR-D has a requirement of 20 minutes. However, in the case that there is a disturbance left after 20 minutes, SvK has the right to continue to activate the resource [34]. Naturally, SvK cannot continue to activate the resource in the case that it has run out of energy during the first 20 minutes of activation.

2.2.4.4 aFRR Automatic Frequency Restoration Reserve (aFRR) is a service that aims to restore FCR. It has a slower requirement for activation, but a higher requirement with regards to durability. The demand for aFRR is based on the quality of the frequency in the grid. Between the Nordic TSOs the demand is between 300 and 400 MW, the Swedish quote being approximately 100 MW for both up and down regulation [30]. aFRR is a service that is activated automatically when the frequency deviates from its nominal value [35]. It is activated proportionally to the frequency deviation, and the bids are activated pro-rata between the bids any given hour. Resources are fully activated for up regulation at 49.9 Hz. The degree of activation is also dependent on how persistent the frequency deviation is. The thesis has found exact numerical expressions further explaining to what extent longer deviations requires different degrees activation.

Since this thesis includes modelling based upon battery activation, the thesis requires a precise activation value of aFRR. Thus, a simple model for aFRR activation is produced. The model builds off of the fact that aFRR is a "slow" frequency regulating service, and that it is meant to restore the frequency to its nominal value. Thus, the basis for the activation aFRR is based upon a moving average over the frequency the last minute (the last 6 data points since it is measured every 10 seconds). In other aspects, with regards to activation intervals, aFRR will act as FCR-N, though divided into two services for up and down regulation respectively. f_6^{MA} will represent the moving average grid frequency. A will be used to denote activation henceforth in the thesis.

$$f_6^{MA} = \frac{f_t + f_{t-1} + ... + f_{t-5}}{6} \tag{4}$$

$$A_{aFRRup} = \begin{cases} \frac{f_6^{MA}}{0.1} & \text{if } 49.9 \leq f_6^{MA} < 50.0 \text{ Hz} \\ 1 & \text{if } f_6^{MA} \leq 49.9 \text{ Hz} \\ 0 & \text{Otherwise} \end{cases} \tag{5}$$

$$A_{aFRRdwon} = \begin{cases} -\frac{f_6^{MA}}{0.1} & \text{if } 50.0 \leq f_6^{MA} < 50.1 \text{ Hz} \\ -1 & \text{if } f_6^{MA} \geq 50.1 \text{ Hz} \\ 0 & \text{Otherwise} \end{cases} \quad (6)$$

2.2.4.5 mFRR Manual Frequency Restoration Reserve (mFRR) is the only frequency regulating service that is not activated automatically. When the previously mentioned services do not supply the sufficient amount of regulation, Svenska Kraftnät can choose to manually activate mFRR [36]. There is no limit to the amount of mFRR that could be procured by SvK [30].

2.2.4.6 Bidding strategies A central task to any supplier of frequency regulating services is deciding upon what bidding strategy should be employed. In this thesis, bidding strategy will refer to when bids are placed, what size they are, and for what service. In reality it is currently the BRP that is in control of the bidding strategy.

There are constraints regarding how bids can be placed on the Swedish regulation market. One of the constraints that is central to any frequency regulating supplier with a limited energy resource (LER) resource, such as BESS, is the requirement of recovery. The recovery requirement stipulates that a supplier with a LER must plan so that the resource can recover after the bidding hour in time for the next hour that the supplier plans to provide frequency regulation again [34].

For example, let's look at the case of a 10 MW/10 MWh BESS. That battery charges/discharges fully in one hour. If the battery places 10 MW bids for FCR-D up regulation in two consecutive hours, it breaks SvK's rules. SvK argues that there's a risk that first hour depletes the battery to the point that it is incapable to provide regulation for the second hour. This is the reasoning behind the requirements of recovery from SvK. A supplier, with the battery proportions mentioned in this paragraph, would be allowed to bid every other hour for FCR-D, due to the need for recovery.

However, SvK launched a Pilot study for LER in 2022 [37]. The study allows participating resources to use more liberal bidding strategies. For example, regarding FCR-D, bidding for 24 consecutive hours is possible. The study will continue till the fall of 2023.

To help suppliers with their bidding strategies, there are aggregators that accumulates multiple resources and handles there power capacity collectively [38]. In Sweden examples of aggregators are Ntricity and Flower Tech. The sometimes conduct data-driven analysis to ensure that the owner receives the highest pay-out possible for any given bidding hour. This is achieved by changing what markets are bid into which hours.

2.2.5 Imbalance settlement

After the power hour, the imbalance for every BRP is computed. The BRP has to pay SvK for the imbalances that occurred in the area of its responsibility. Besides some fixed costs, the costs for not being in balance is 1150 Euros per MWh [15], [17].

2.3 Lithium-ion battery

A battery is tool to store energy electro-chemically. At a given signal the chemical energy can be transformed into an electric current in a circuit. Out of batteries available on the market, Lithium ion batteries (Li-ion batteries) are currently the most prominent due to their high energy density and low cost [39]. Li-ion batteries also have a quick response time for reaching full power. This gives them the opportunity to participate on all of the frequency regulating services in Sweden [13].

The capital costs of li-ion batteries has gone down considerably in the last decade [2], [10]. The decrease in price for Li-ion batteries has naturally resulted in lower costs for grid scale BESS as well. From 2015 to 2019 BESS saw a 72 % price drop [40]. Capital costs for BESS vary depending on the capacity of the battery as well as on the proportion between the capacity and the discharging power [41]. Batteries with higher power to capacity proportion are more expensive per kWh. The cost of a 2-hour battery, i.e. a battery that charges or discharges in 2 hours at full power, is estimated to cost 4.6 kSEK per kWh. A battery with even higher power to capacity proportion can cost between 5-8 kSEK [5] [10].

Other costs to consider for Li-ion batteries are ones for operation and management (O & M) of the battery. These costs are considered to be rather low in comparison with costs of investment. The literature suggest cost below 1 % of investment costs [7], [10].

Lastly, there are the costs of degradation. These are not direct costs for the battery; it will not result in negative cash flows during operating. However, costs of degradation are still important aspects to consider when computing profitability for BESS on frequency regulation markets [4], [10], [42]. Wear of the battery affects its life span and thus future revenue streams.

Degradation in batteries is defined as the maximum energy capacity of the battery reducing. Battery degradation can be measured by the state of health (SoH) of the battery, i.e. how much of the original maximum capacity currently remains. Batteries experience two types of degradation: calendar degradation and cycling degradation. Calendar degradation occurs naturally over time as the battery is idle [43]. Calendar aging is typically a small proportion of the total degradation of the battery.

Cycling degradation is dependent upon the depth of discharge (DoD) per cycle, and the numbers of cycles. DoD is a measurement of how much of the maximum energy capacity is discharged/charged for a cycle. Larger DoD result in faster degradation, smaller will make the BESS last through more cycles. How many cycles that are run together with the DoD per cycle are the two main factors for cycling degradation [44]. There are other factors as well contributing to battery degradation, such as operating temperature [43].

A battery is typically recognized to be at the end of its life when SoH is at 60 % [43]. Given a DoD of 100 %, the maximum number of cycles under the battery's life span can be estimated to be 3000. DoD of 80 % (staying between 10 - 90 % State of Charge (SoC)) would result in an estimated 5000 life cycles [45].

For li-ion BESS 15 years economic life spans can be used to project economic feasibility, given that the battery not has reached EoL already [10].

3 Method

3.1 Research purpose

The objective of this thesis is to investigate the economic feasibility of BESS on the Swedish frequency regulation market. Economic feasibility, or profitability, is highly dependent on cash flows for the years the investment is active. As investments in BESS have a life span of many years, the profitability will be dependent on the revenues and costs of the same number of years. And, since the profitability of an investment varies through its life span, predictions of trends are important to add information to a investment decision.

3.2 Research design

The method approach chosen for this thesis is a mixed method approach. Such a method combines quantitative and qualitative data for the analysis [46]. Mixed method approach can be useful when neither quantitative nor qualitative data in and of itself is predicted to sufficiently describe and answer the research problem. In this thesis, the research problem was found to be of said character. As the frequency regulation market is a complex market, and a market going through rapid changes, it was noted that simply analyzing quantitative data not would be enough to properly answer the research questions. Therefore, both historical data (quantitative) and an interview study (qualitative) is used as data in this thesis. The two data types are used together in what is called a Convergent Parallel Design (sometimes referred to as Concurrent Parallel Design) [47]. In such a design, data collection and analysis are initially completed separately. Then, in a final step, the two parts are integrated, discussion presented, and conclusions made. The outline of the methodology is shown in Figure 5.

A Convergent Parallel Design is practical in the sense that it highlights either divergence or convergence between the result of the two methods. Additionally, the qualitative data can be used to better understand of the results from the quantitative data, or to draw further conclusions from them, and vice versa. To give further background to the decision of choosing the mixed method approach, the opportunities, and limitations, of each data types is discussed.

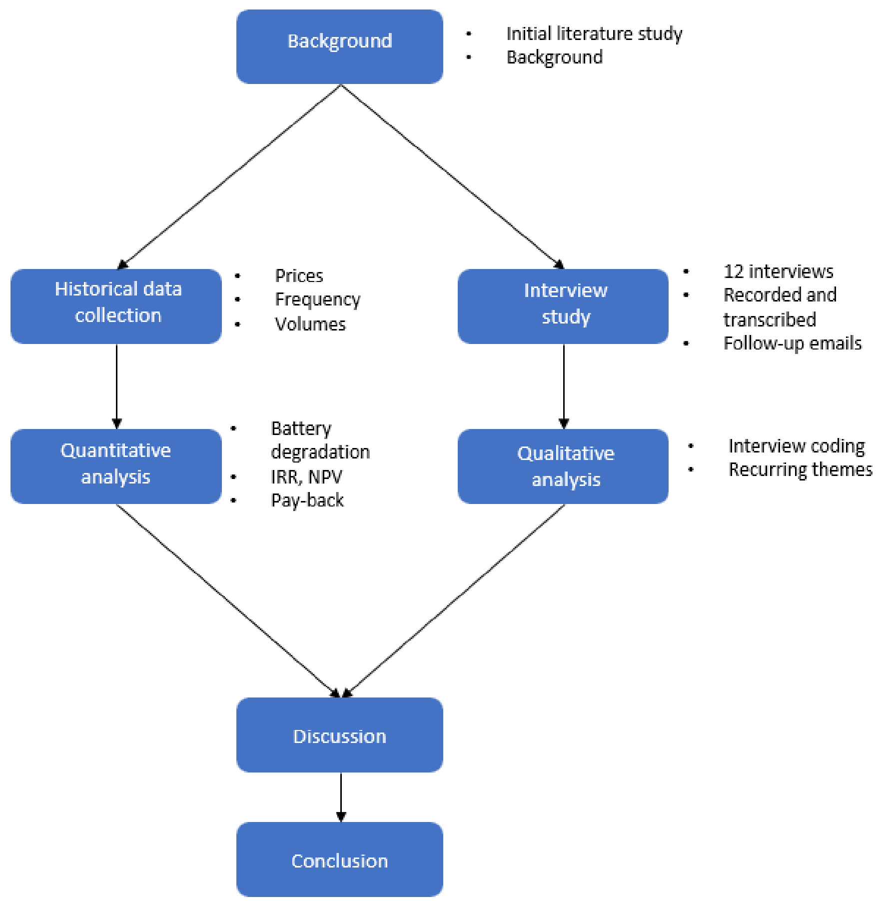


Figure 5: The Convergent Parallel Design used in the thesis.

The historical, quantitative, data provides tangible and important information of what the economic feasibility of BESS has been, or currently is. In this thesis the quantitative data includes price data as well as grid frequency data. The substantial and exact properties of the data can provide key figures describing economical feasibility. Useful, for example, when deciding upon an investment in BESS. However, the data will lack indications of what can be expected in terms of future profitability. Historical data is, as can be heard in the name, restricted to information of what has already happened. Information about the future is not given by historical data. Extrapolation, or predicting future data based off of historic data sets, is something that could have been used to compute future profitability in this thesis. However, such tools do intrinsically include uncertainty. They would be based on a set of assumptions, e.g. regarding price levels. Furthermore, the uncertainty of such predictions will increase as they stretch over greater distances of time - guessing the price tomorrow is easier than the price in 10 years. For these reasons, extrapolation was not used in the thesis.

An interview study was chosen to compliment the historical data. The study aims to provide a perspective on the economic and technical feasibility of BESS. By interviewing experts on the subject, knowledge and opinions will be gathered. The interview study was an explorative study. Semi-structured interviews were used to gather new insights on the topic. Through this additional data, further conclusions regarding the viability of BESS can be drawn. One of the reasons that an interview study was found to be a logical part of the methodology was due to the novelty of the business case of BESS for frequency regulation. It is only in the last few years that BESS has become a possible supplier in these market. For that reason there is a lack of research on the subject. An interview study can aim to gather information from different categories of interview subject, information that not has yet to be published by researchers.

Together, the two data types and the two methods, aim to answer the research questions. Below follows a more in-depth description of how to the to methods were carried out.

3.3 Quantitative analysis

The quantitative analysis was conducted by producing the profitability for six out of seven frequency regulating services. Unfortunately, data for mFRR was unavailable and therefore excluded from the quantitative analysis. Thus, the six services FFR, FCR-D up and down, FCR-N, aFRR up and down, are analyzed in the quantitative part of this thesis.

In the last part of this Section a scheme of the Python program is presented.

The length and time for the data sets in the quantitative analysis was the entire year of 2022. There were a number of reasons for not using data before 2022, the first being that FCR-D down was implemented at the start of 2022. Also, other data sets, such as up/down activation remuneration, were not available either for the entirety of year 2021. Furthermore, completing the analysis for a year, and a year exactly, makes the result more comprehensible. It is for example common to describe revenue in yearly figures.

Furthermore, all data, with the exception of the grid frequency, are in hourly measured time series. The grid frequency was initially downloaded at 10 Hz, resulting in 864000 data points per day. To reduce computational power needs, the grid frequency was re-sampled with 1/10 Hz, resulting in 8640 samples per day. Provided the re-sampling, the grid frequency used in the modelling is updated every 10 seconds.

As already has been mentioned, there are two types of quantitative data sets used for this part of the analysis. They are prices and grid frequency.

The price category include three types of data sets: prices for all frequency regulation services, spot prices, and prices for up and down activation remuneration. Some prices are specific to each electrical area in Sweden. These are spot prices, aFRR up/down prices, and up/down remuneration prices. All these data sets were gathered for each electric area specifically, to provide a result that for all areas in Sweden.

Frequency regulation prices were found through SvK's data web page, Mimer [1]. FFR prices, however, were downloaded directly through SvK [23]. Prices were presented in EUR/MW, and were translated to SEK prices through a conversion data set also provided by Mimer, appropriately enough. For the FCR prices, Mimer only published average, volume-weighted, prices. That means that there are both cheaper and more expensive bids accepted for every given hour. The price for the highest bid is not known, and thus the highest possible profit for a given hour is not known.

Spot prices were provided by NordPool [48]. NordPool does not normally provide market information for free, but does so for this study due to a student cooperation initiative.

Prices for up and down activation remuneration was found through eSett, a company providing imbalance settlements for the Nordic TSOs [49]. These prices were also area-specific.

Finally, the grid frequency was provided by the Finnish TSO, Fingrid [31]. With regards to the frequency data, an import aspect to notice was that the data sets were not all gathered in the same time zones. Specifically, the grid frequency data was measured, and indexed, in GMT+3, while the rest were indexed in GMT+2. Consequently, the data sets were shifted in order to be synchronized. In detail, the all price data sets were shifted forward to match the grid frequency.

To continue the data analysis, the data quality was assessed. The data for the frequency regulating services and the activation remuneration data was found to be good: there were no missing data points or any irregularities. For the spot price data certain data points were NaNs. These data points were replaced through linear interpolation - they were set to be the average of the previous and the next spot price. For the grid frequency data more effort had to be made. It was found that five days during 2022 had significant data missing. For some reason, the frequency measurements stopped for several hours for each of the days. To avoid having to recreate the frequency time series for those days, and being exposed to risks of flawed time series modelling, it was chosen that the previous day was to be used again. Thus, the grid frequency of five days during 2022 are used more than once. Over the whole year, however, this should affect the result minimally.

3.3.1 Modelling

The modelling was conducted in Python. For the modelling, the economic viability of BESS on the Swedish market in 2022 was investigated. After presenting the background to the modelling, a scheme of the Python program will be presented.

The results are based upon a set assumptions and parameter values. Below are the assumptions used in the modelling. After presenting them they will be discussed.

- BESS is allowed to bid on every second hour. The following hour is set aside for recovery
- BESS bids on a single service for a given hour. It does not split its capacity
- BESS bids with all of its capacity
- Price and frequency data is known
- BESS is a price taker, its presence do not affect prices
- For services with pay-as-bid, the BESS takes the average, volume-weighted, price
- mFRR is not included in the model due to unavailability of information
- Activation of FFR is not considered due to short activation times
- Activation of FCR is done according to Equations 1, 2 and 3
- Activation of aFRR is done according to Equations 4, 5, and 6

- BESS experiences no calendar aging
- Cycling aging does not affect the pre-qualified capacity
- The BESS investment has a maximum life span of 15 years

Before continuing with the modelling, some words about the assumptions. To be allowed to bid every second hour is an assumption based on SvK's requirements of recovery. The assumption that the battery only bids on a single service for every hour is an assumption made to avoid unreasonable demand for computational power. Technically speaking, the battery would be able to perform frequency regulation with multiple services during a single hour. Moreover, to ensure that the modelling is kept at a reasonable level, computationally, it was decided that the BESS will bid on a with all of its capacity on a single service. The assumption that the prices of services with pay-as-bid is simply taken by the BESS might be questioned: it is difficult in reality to place the bid there at every hour. Here it is reiterated that services with pay-as-bid will move over to marginal prices during the start of 2024. The fact that this transition is forthcoming supports the assumption. Lastly, a maximum life span of 15 years is stipulated for the BESS investment. Such a life span has been

Next, the variables used in the model are presented. These are the four input data set categories presented earlier in the Section. Prices are indexed with electrical area a, frequency regulation service s as well as hour h. Spot prices are also indexed with electrical area and hour. Grid frequency regulation data is simply indexed with the 10 second interval t.

Table 6: Variables used in the model

Variable	**Description**	**[Unit]**
$P^{s,a}_{bid,h}$	Availability remuneration for service s hour h and electrical area a	[SEK/MW]
$P^{s,a}_{act,h}$	Activation remuneration for service s hour h and electrical area a	[SEK/MWh]
$C^{a}_{spot,h}$	Spot price for s hour h and electrical area a	[SEK/MWh]
f_t	Grid frequency in 10 second interval t	[Hz]

To give the reader some further insight into what the input data looks like, examples are presented below. In Figure 6 hourly availability prices for FCR-D up and down as well as FCR-N are presented. Moreover, in Figure 7, remunerations for up and down regulation is presented. The reader is reminded that these remunerations are affecting the revenues for aFRR and FCR-N. Lastly, in Figure 8, prices for FFR are presented. Note that prices for FFR are zero for parts of 2022; FFR is only procured during certain months of the year when the inertia in the grid is low. Lastly, in Table 7, average prices over the year are presented to give further insight into the input.

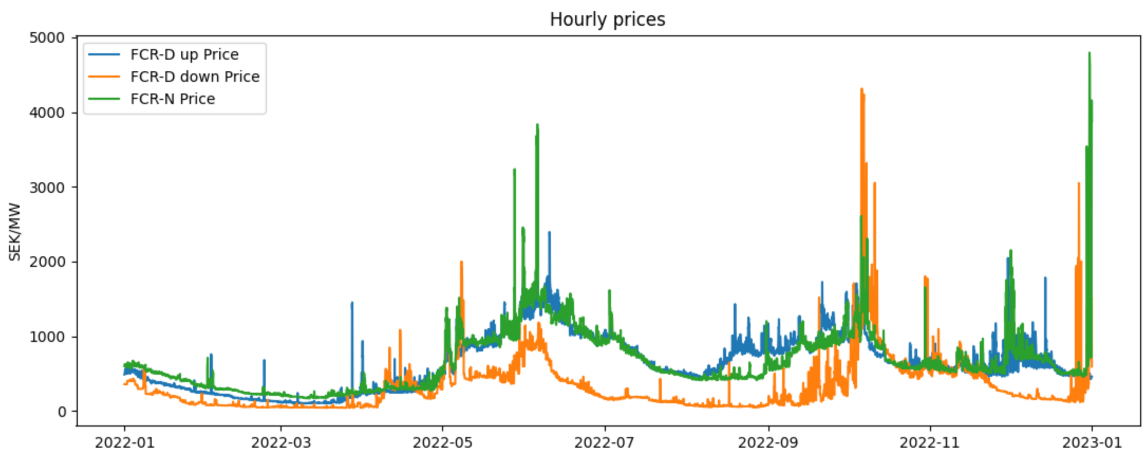


Figure 6: Hourly availability prices for FCR-D up and down and FCR-N during 2022. (SEK/MW)

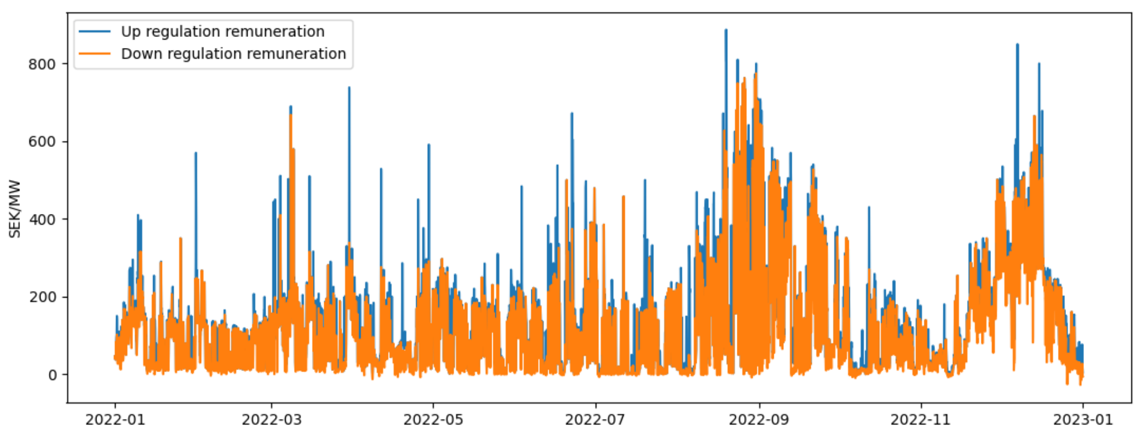


Figure 7: Hourly up and down regulation remuneration during 2022. (SEK/MW)

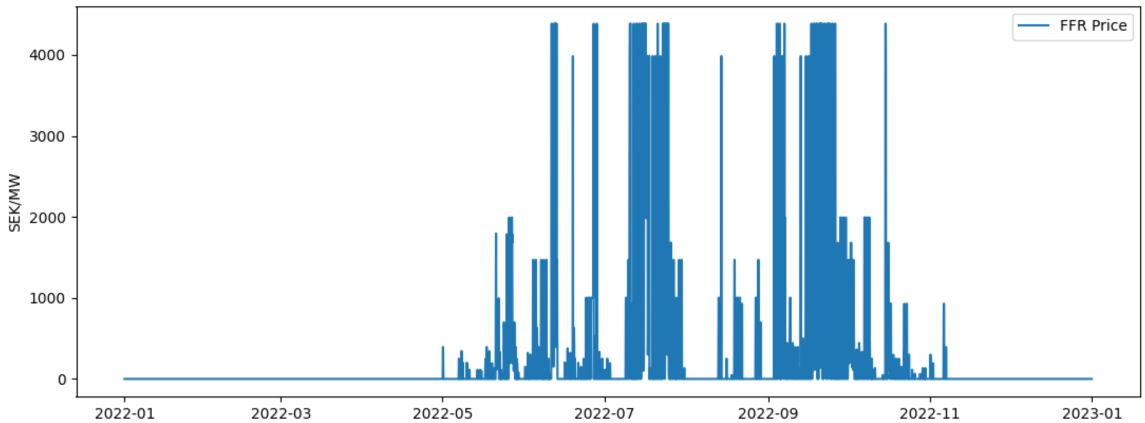


Figure 8: Hourly FFR prices during 2022. (SEK/MW)

FFR	FCR-N	FCR-D up	FCR-D down	aFRR up	aFRR down
213.9	659.1	642.2	326.5	658.0	481.9

Table 7: Average hourly availability prices in 2022. (SEK/MW)

Finally, the parameters are presented. They are based on the results found in Section 2. Size of the battery, i.e. capacity and charging/discharging power, was chosen through conversations with Eolus Vind.

Table 8: Parameter values used in the model

BESS parameters	**Description**	**Value [Unit]**
E_{BESS}^{max}	BESS maximum energy capacity	10 [MWh]
P_{BESS}^{max}	BESS maximum charging/discharging power	10 [MW]
C_{CAPEX}	Capital costs	$6.5 \cdot 10^7$ [SEK]
C_{OPEX}	Operational costs	$6.5 \cdot 10^5$ [SEK/year]
N_{max}	BESS life cycles	3000 [-]
C_{cycle}	BESS degradation cost	$2.1 \cdot 10^4$ [SEK/cycle]
r_{wacc}	Weighted average cost of capital	8 [%]

Table 9: Data parameters used in the model

Data parameters	**Value [Unit]**
Grid frequency resolution	0.1 $[Hz]$
Availability remuneration resolution	1 $[hour^{-1}]$
Activation remuneration resolution	1 $[hour^{-1}]$
Spot price resolution	1 $[hour^{-1}]$

As the variables and parameters has been presented, the model employed in this thesis will be laid out. One important aspect in the quantitative analysis is the cycling degradation of the battery. To calculate to what extent different types of services affect the SoH of the battery, the energy throuhghput for a given bidding hour needs to be produced. Energy throughput can be found by checking the degree of activation for every data point of grid frequency for that hour. Under the assumption that the frequency is constant in this 10 second interval, the energy throughput can be computed. Given the grid frequency resolution of 0.1 Hz the model has 360 frequency measurements per hour. The energy throughput equation used in the model is presented in Equation 7. Since activation can be both positive and negative, absolute values were introduced. Energy throughput is something absolute.

$$E_h^s = \sum_{t=1}^{360} \frac{|A_t^s \cdot P_{BESS}^{max}|}{360} \tag{7}$$

Moreover, to compute how many cycles were ran for any given hour, another equation was adopted. In the thesis a cycle refers to a charge/discharge cycle with a DoD of 100 %, i.e. fully discharging and then charging the battery. Hours which did not complete 100 % DoD cycles were converted to a percentage of a 100 % DoD cycle. For example, if the battery performs up regulation a given hour, discharging the battery to 70 %, this corresponds to 0.3 full cycles. The choice of 100 % DoD cycles is connected to the 3000 life cycles, shown in Table 8. Thus, the number of cycles can be computed as shown in Equation 8.

One should keep in mind that even though discharging the battery does not result in a full cycle in and of itself, the supplier needs to recharge the battery in order for it to be ready for the next bidding hour. In this manner the DoD for a specific hour will correspond to the same number of cycles. If the battery goes from 100 % SoC to 50 % during an hour, that is a half cycle.

There is however one exception to this: FCR-N. Since FCR-N is a symmetrical service, there is a possibility that FCR-N both discharges and charges the battery during a single hour. If this is the case, there will be less need to restore the SoC during the hour of recovery. To include this in the model, a separate cycling equation was produced for FCR-N. This is shown in Equation 9. The reader should think of the equation in the following way. There is a possibility that FCR-N bring both up and down regulation for a single hour. Since this possibility always is present, the numbers of cycles run during the delivery hour is the energy throughput divided with the capacity and the factor 2. The 2 appears naturally here, since a cycle goes two ways. However, depending on if the SoC has drifted during the delivery hour, it might be needed to recover the SoC to the next bidding hour. Thus, how much the SoC has drifted, in Equation 9 simply referred to as DoD (though it can be positive as well), divided with two should be added to completely encompass the cycling of FCR-N.

$$N_h^s = \frac{E_h^s}{E_{BESS}^{max}} = DoD_h^s \tag{8}$$

$$N_h^{FCR-N} = \frac{E_h^s}{2 \cdot E_{BESS}^{max}} + \frac{DoD_h^{FCR-N}}{2} \tag{9}$$

Further, some context can be added to the cycling. Given the parameters chosen in Table 8, the maximum numbers of cycles completed in a single hour is exactly 1. This follows from the fact that there is a 1:1 proportion between energy and power, in the hour perspective. And, in this model, there are 4380 hours on which the BESS will participate in bidding. Again, this is due to the assumption that the battery only is allowed to bid on every second hour, for recovery reasons. And, 4380 comes from the total number of hours a year, 8760, divided by 2.

For any given hour, h the revenue for a single bid on frequency regulating service s can be computed as shown in Equation 10. In the case that service s performs down regulation the cost of the spot price will change sign. If the battery performs down regulation it charges the battery, something the thesis considers an income. The cost, or revenue, received from energy throughput is decided by the prices *next hour*, since the recovery to the suitable Soc is done the hour after delivery. For example, when performing up regulation, if the hour completely depletes the battery then the next hour the battery will have to recharge with the spot prices that are present. Thus, $h + 1$ is the hour that energy costs or revenues are based on.

$$R_h^{s,a} = P_{bid,h}^{s,a} + E_h^s(P_{act,h}^{s,a} - C_{spot,h+1}^a) \tag{10}$$

There is a reason that battery degradation not is included in Equation 10. Costs of battery degradation are not costs that result in negative cash flows. Instead, the degradation affects the life span of the battery. In turn, life span sets the limit for how long the investment will see revenues. The model used in this thesis will investigate the economic feasibility of BESS based on three different key performance indicators: IRR (internal rate of return), Pay-back time and NPV (net present value). NPV is the sum of all future cash flows discounted with the interest rate. In the case that there is a residual value, which will be discussed below, the residual value will be accounted for as a positive cash flow at the end of the investment's life span. IRR is the interest rate at which the NPV is exactly 0; it says how high the interest rate can be in order for the investment to remain profitable.

IRR and NPV depend heavily on the economic life span of the investment. As can be for deducted from previously presented equations and Section 2, the choice of frequency regulation service affect the cycling and thus the life span of the battery. To be able to compute the KPIs used to determine economic feasibility, the life span of the BESS investment is presented in Equation 11. Again, in accordance with the literature, 15 years was chosen as the maximum life span of the BESS. When producing the IRR and NPV for the model, 2022 year's data was used for all of the economic life span. In other words, the IRR and NPV will present the economical feasibility of the investment, projecting 2022's data forward for its entire life span.

$$T_{life} = max(15, \frac{N_{max}}{N_{2022}}) \tag{11}$$

Additionally, if the BESS still had not run the 3000 cycles after 15 years, a residual value was given to the BESS investment according to Equation 12. SoH was projected by assuming the BESS would continue to cycle at the same rate as was seen in 2022. By projecting how many cycles were ran throughout the 15 years, the SoH was computed according to Equation 13.

N_{15} denotes the projected number of cycles during the 15 years. In conclusion, the investment in BESS will receive a residual value proportionate to the SoH of the battery. The maximum residual value it could receive is 15 % of the original investment. It should be mentioned that the residual value should affect the NPV and IRR rather little, considering it is a cash flow that occurs after 15 years. Naturally, if the battery has been degraded fully before the 15 years, no residual value is produced.

$$P_{res.val.} = 0.15 \cdot SoH \cdot C_{CAPEX} \tag{12}$$

$$SoH = \frac{N_{15}}{N_{max}} \tag{13}$$

Finally, all the tools needed compute the profitability for the frequency regulating services have been laid forward. In Figure 9 the Python program is summarized. Inside the hourly box is the function that is produced hourly. Considering the assumption that the battery only bids every other hour it is reiterated that 4380 hours were used in 2022. For every hour the earnings of each bid were produced, represented in the scheme with \$. When the result from all hours is completed they are added together to find yearly earnings, represented in the scheme by Σ.

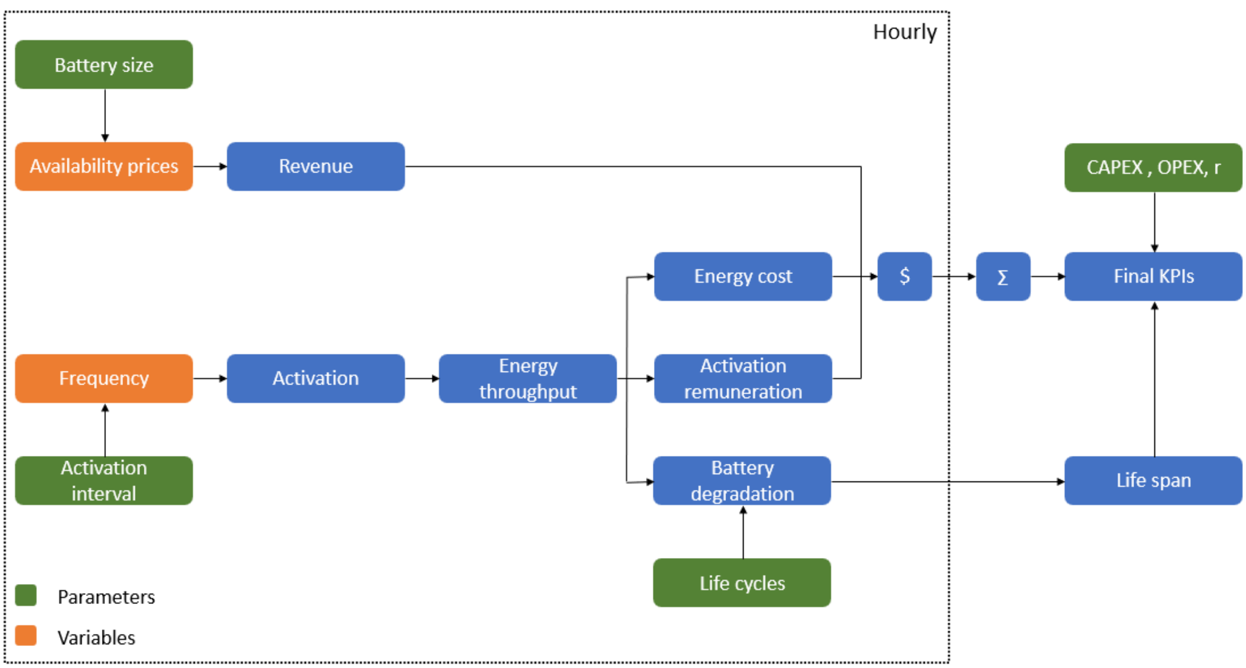


Figure 9: Scheme for the Python model.

Ultimately, the economic case for BESS on the Swedish frequency regulation market was performed in two different aspects. Firstly, the profitability of the frequency regulating services were computed separately for each service. This was considered a logical first modelling task.

One of the reasons behind investigating the services individually becomes evident when considering the aspect of pre-qualification. Since pre-qualification is different in-between different frequency regulating services, it is not certain that an owner of a BESS will go through with all of the separate qualifications. Thus, it is useful to know what the profitability of a specific service is, on its own. To investigate the entire Swedish market, computation all four electrical areas were conducted.

Secondly, the profitability was produced through the application of a simple optimizing algorithm. The algorithm followed a simple rule: for each hour choose the highest paying frequency regulating service according to Equation 14, where S is the full set of frequency regulating services (excluding mFRR). Unlike in the previous model, battery degradation is now considered. Before delving further into the algorithm, the degradation cost parameter in Table 8 has to be explained. This value is found by dividing the investment (capital) cost with the number of life cycles, in this manner resulting in costs per cycle.

Including degradation is reasonable when comparing multiple, competing, service choices. While the degradation does not result in an immediate negative cash flow, it will affect the life span of the battery. However, when choices regarding what services is optimal for all hours, the KPIs are produced without the degradation costs. To summarize: degradation costs were only used in the model when deciding upon the most suitable service for a single hour.

This case, too, was conducted of all four different electrical areas, a. The optimized algorithm will provide the optimal bidding strategy for every single hour. In reality it is a hard task to predict prices beforehand and to successfully predict the most economically advantageous choice. Still, the optimized algorithm aims to provide the thesis with a distribution among the service. How many hours a year is a given the service the most profitable to bid on?

$$s_h^{opt,a} = \arg\max_{s \in S}(R_h^{s,a} - N_h^s \cdot C_{cycle}) \tag{14}$$

For both cases, economic feasibility is presented in the form of IRR, Pay-back time, and NPV. To provide more depth to the result of the data analysis, a sensitivity analysis was conducted. The sensitivity analysis was performed both for interest rate and price level. Interest rate, in the thesis referred to as r_{wacc}, is one of the more uncertain parameters. It depends on the current state of the economy, as well as on the risk identified with the investment, sufficient reasons to include it in the sensitivity analysis. When varying the interest rate, only NPV is affected. Additionally, sensitivity analysis for the price level was completed. The price level on the market is something that has been discussed already in the thesis. Average prices doubled from 2021 to 2022, highly affecting profitability. Price level, denoted L, was included as can be seen in Equation 15.

$$R_h^{s,a} = L(P_{bid,h}^{s,a} + E_h^s(P_{act,h}^{s,a} - C_{spot,h}^a)) \tag{15}$$

As can be seen in the equation, also spot prices were included in the price levels. Price level was set to affect availability prices, activation remuneration as well as spot prices.

3.4 Qualitative data

The qualitative data in the Convergent Parallel Design is an interview study. The purpose of the study is to give insights to the economic feasibility and the technical viability of an investment in BESS in the Swedish grid. Whereas the quantitative part is limited with regards to insights of future trends, the interview study aims to fill that gap. In addition to giving information of what can be expected of future profitability and market development, the interview study should also provide further understanding of the results from the quantitative phase.

The interview study followed a semi-structured manner. The same set of open questions, from an interview guide, were posed to all interview objects. Since the interview study was conducted to answer the second research question, the study was of an exploratory nature. The purpose of it was to find what changes are expected to occur on the frequency markets. Depending on the expertise of the interview object, the interviews could have a varying set of topics. The basis for all questions asked in the interview study is based on information gathered in the background. Due to a good understanding of topics central to the research problem, additional questions could be posed continuously through the interview.

A majority of the interviews were conducted online, through video or audio calls. Two interview were done in person. This came naturally, as most interview candidates did not have offices where the thesis was written. The interviews lasted between 25 - 65 minutes, depending on the availability of the interviewee as well as the amount of topics covered.

3.4.1 Interviewee selection

To perform a rigorous and objective interview study, the way in which that interviewees are chosen is important. An initial part of the interview study was to identify categories of organisations interesting to the research topic. Identifying the different interviewee categories was completed based of information gathered in Section 2. The categories found are presented in Table 10.

Table 10: Identified categories for the interview study.

Parties
TSO
BRP
BSP
DSO
Aggregator
Battery producer
Interest groups
Research institutions

To provide a reliable result, the interview study aimed to gather interview candidates from many of the identified categories, preferably from all. Furthermore, a selection of multiple candidates from a single category could further enhance the reliability of the result of the study.

After the central categories had been identified, a search for appropriate interview candidates was initiated. When a possible interview candidate was found, contact was initiated, either through mail or through LinkedIn. In some cases, contact with possible interviewees was initiated with through recommendations from the supervisors.

As contacts were gathered, and interviews conducted, it was often the case that new potential interviewees was found through the contact of the previous interviewee. This sort of interviewee selection is called *snowball sampling* [50]. It can be a useful tool if the central interviewees not are easy to identify before the interview study commences. In this study, new interviewees were found through snowball sampling in two ways. At times, interviewees were simply posed the question: do they know candidates within category X that could be potential interviewees in the thesis? Other times it occurred that interviewees themselves referred to a new, potential, interviewee. This could be the case if the interviewee was unable to provide information over topics discussed during the interview.

Naturally, there were limitations to the interview study. Firstly, the time limitations of the thesis put boundaries to the study. Interviews are time consuming. Finding an appropriate candidate, preparing the interview, conducting the interview, and finally summarizing the interview is extensive labour. Secondly, the interview candidate identified was not consistently available. Inability to get in contact was a obstacle for the study; not all candidates had public email addresses. In other cases contact was established, but the interview candidate was unable to set a side time in time for the thesis to finish.

On the basis laid out above, the interview study was conducted.

4 Results

4.1 Quantitative data

In the quantitative data of the thesis, the prices and frequencies, together with the set of parameters presented in Table 8 and Table 9 were used to answer research question 1. and 2. The result is presented below.

Firstly, the frequency regulating services were assessed individually. Computations were completed for all four electrical areas in Sweden. The result are found in Table 11.

Table 11: Summary of outcome for BESS applied to frequency regulation services individually, for each electrical area respectively, during 2022. IRR is in %. All monetary numbers are in kSEK.

Service	**2022 earnings**	**Cycles**	**Life span**	**IRR (%)**	**Pay-back**	**NPV**
SE1						
FFR	9228	0.0	15	10.2	7.6	9391
FCR-N	28822	1045.3	3	14.4	2.3	7603
FCR-D up	28123	1.8	15	42.0	2.4	171114
FCR-D down	14233	2.4	15	19.5	4.8	52222
aFRR up	32184	670.0	4	33.0	2.1	39445
aFRR down	22598	708.4	4	13.2	3.0	7695
SE2						
FFR	9228	0.0	15	10.2	7.6	9391
FCR-N	28824	1045.3	3	14.4	2.3	7607
FCR-D up	28122	1.8	15	42.0	2.4	171109
FCR-D down	14233	2.4	15	19.5	4.8	52224
aFRR up	32427	670.0	4	33.5	2.0	40249
aFRR down	22673	708.4	4	13.4	3.0	7942
SE3						
FFR	9228	0.0	15	10.2	7.6	9391
FCR-N	28794	1045.3	3	14.3	2.3	7530
FCR-D up	28111	1.8	15	42.0	2.4	171016
FCR-D down	14251	2.4	15	19.5	4.8	52379
aFRR up	30661	670.0	4	30.0	2.2	34401
aFRR down	20306	708.4	4	8.1	3.3	102
SE4						
FFR	9228	0.0	15	10.2	7.6	9391
FCR-N	28768	1045.3	3	14.3	2.3	7463
FCR-D up	28106	1.8	15	42.0	2.4	170972
FCR-D down	14261	2.4	15	19.5	4.8	52458
aFRR up	30803	670.0	4	30.3	2.2	34870
aFRR down	20131	708.4	4	7.7	3.3	-477

In Table 11 the frequency regulating services were investigated individually, and their profitability over the year 2022 compared.

Secondly, the result for the optimized study is presented. The results for the optimized version of the bidding strategy is presented in Table 12.

Table 12: Summary of outcome for BESS applied to frequency regulation services optimally, for each electrical area respectively, during 2022. All monetary numbers are in kSEK.

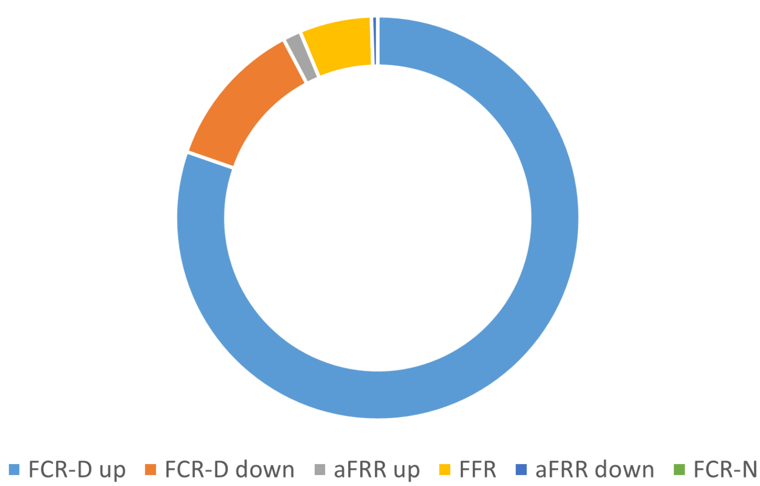
Area	2022 earnings	Cycles	Life span	IRR (%)	Pay-back	NPV
SE1	40041	5.8	15	60.6	1.7	273108
SE2	40038	5.8	15	60.5	1.7	273079
SE3	40017	5.7	15	60.5	1.7	272898
SE4	40015	5.7	15	60.5	1.7	272886

For the optimized version of the model, it is also interesting to see the distribution between the services included.

Table 13: BESS-optimal share of bids to each frequency regulation service, for each electrical area respectively, during 2022.

Area	FFR	FCR-N	FCR-D up	FCR-D down	aFRR up	aFRR down
SE1	0.058	0.0	0.802	0.119	0.016	0.005
SE2	0.058	0.0	0.802	0.119	0.015	0.005
SE3	0.058	0.0	0.803	0.12	0.014	0.005
SE4	0.058	0.0	0.803	0.12	0.014	0.005

Figure 10: Chart of BESS-optimal shares for SE3 during 2022.



4.1.1 Sensitivity analysis

To provide more insight into the result in of the data analysis, a sensitivity analysis was conducted. With a sensitivity analysis the economic feasibility will be evaluated by varying the variables or parameters of the model. For this thesis, the interest rate, r_{wacc} and the general price level was the parameters investigated in the sensitivity analysis.

Table 14: NPV for individual and optimized model, varying r_{wacc}. All monetary numbers are in kSEK. Data for electrical area SE3 is used.

r_{wacc}	**4 %**	**6 %**	**10 %**	**12 %**
FFR	33369	20005	804	-6250
FCR-N	13102	10229	4990	2597
FCR-D up	243306	203395	144428	122359
FCR-D down	89196	68778	39006	27959
aFRR up	43938	38992	30132	26155
aFRR down	6348	3109	-2694	-5299
Optimized	375613	318987	234968	203436

Table 15: IRR, Pay-back and NPV for individual and optimized model, varying the price level. Data for electrical area SE3 is used.

	Life span	**IRR (%)**	**Pay-back**	**NPV (kSEK)**
Price level = 0.4				
FFR	15	-1.3	21.4	-38003
FCR-N	3	-27.9	6.0	-36993
FCR-D up	15	14.1	6.1	26644
FCR-D down	15	2.9	12.9	-20812
aFRR up	4	-12.2	5.6	-26531
aFRR down	4	-25.2	8.7	-40251
Optimized	15	22.5	4.2	67386
Price level = 0.6				
FFR	15	2.5	13.3	-22205
FCR-N	3	-12.2	3.9	-22152
FCR-D up	15	24.0	4.0	74768
FCR-D down	15	8.9	8.2	3585
aFRR up	4	3.6	3.7	-6220
aFRR down	4	-12.4	5.6	-26800
Optimized	15	35.6	2.8	135890
Price level = 0.8				
FFR	15	6.4	9.7	-6407
FCR-N	3	1.6	2.9	-7311
FCR-D up	15	33.1	3.0	122892
FCR-D down	15	14.4	6.0	27982
aFRR up	4	17.4	2.7	14091
aFRR down	4	-1.6	4.2	-13349
Optimized	15	48.1	2.1	204394
Price level = 1.2				
FFR	15	13.8	6.2	25189
FCR-N	3	26.2	1.9	22371
FCR-D up	15	50.8	2.0	219140
FCR-D down	15	24.4	4.0	76776
aFRR up	4	41.9	1.8	54712
aFRR down	4	17.0	2.7	13553
Optimized	15	72.9	1.4	341402

4.2 Interview study

Firstly, the conducted interviews will be presented in Table 16.

Table 16: Interviews conducted in the interview study, presented chronologically.

Party	Organisation	Person	Role
BRP	Modity	Pernilla Ademar	Head of Business Develop.
TSO	SvK	Marko Miletic	Analyst, Balancing Markets
Aggregator / BSP	Ntricity	Lars Skoglund	CEO
DSO / BSP	Ellevio	Carl Liljewall	Head. New Business Develop.
DSO / BSP	Öresundskraft	Sara Norman	Business Innovator Energy Storage
TSO	SvK	Maja Isaksson Charlotta Ahlfors Filippa Pyk	Analyst, Balancing Markets Power System Analyst Invest., Balancing Markets
Interest org.	Energiföretagen	Carl Berglöf	Sr. Advisor Nuclear Power
Interest org.	PowerCircle	Anna Wolf	Vice President
Aggregator / BSP	CheckWatt	Ulf Wingstedt	Business Developer
DSO / BSP	Eolus Vind	Fredrik Liljehov	Business Developer
DSO / BSP	Vattenfall Eldist.	Arne Berlin	Business Strategist
DSO / BSP	Varberg Energi	Jens Nordberg	Head of Energy Trading

To mediate the results from the interview study, the study will be presented by a set of themes or topics. These were recurring themes of the study. For some themes, opinions on the subject was shared between multiple interviewees. Other times contradictory opinions were gathered. To provide an overview of the result it is initially presented as a list of themes below. Subsequently the themes are discussed in detail.

The themes found in the interview study are:

- FCR-D and FFR suitable services for BESS
- FCR-D up and FCR-D down combination is highly profitable
- Currently short pay-back time due to high prices
- Increase in BESS supply on the Swedish grid
- Penetration of V2G
- New FCR requirements enables more liberal bidding strategies for BESS
- Questions regarding the hydro power's possibility to participate with new technical FCR requirements
- 15 min bidding periods widens the scope for BESS
- New European markets for aFRR and mFRR
- Future demand for frequency regulation services
- Potentially new frequency regulating services

- BSP/BRP separation simplifies operation for suppliers
- Lack of experience concerning BESS projects
- Importance of flexibility of BESS operationality
- Future price levels

Throughout the interview study it became apparent that there is a wide consensus regarding what services currently are suitable for BESS. These are FCR-D up/down and FFR. There are two primary reasons for this. Firstly, the services requires quick response times, something that is met by the capabilities of BESS. This capability is something that makes BESS stand out among the competition. Secondly, these services result in little cycling of the battery. Cycling batteries carefully is important when caring for the life span of the battery. The interview also found that, even though FCR-D and FFR are the most attractive frequency regulating services, technically, BESS is compatible with all frequency regulation services.

Moreover, it is apparent from the study that a highly profitable bidding strategies is found by placing bids for FCR-D up and FCR-D down simultaneously during one hour. Ulf Wingstedt (CheckWatt) points out that the SoC can be kept at around 60 % in order to place two bids simultaneously. Marko Miletic (SvK) confirms that is possible to employ such a bidding strategy. The idea behind the strategy is quite simple. If the frequency falls out of the interval 49.9 - 50.1 Hz it will activate either FCR-D up or FCR-D down, never both. And as long as the 20 min durability requirement is met, it is thus allowed for two simultaneous bids in this manner. For example with a 10 MW/10 MWh BESS, two 10 MW bids for hour h could be placed on FCR-D up and FCR-D down respectively, given that the SoC is kept around 50 %. The study gathered no information about other possible bidding combinations, with full capacity for both bids.

Furthermore, the study concludes that BESS currently are profitable on the frequency regulation market, when supplying FCR-D and FFR support. Interviewees report of pay-back times as low as one year with prices seen in 2022 and during the start of 2023. Arne Berlin (Vattenfall Eldistribution) points out that the war in Ukraine has highly affected the energy market as a whole with high electricity prices and high volatility as a result. He sees this as something that has resulted in high prices for the frequency regulating services. Lars Skoglund (Ntricity) emphasizes the fact that it is the hydro power in Sweden that, to a large extent, sets the prices on the frequency regulation markets. He points out that spot prices in SE1 and SE2, where the hydro production lies, is an important aspect for the price of frequency regulation in Sweden. If spot prices are high in said areas, the hydro power will see the opportunity of selling their energy on the day-ahead market instead, leading to a price increase on the regulation market.

Moreover, the study found that an increase of supply from BESS on the Swedish frequency regulation market is likely to be seen due to the attractive business case. Arne Berlin (Vattenfall Eldistribution) reports that Vattenfall has received many new applications for BESS that want to connect to the grid. He has seen a large increase in interest in BESS the last two years.

Besides BESS, there is another new type of supplier of frequency regulation services is expected to penetrate the market. Vehicle-to-grid (V2G) is something that both Anna Wolf (Powercircle) and Arne Berlin (Vattenfall Eldistribution) mention as an up-and-coming provider of frequency regulation. The aggregated power that the electrical vehicle (EV) fleet holds is large. Arne Berlin (Vattenfall Eldistribution) argues that V2G will have entered the frequency regulation market in five years. He also points out that, referring to discussions with Swedish automakers, the next generation of EVs will be highly compatible with performing V2G. He also highlights the fact that most EV chargers at home do not tap into all of the power of the EV. A charger of 11 kW reduces the EV's possibility to participation on the frequency regulation market to precisely that amount. Anna Wolf (Powercircle) poses some other thoughts on the topic. When performing V2G, vehicle owners essentially lend their batteries to an aggregator that controls them, e.g. participating on the frequency regulation market. She mentions that the human factor might be an obstacle for V2G; all owners might not necessarily be interested in having their batteries controlled remotely. One reason for this could be fear of wear on the battery through cycling. Moreover, she points out that not all car manufacturers currently allows for V2G grid. However, she also mentions other car producers that show motivation in enabling the transition to V2G. Anna Wolf (Powercircle) goes on to point out that the EV fleet is expected to grow until 2030. At that point fleet growth might stagnate as car pooling and automation reduces the need for even more EVs.

Another recurring topic in the study was the new technical requirements for FCR that are being implemented. The new requirements will be put in place September 2023 for all new suppliers, and mandatory for all suppliers in 2028. According to Maja Isaksson (SvK), the new requirements will make it possible for LER, amongst them BESS, to bid 24 hour a day on the FCR-D market. However, she emphasizes that the supplier must provide a plan for how a suitable SoC of the BESS is to be kept. For FCR-N, the same changes regarding bidding strategies is not confirmed. While the new requirements provide attractive bidding opportunities, they also come with new technical challenges. Lars Skoglund (Ntricity) mentions that the requirements demands changes to how the BESS is operated. His initial testing of the new requirements indicate that transitioning to the new rules will be difficult. Ulf Wingstedt (CheckWatt) also mentions that his organisation puts a lot of time and energy in adapting to the new FCR rules.

The new requirements does not only affect LERs and BESS, but also the existing suppliers of FCR. Hydro power, being the most significant supplier today, will likewise be affected by the new technical requirements. According to Lars Skoglund (Ntricity) and Fredrik Liljehov (Eolus Vind), hydro power will see new challenges in participating in the FCR markets. Specifically, Kaplan turbines will be affected negatively by the regulations: the new rules will make them too slow to participate on the FCR market. Lars Skoglund (Ntricity) also mentions that the other common hydro turbine, the Francis turbine, tend to have higher costs than Kaplan turbines. Maja Isaksson (SvK) points out that the new technical requirements were created while considering that "a large enough share of existing hydro power will meet the new technical requirements".

Furthermore, the discussion regarding bid length, or bid period, was also present in the study. Lars Skoglund (Ntricity) presents his opinion that there will be a transition to 15 min bidding period for the frequency regulating services. He mentions that the system is already transitioning towards a 15 min period, by introducing a 15 min imbalance settlement period (ISP), and that it would be natural if the whole electrical system followed. He further points out that at 15 min bidding period could make it easier for BESS to participate on aFRR and mFRR, markets that perhaps previously were inaccessible due to the requirement of durability. He goes on to say that a transition towards 15 min period is initiated through the Nordic Balance Market (NBM). In a similar manner, Jens Nordberg (Varberg Energi) also points out that a 15 min electrical system will increase the possibility for BESS to participate on the aFRR market. He means that the energy throughput of aFRR can be too high for BESS, especially the BESS with a high power/energy ratio. According to Filippa Pyk (SvK), the preliminary start of 15 minute bids on the mFRR market is due Q2 2024. Maja Isaksson (SvK) points out that there are currently no dates for when FCR or aFRR are supposed to transition 15 minute bids.

NBM is, according to Filippa Pyk (SvK), the first step towards connecting to the European markets for aFRR and mFRR, PICASSO and MARI. NBM is a way for the Nordic countries to coordinate before connecting to said European markets. The Swedish markets will have to connect to PICASSO and MARI by July 2024. Jens Nordberg (Varberg Energi) argues that connecting to the European markets can result in higher availability prices, possibly increasing the profitability for suppliers of aFRR and mFRR.

Another common topic in the interview study was the future demand for frequency regulating service. Anna Wolf (Powercircle) and Carl Liljewall (Ellevio) both share the view that increased penetration of VRE will increase demand for frequency regulation in general. Arne Berlin (Vattenfall Eldistribution) also subscribes to the opinion that the demand for frequency regulation has to increase. Marko Miletic (SvK) highlighted that the demand for FCR-D is something that is fix value, based on the largest producer or consumer in the grid. He has heard of no plans to change the formulation of demand for FCR-D. In the case of FFR, on the other hand, it might be different. FFR is a service that handles the issues with low inertia in the grid. Fredrik Liljehov (Eolus Vind) emphasizes that wind and solar power does not provide any inertia to the grid. Even though wind power creates energy by transforming kinetic energy to electricity, no inertia is added from wind power. As the share of those types of electricity increase, inertia in the grid will decrease. Maja Isaksson (SvK) confirms that less inertia in the system will result in increased demand for FFR. She goes on to point out that demand for aFRR and mFRR is forecasted to increase. The interview study provided no predictions for the demand of FCR-N. If, or when, the transition to 15 min bidding period is completed, Carl Berglöf (Energiföretagen) argues that the demand for the quick frequency services may decrease. He means that a 15 min period can provide more accurate predictions of consumption and production, resulting in smaller imbalances and thus reducing the need for frequency regulation.

In addition to the future demands, new services on the frequency regulation market was brought up in the study. Anna Wolf (Powercircle) predict that higher penetration of VRE will create the need for additional services. She points to countries such as Ireland, a country already with high VRE penetration, that has far more different services than can be seen in Sweden. Sara Norman (Öresundskraft) subscribes to the view that new services are going to be initialized in Sweden.

The construction of BRP / BSP was too a recurring theme during the interview. The two parts in the constructions are due to be remade, separated to be precise. In the future, a supplier of frequency regulation (BSP) will not have to go through a BRP to access the markets. According to Ulf Wingstedt (CheckWatt), the separation will be beneficial for frequency regulation suppliers. Separating the two will alleviate the need to go through the BRP to provide frequency regulation. On the subject Pernilla Ademar (Moditity) mentions that BRPs not necessarily provide all different regulation services. The separation of BRP and BSP is something Ulf Wingstedt (CheckWatt) means will make it simpler for suppliers to optimally operate their resources. He points out that it will give the suppliers full control over the bidding process, a responsibility currently subscribed to the BRPs. Sara Norman (Öresundskraft) also mentions that the dissolution of BRP/BSP will enable new suppliers to enter the frequency regulation markets, suppliers such as factories. In the same manner, Maja Isaksson (SvK) explains that SvK hopes the separation of BRP and BSP will allow for new types of suppliers to enter the markets. During the final part of this thesis it was announced that BSP / BRP separation will be implemented no later than the 17th of May 2024 [51].

In the study, knowledge gap regarding BESS was also discussed. Lars Skoglund (Ntricity) argues that it can be hard for new projects to get everything right from the start. He mentions that potential owners of BESS might not be technically used to battery technology. Unsuccessfully interpreting the technical specification when purchasing a battery can lead to lower-than-expected power output when completing the SvK pre-qualification. He points out that this can affect an investment calculation heavily. He goes on to mention cases where new projects have procured BESS that are not sufficiently quick to participate on the quickest frequency regulating services. Arne Berlin (Vattenfall Eldistribution) mentions the knowledge gap with regards to grid companies that own the grids to which BESS are connected. The grid companies are not used to the the type of customer that BESS is, changing between consuming and producing electricity. He says that a cost model for BESS has yet to be crystallised in the grid companies. He goes on to argue that a BESS owner either way has to keep track of what tariff is being paid to the grid companies. Different frequency regulating services will require different grid subscriptions. The grid costs vary both depending on the maximum power as well as on the energy throughput produced by the battery. In cases Arne has seen the tariffs can vary with a factor 10, the maximum tariffs reaching upwards of 3 million SEK yearly for a 5 MW, 20 MWh BESS. Jens Nordberg (Varberg Energi) also points out that grid companies not yet are certain for the pricing model of grid tariffs for BESS. He mentions to the novelty of BESS on the market as the main explanation. He, like Arne, means that what types of operation the BESS is used for affects the costs affiliated with grid tariffs. Frequency regulation services that require higher energy throughput, such as aFRR, will lead to greater expenses in the form of grid tariffs. He goes on to say that BESS projects in Sweden has a tendency to be delayed. Pre-qualification for SvK is something he means can be harder, and take more time, than projected. Furthermore, he emphasizes the point that frequency regulation services with a higher energy throughput also leads to more cycling of the BESS. Higher cycling leads to more wear on the battery and should therefore be seen as leading to higher costs.

Another topic of interest in study was the BESS' ability to be flexible in changing between different markets. Jens Nordberg (Varberg Energi) and Lars Skoglund (Ntricity) both put focus on agility. New requirements, new services, and changing revenue streams are reasons they deem important for the future business case of BESS. They emphasize that the BESS will need to change its operational strategies throughout its life span to secure revenue streams. Together with Arne Berlin (Vattenfall Eldistribution), Sara Norman (Öresundskraft), and Carl Liljewall (Ellevio) they all mention they point that revenues for BESS may come from multiple revenue streams in the future. Terms such as "service stacking" and "value stacking" appear in these interviews. They mention local flexibility and behind-the-meter applications as possible streams of revenue, applications that lie outside the scope of this thesis. Though not the focus of the thesis, it is noted that multiple interviewees see the BESS having revenue streams besides those coming from the frequency regulation market in the future.

In this interview study, future price levels was a frequent topic of discussion. The economic feasibility of BESS on the frequency regulation market is strongly connected with the general price level. Carl Liljewall (Ellevio) predicts that prices will fall in coming years. His main reasoning behind this is that the currently high prices will attract new suppliers, thus increase the total supply and lowering market prices. Sara Norman (Öresundskraft) also hold the view that prices will go down as new suppliers enter the market, attracted to the profitability that is currently.

4.3 Integration

The interview study revealed a new possibility regarding the bidding operation of BESS, namely submitting bids to FCR-D up and down simultaneously. To encompass this finding in the thesis, it was included in the quantitative model as well. Thinking of FCR-D up + down as a single, the combination could be evaluated as shown in Table 17.

Table 17: Outcome for BESS applied to FCR-D up + down, during 2022

	2022 earnings	**Life span**	**IRR (%)**	**Pay-back**	**NPV (kSEK)**
FCR-D up + down	42356	15	64.1	1.6	292930.2

5 Discussion

In the discussion the results presented in Section 4 will be discussed in light of the research questions. The discussion is initially conducted separately between data analysis and interview study and then a summarized discussion is presented. Throughout the discussion multiple perspective of the results are presented. A summary of the result is followed by the interpretation of the result. Then, implications and limitations to the results are presented. Finally, suggestions regarding future research are introduced.

5.1 Quantitative data

Firstly, the result of the quantitative data will be discussed. The results were produced in two ways: analysing the services individually and analysing them according to the optimizing algorithm presented in Section 3.

Individually analysing the services showed that BESS, during 2022, was economically feasible on all frequency regulating services, and for all electrical areas, with the exception of aFRR down localized in SE4. Here, negative NPV was noted. Even though the majority of the services saw profitability for all areas, how they became profitable, and to what extent, varied. BESS for FFR was restricted to the amount of hours that SvK actually procured the service. This was seen through the yearly earnings, a value that was far lower than for other services. FCR-N, on the other hand, saw high earnings. But, due to the heavy cycling, the life span was low. Subsequently, the BESS dedicated to FCR-N only saw revenues for three years, lowering NPV and IRR. For FCR-D up the highest IRR and NPV was noted. Here, the battery lasted the maximum 15 years. In the case of FCR-D down, the yearly earnings were rather low. Still, with the battery lasting the maximum life span, FCR-D down saw the second highest NPV. aFRR up/down both saw rather high cycling numbers, resulting in life spans of 4 years. This directly affected their NPV and IRR respectively. It should be mentioned that aFRR saw the highest yearly earnings, and the shortest pay-back time, of all frequency regulating services. Moreover, in the case of aFRR up/down, there was a large discrepancy in profitability between SE1 SE2 and SE3 SE4. A BESS placed in SE1 or SE2 was more profitable than one placed in SE3 or SE4. With the exception of aFRR, frequency regulation services performed similarly in between different electrical areas. The optimized model performed better than any individual service, around 60 % better FCR-D up when comparing NPV. It mostly focused on FCR-D up/down and FFR. They represented 99 % of bidding choices.

From the modelling, both the individual and the optimized part, it is evident that it currently is very economically feasible for BESS to participate on the Swedish frequency regulation markets. It is also clear that focusing on FCR-D up/down and FFR will result in the highest profitability. The primary reason that the other services, FCR-N and aFRR, not provide the same high level of profitability is due to their wear on the battery. Providing these services will shorten the life span on the battery and reducing the number of years the investment can see profits.

The implications of the findings are that there currently exists a profitable business operation in BESS for frequency regulation. They also imply that the focus should lie on FCR-D up/down and FFR. Considering this distribution among the frequency regulation services it is of no importance where the BESS is placed geographically. Furthermore, the optimized model shows that significant value can be added if predictions regarding future prices are accurate.

There are limitations to what the result show. The limitations are primarily based on the parameters and assumptions presented in Section 3. The outcome of the quantitative analysis is a result of these pre-defined assumptions and values. For example, the parameter for cycling cost is a parameter that affects the result of the optimized model. Choosing a lower value for cycling cost will make the model more likely to choose the higher cycling services, that were previously overlooked for FCR-D and FFR. In this thesis the cycling cost was based upon the number of life cycles estimated for the battery. As explained in Section 2, the number of life cycles is dependent on DoD per cycle. If the model had chosen to restrict the battery to a lower DoD, say 80 %, the battery would have more life cycles and in turn a lower cycling cost. However, this would also change the pre-qualified capacity by SvK, and thus lower the yearly earnings. Moreover, it is reiterated that the optimized algorithm used in the thesis is an all-knowing model. The KPIs presented by this model are not to be taken for granted. They can only be achieved by accurate predictions of coming prices.

Ultimately, the choice of parameters and assumptions will naturally affect the outcome of the result. In this thesis they were made with respect to the literature. Simplifications are necessary to progress from problem formulation to solvable task.

5.2 Interview study

The interview study is summarized in Section 4 under a list of recurring themes from the interviews. A short rundown of the interview study is presented in the paragraph below.

Firstly, the study concludes that BESS is currently economically feasible for frequency regulation in Sweden, and that FCR and FFR are the most suitable services for BESS. The study further goes on to present a number of trends and changes on the frequency regulation market. There are changes in supply: new categories of suppliers are entering the market. There are changes in market regulation: new technical requirements for FCR, initiating NMB and entering European markets for aFRR and mFRR. And there are changes in demand: potentially new services may enter the Swedish market, and the demand for the already existing services is generally expected to increase. These three types of changes affect the interviewees outlook on price levels on the market in the future. There is a general view that prices will not stay as high as they have been in the last year.

Additionally to the rundown, interpretations of the result are presented below.

That the price level is expected to decrease naturally affects the outlook of economic feasibility for BESS. However, to what extent, and at what time, the prices will fall is complicated to deduct. The fall in price levels originates from an expected increasing of supply. It is also connected to the fact that demand not will increase as quickly. With regards to supply, it is predominately BESS and V2G that is anticipated to bring new supply to the markets. For BESS, lack of experience and expertise, in combination with pre-qualificaiton difficulties, may delay the time of entry for new suppliers. For V2G, it will take an estimated 5 years for the technology to penetrate the frequency regulation market. In the case of V2G there needs to be technological and regulatory advancements made to enable the transition, as well a human behavioral changes to accept the prospect of lending out ones battery. Thus, it can be expected that rate of increase in supply will be rather slow at first, but that the rate of increase in supply will pick up pace in the coming five years.

Additionally, since new FCR regulations may disable part of the hydro power from participating on the FCR markets, there is a possibility that there will be a drop of supply from this end. The same set of FCR rules will also enable more liberal bidding strategies for LER, as long as a SoC management is presented. The possibility of bidding at every hour can double the earnings for BESS participating on the FCR markets. This will further enhance revenues for BESS.

Moreover, since price levels are high currently, with pay-back times as low as a year, falling price levels does not necessarily mean that BESS will become unfeasible, economically. Besides the discussion regarding price levels, the interviewees discussed the term "service stacking". The fact that this term was recurrent in the study can be interpreted as a belief that BESS will not solely be applied to frequency regulation in the future. The notion of splitting the BESS' capacity among different functions is an indication that frequency regulation alone not will result in the highest profitability for the battery.

Furthermore, BESS will face technical challenges, and opportunities coming years. New technical requirements will demand rigorous testing for pre-qualification for FCR services. In the same time, the new regulations regarding the separation of BSP and BRP is something that will empower BESS owners. From this point on they will be able to control their own resource, using bidding strategies as they wish (granted that they obey SvK's rules).

Ultimately, the implications of the study is that BESS will provide strong earnings on the Swedish frequency regulation markets, but that the prices on the market will decrease from the levels seen in 2022. Separation of BRP/BSP together with liberal bidding rules makes BESS owner more empowered and will increase the share of bidding hours that the BESS can draw revenue from.

When it comes to limitations of the interview study, the number of interviewees, and the spread of these, presents a limitation. The thesis includes a total of 12 interviews, with a spread among 6 categories out of 8 initially identified categories presented in Table 10. The study does not present the perspective of these categories.

5.3 Integrated discussion

When the results of both the quantitative and the qualitative data is discussed further interpretations are made.

Firstly, both studies concluded that FCR-D up, FCR-D down, and FFR were the most suitable services for BESS on the Swedish markets. The fact that both studies point to the same three services strengthens the result.

Furthermore, a combination of simultaneous FCR-D up and FCR-D down bids was discovered in the interview study. It turned out to be useful, in terms of profitability. The FCR-D up/down bidding combination can be considered a single service for comparability with previously conducted quantitative analysis. It acts as one in the sense that both bids will receive 100 % of the bidding capacity. A 10 MW BESS will bid 10 MW FCR-D up and 10 MW FCR-D down for a single hour. As presented in Table 17, this combination is highly profitable.

Moreover, the sensitivity analysis regarding price levels give insights to the opinion that prices not will remain at 2022's levels. Given a decrease in price level of 60 % most services became unfeasible economically. FCR-D up, however, remained profitable. As described in the previous paragraph, additional earnings would provided by employing the FCR-D up + down combination. In conclusion, even considering a 60 % price level decrease, the model points out that the BESS still will be profitable.

5.4 Future research

During the writing of this thesis, interesting topics for future research has been gathered. It is particularly simple to discover research ideas due to the freshness of the topic of BESS for frequency regulation. Two possible ideas for future research are presented below.

- Data-driven investigation of possibility to predict service prices
- Technical viability of combination of local flexibility and frequency regulation

The data-driven research proposal could investigate how AI/ML could be used to predict prices for different frequency regulation services. As presented in this thesis, given accurate predictions of future prices, the profitability of an investment in BESS can increase. The investigation could additionally possibly include correlations; providing information of important factors to estimations of frequency regulation prices. In a similar manner, data-driven predictions of grid-frequency could also be investigated.

Another interesting topic would be to investigate how technically viable it is to implement the previously mentioned "service stack". Are there any technical difficulties to consider when using the BESS for different functions, perhaps simultaneously? A combination to investigate could be frequency regulation and local flexibility.

6 Conclusion

The conclusions of this thesis answers the research questions of the thesis, namely:

1. *What is the economic feasibility and technical viability of Battery Energy Storage Systems (BESS) participating in the Swedish frequency regulation market?*
2. *What frequency regulation services are the most suitable for BESS in the Swedish market?*

6.1 Research question 1

The technical viability of BESS on the Swedish frequency regulation market is high. BESS inherently holds technical qualities required by the frequency regulation services on the Swedish market. Furthermore, there are new opportunities arising by enabling suppliers to skip the BRP middleman from 2024 and onward, resulting in more independent BESS operations for owners. Simultaneously, new FCR requirements can result in delaying BESS projects through difficult pre-qualification processes.

The economic feasibility of BESS is currently very high. Even with prices falling to half of what they were during 2022, BESS investments are profitable. But, due to the many changes occur on the market, economic feasibility of BESS for frequency regulation is difficult to predict.

There are some factors that will decrease economic feasibility for BESS. An increase in supply is expected to drive the prices down coming years, making BESS projects sensitive to at what time they enter the market. There is also an industry-focus on BESS being applied to functions beside frequency regulation, indicating that other applications will be competing with frequency regulation in terms of profitability.

There are also factors that are expected to increase economic feasibility. Regulatory changes will make BESS able to partake in more bidding hours for FCR-D, increasing these revenues. New frequency regulation services, and new European markets will act to the benefit of BESS.

6.2 Research question 2

The thesis found that FCR-D up, FCR-D down, and FFR are the services most suitable for BESS on the Swedish regulation market. The combination of high prices and low wear on the battery makes these service ideal for BESS. Moreover, the thesis concludes that it is on these services that BESS are highly competitive with other suppliers of frequency regulation. The thesis also put forward the possibility to bid on FCR-D up and down simultaneously, with full capacity for both bids. Given the findings regarding the most suitable services, the localization of the BESS within Sweden is of no importance; FFR and FCR-D saw the same economic feasibility for all electrical areas.

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Appendix

Interview guide

- Present myself and the thesis
- Ask them to introduce themselves, and the organisation they represent
- How is your organisation connected to BESS and frequency regulation?
- Is your organisation a profit-driven organisation?
  - If yes: How does your organisation profit from BESS/frequency regulation?
- What possibilities do you see for BESS on the frequency regulation market?
- What barriers/risks do you see for BESS on the frequency regulation market?
- How does regulatory changes affect the frequency regulation market?
- What trends do you expect to see on the market? Also regarding the price level?
  - Coming 1-5 years?
  - In 5-10 years?

Interview dates

Table 18: Interview dates, presented chronologically.

Person	Date
Pernilla Ademar	230313
Marko Miletic	230329
Lars Skoglund	230405
Carl Liljewall	230411
Sara Norman	230418
Maja Isaksson Charlotta Ahlfors Filippa Pyk	230424
Carl Berglöf	230427
Anna Wolf	230502
Ulf Wingstedt	230510
Fredrik Liljehov	230510
Arne Berlin	230516
Jens Nordberg	230519