Exploring the value-stacking opportunities of batteries providing frequency containment reserve services in different regulatory environments

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Preface

Before I invite you to read my master thesis, I would like to express my sincere gratitude for all the people that helped me throughout this research process. First of all, I would like to thank my first supervisor Petra and advisor Özge for their helpful comments and guidance. Their experience and knowledge helped me to search into new research directions and to critically reflect on my thesis work. I would also like to thank my second supervisor Martijn for his constructive feedback.

I would like to express my gratitude to Evert and Ruben for their guidance during my internship period at Alfen. I really liked the discussions we had about the frequency containment reserve regulations in the European Union and the insights that you gave me into the work Alfen is doing on Lithium-ion battery energy storage systems.

I would like to thank my family and friends who helped me during the writing process of this thesis. They helped me by proofreading the master thesis and by discussing the overall structure of my thesis work.

I realize that the period in which I conducted this master thesis research was challenging. I had to cope with a change in the working environment due to the coronavirus measurements and had to maintain focus on the master thesis subject in the meanwhile. Given the circumstances, I am proud of the work that I have done. Getting familiar with a programming language (Python) I was not familiar with, using research methods (time-series analysis) that I had never used before and doing all this in a period just over 4 months seems to be a very good achievement. I am therefore happy to provide you with the results of my master thesis research and hope you will enjoy reading it.

J.L.R. Visser
Leiden, August 2020

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Executive Summary

The security and reliability of the European power system network that is used to transmit electricity from producers to consumers is under increasing pressure. The penetration of renewable energy resources that have a variable and unpredictable energy output and the rising cost of the operation of fossil-based power generators are negatively influencing the availability of controlling power that is critical for normal system functioning. Without this controlling power, there is a risk of electricity network imbalances and complete electricity blackouts.

To be able to guarantee the continuity of electricity supply, transmission system operators are required to search for new and alternative flexibility resources, including resources that could provide the primary system response (frequency containment reserve) to these grid imbalances. Battery energy storage systems are one of the most promising alternative resources that could provide this load controlling capacity. These systems are, however, extremely cost-intensive.

Using a battery for multiple battery applications simultaneously could improve the financial viability of these battery energy storage systems and thereby, accelerate their deployment in society. To be able to get the full potential out of this value-stacking opportunity, more insight into the technical and operational compatibility of using a battery for frequency containment reserve and other battery applications is required.

In this master thesis, a research was conducted to obtain a better understanding of the opportunities to create added value in the utilization of a battery that is providing frequency containment reserve services. By means of a (multiple-)case study research (including a literature review, a simulation model and a time series analysis and forecasting model), more insight was obtained in the power and energy capacity utilization of a battery that is providing frequency containment reserve services and the usability of the leftover capacities of this battery for serving other battery applications.

In the literature review that was performed, it was demonstrated that the activation of batteries for frequency containment reserve is mainly dependent upon the regulations and grid characteristics that are present in the area of interest. These regulations provide terms and conditions for the theoretical use of a battery's power and energy capacity and therefore, the theoretical opportunities for value-stacking. These value-stacking opportunities include the use of moments in which a battery is idle and the time periods in which a battery is not using its full energy capacity.

The simulation study that was performed subsequently showed that for all frequency containment reserve markets examined in this research, there are moments and periods in time in which a battery is not using its entire reserved frequency containment reserve power and energy capacity. This indicates that using a battery at these particular moments and periods in time for other battery purposes might create substantial added value to the overall system operation.

The analysis of the data that was obtained from the simulation study showed that the practical usability of these moments and periods in time for value-stacking opportunities seems limited. Although it was illustrated that there are moments in which the battery's power capacity is not used, no clear prediction can be made of these so called 'idle moments'. Consequently, it is uncertain at what exact moments in time the battery is idle and could be used for other battery purposes. The duration of the idle moments is furthermore relatively short, which makes it difficult to use these idle time periods for applications that require consecutive power supply or energy storage.

Results of the time series analysis and forecasting model demonstrated that there might be opportunities to predict the required energy capacity for frequency containment reserve. This indicates that forecasts can be made of the state of charge development of a battery over a certain time period. This information can be used to identify the underutilized battery energy capacity, which subsequently could be used for other battery applications.

The combination of both the power and energy capacity limitations prove to be a challenge when aiming at value-stacking of a battery. Using the idle moments and the forecasted available energy capacity of a battery for other battery applications requires expert knowledge of the energy capacity that is needed for the additional application and seems to require flexibility of power capacity utilization of the additional application itself.

Further research should focus on the improvement and validation of the frequency containment reserve activation forecasts to be able to make a better estimation of the battery energy capacity that is available for serving other battery purposes. Research should moreover be conducted to examine the energy and power requirements of other applications over time. This includes the need for state of charge control. The information that is obtained from these studies is essential to identify how various battery applications, including frequency containment reserve, can be properly aligned and could add value to the battery system operation.

1

Introduction

Electricity is a form of energy that is constantly used in our daily lives. It is used to charge our mobile phones, light our houses and power the laptop that was used for writing this master thesis. In today's society, the use of electricity is very common and even crucial within urban areas, providing the energy needed for public security, financial transactions and healthcare systems.

The electricity network or electricity grid is the network through which the electricity that is generated by power generators is transmitted and distributed to consumers. Various electric power generators, including coal- and gas power stations, hydropower plants, nuclear power plants, wind turbines and solar panels are all generating the electricity that is required by the consumers to perform their daily tasks.

These power stations are, however, often far away from the region where there is a demand for electricity. Power plants are often located close to their energy resource (e.g. gas power stations close to gas fields), whereas consumers are often localized in high urban regions. Transmission and distribution power lines and transformers between the various parts of the electricity network are therefore necessary to transfer the generated electricity to their end consumers efficiently and safely.

Electricity is difficult to store in its original form, which means that the electricity that is generated by the various power plants has to be used almost instantaneously by its consumers. However, consumers that require electricity at a certain time point generally prefer to be served immediately. To guarantee a continuous supply of electricity, the electricity demand and electricity generation should therefore be balanced for 24 hours a day, 7 days a week.

Although the various market players that are participating in the electricity market are trying their best in keeping a continuous balance between electricity supply and electricity demand, it is not always possible to perfectly match these. Demand load predictions are not perfectly accurate, generator outputs can vary significantly over time and power system components can fail (Milligan et al., 2010). All these different aspects can lead to an imbalance between electricity generation and demand within the electricity supply chain.
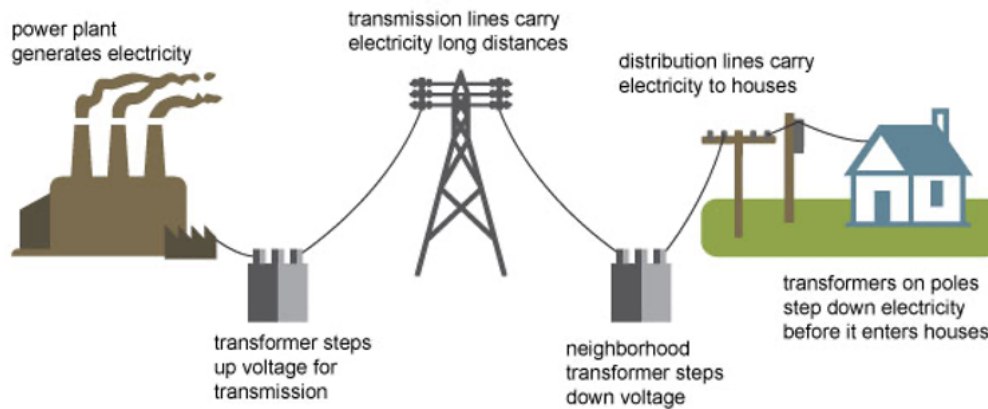
Figure 1.1: Electricity network overview. Source: EIA (2019)

Balancing problems in high-voltage transmission networks can be a real threat to proper grid functioning. A sudden and persistent imbalance between electricity generation and demand in the power system network may lead to blackouts that could cause huge economic losses for the power industry and energy consumers (Shuai et al., 2018). Major blackouts, as experienced in the European electricity grid in 2003 and 2006, have caused electricity grid outages that affected areas with over 15 to 60 million people (Bialek (2007); Corsi and Sabelli (2004)).

The affected areas of these blackouts are not limited to one country only. The 'European Blackout' that happened in November 2006 affected electricity supply in over 20 other European countries. The accident in Northern Germany generated a cascade of grid failures in neighboring countries and grid disturbances that reached up to Morocco, Algeria and Tunisia within a matter of seconds (van der Vleuten and Lagendijk, 2010). This event highlighted the vulnerability of the transnational electricity infrastructure and the need for an international cooperation in controlling and securing a reliable and stable electricity grid.

1.1. Power system flexibility

To secure the reliability and stability of the electricity supply chain, power system operators nowadays have to compensate for the differences in power system variability. The various power system operators use real power generator control capacity services (or ancillary services) to restore any form and duration of imbalance in the power system network (Raineri et al., 2006). Up until now, the instantaneous and continuous balance between electricity generation and demand in the electricity supply chain is mainly assured by adjusting the power output of fast ramping thermal generators (Carlini et al., 2019). These conventional, fossil-based energy resources are able to ramp up or ramp down their power output in response to a sudden electricity system imbalance.

Although the conventional power resources have reached a good maturity in dealing with load variability, threats for future grid stability and reliability have been identified. An increased need for grid flexibility capacity and a decreased availability of current flexibility service providers in the provision of ancillary services are both threats that emphasize the need for new and alternative methods to deal with electricity network imbalances.

1.1.1. Increased need for load controlling capacity

The urgency for developing a reliable, safe, sustainable and low carbon energy sector has been recognized by many different entities on both international (European Commission, 2011) national (Siksnelyte and Zavadskas, 2019) and local (Kern and Rogge, 2016) scale. In 2014, the European Union proposed a policy plan for shaping a competitive and low carbon European economy by 2050 (European Commission, 2014). This strategy plan has several energy system related objectives for the year 2030, including 40% less greenhouse gas emissions compared to 1990, a 32% share for

renewable energy in the gross final energy use in the European Union and a 32.5% improvement in energy efficiency relative to the 2007 baseline. For 2050, even more stringent objectives have been proposed.

The different action plans that have been set up to fight climate change have already driven energy- and climate-related policy changes and a significant transition from fossil-based energy systems to renewables (Chakraborty and Lukszo, 2017). In terms of final energy consumption, the share of renewable energy resources (RES) in the European Union has been almost doubled from the period in the period 1995-2016 (Mehedintu et al., 2018). The targets that are set by the European Union to further reduce the greenhouse gas emissions by 2030 and 2050 are expected to further increase the share of renewable energy resources by its member states (European Commission, 2011).

The implementation and integration of all these RES in existing electricity grids comes with challenges. The intermittent behavior of wind turbines and solar panels makes them unreliable for stable energy supply (Edenhofer et al., 2013). Local weather conditions can change relatively fast and affect the output of wind and solar resources. As the penetration of these intermittent renewable resources significantly increases, this can have negative consequences for the predictability of the electricity supply and increase the chance of balancing problems in low-voltage distribution grids (Faessler et al., 2017) and high-voltage transmission networks (Hirth and Ziegenhagen, 2015).

The variable energy output of solar panels and wind turbines requires other resources to adapt their power output to maintain the balance in the electricity supply chain. The necessity for flexible energy resources is therefore not only needed for mitigating the variability in the medium and long term predictable output of these RES, but also for mitigating the short term, unpredictable output (Carlini et al., 2019).

The need for more load controlling capacity in the electricity supply chain due to an increased penetration of RES has been recognized by many different studies (Denholm and Hand (2011); Hollinger et al. (2017); Koltsaklis et al. (2017); Kroposki et al. (2017)). To guarantee the stability and reliability of future electricity supply, more balancing service capacity in the future electricity grids seems required.

1.1.2. Decreased availability of current flexibility service providers
Another concern for the stability of the future grid is that high penetration of RES and other environmental concerns can affect the profitability of the current flexibility service providers. As described by Hollinger et al. (2017), the main problem that is encountered in the use of conventional power plants for short term grid flexibility services is that these power plants often have relatively long start up times. As a consequence, thermal power plants providing flexibility services that require short activation times must stay in continuous operation. This 'must run' status can have a significant impact on the profitability of a power plant, since these plants are also required to run in times of low electricity prices.

In the upcoming years, it is expected that the profitability of a conventional power plant providing ancillary services will further decrease and may even become economically infeasible (Hollinger et al., 2017). Due to an increasing penetration of intermittent RES in the electricity supply chain, electricity prices are expected to decrease (Ketterer, 2014). Additionally, negative electricity prices in time periods of high renewable energy output are more likely to occur (Paraschiv et al., 2014). Prices on carbon dioxide emissions (e.g. European Union's Emissions Trading Scheme) are furthermore affecting the operational cost of fossil based power stations (Bredin and Muckley, 2009). These factors can have negative consequences for the profitability and availability of the current grid balancing services providers providing (short-term) grid flexibility services, thereby posing a potential risk for future grid stability.

1.2. Electrical energy storage
One of the alternative technologies that can be used for the provision of grid balancing (=ancillary) services is the use of electrical energy storage (EES) systems. EES systems can store excess energy generated by energy resources and redispatch the energy after a certain time delay (Faessler et al.,

2017). Energy is hereby converted from one form (mainly electrical energy) to another, storable form and converted back to electrical energy when needed.

An EES system generally consists of two main components: a power conversion system (PCS) and an energy storage unit (see Figure 1.2). The PCS is responsible for converting the current, voltage and other power characteristics from the energy that is transferred from the grid or generator to the storage device and vice versa (Zakeri and Syri, 2015). The energy storage unit is the reservoir for the energy that is stored within the EES system (Zakeri and Syri, 2015). Other parts of an EES system include monitoring and control systems, necessary for a proper EES operation (Zakeri and Syri, 2015).
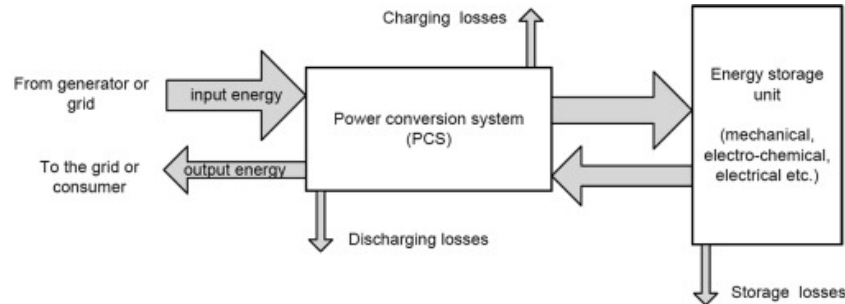

Figure 1.2: Systemic overview of an electrical energy storage (EES) system. The EES system consists of two main components: a power conversion system and an energy storage unit. Source: (Zakeri and Syri, 2015)

Up until now, the main electrical energy storage technology used world-wide and within Europe is pumped hydro storage (PHS). About 99% of the installed capacity of electrical energy storage systems are made up of these PHS systems (Geth et al., 2015). Other energy storage technologies that have been deployed in society include compressed air energy storage (CAES), super conducting magnetic energy storage (SMES), flywheels, capacitors and battery energy storage system (BESS) (Geth et al., 2015).

Although all these different energy storage technologies can, in theory, be used to provide grid balancing services, they are not always considered a good alternative for the conventional generators that currently provide the load controlling capacity. Technical limitations and economic considerations are factors that influence the ability of these energy storage technologies to substitute the conventional thermal generators in their provision of grid balancing services. PHS and CAES systems can be very useful and relatively cost effective for medium to long term storage applications. However, the potential of deploying new PHS and CAES systems in society is limited. Due to the relatively low energy and power density of these two EES technologies, the storage reservoirs of these systems have to be relatively large. Moreover, they require special sitings for installation (Poonpun and Jewell, 2008). Flywheels, SMES and capacitors are, on the other hand, most cost effective for short term storage applications. The daily self-discharge of these EES technologies is, however, relatively high (Akinyele et al. (2017); Chen et al. (2009); Luo et al. (2015); Yeleti and Fu (2010)), which makes them less useful for medium to long term storage applications.

Based upon the technical characteristics, batteries show various advantages over the other energy storage technologies. BESSs have a relatively fast response time, high efficiency and a low self-discharge (Hesse et al., 2017). BESSs have the ability to react to grid demands within a matter of milliseconds, but also have the ability to function over longer time periods (Helwig (2016), Lawder et al. (2014). Consequently, BESSs are able to be used for many different grid applications on different timescales (Divya and Østergaard, 2009). Other advantages of BESSs can be found in the fact that these systems are extremely flexible in their capacity and siting (Lawder et al., 2014). This is mainly due to the modular structure of a battery, which makes the scaling of a BESS very feasible (Hesse et al., 2017) and therefore, easily deployable in various environments.

1.3. Battery energy storage system: the implementation challenge

In literature, the different grid services that a battery can provide are also widely addressed. The short-term (<1 minute) applications of batteries are mainly found in the possibility to use these energy storage systems for frequency control (Thien et al., 2017) and reactive power control (Barton and Infield, 2004). Medium-term (1 minute – 5 hours) applications involve the use of BESS for secondary and tertiary control reserve (Stephan et al., 2016). The main reason for using BESS long-term (>5 hours) is that new costs for generation and transmission assets can be avoided by means of congestion management (Hu et al. (2017); Kaushal and Hertem (2019)).

Although literature shows that many different grid applications are available for BESS, the installed capacity of these storage systems in society is still very small (Lawder et al., 2014). The main reason is that batteries require high capital cost (Culver, 2010). Despite the fact that the costs of BESSs have decreased and their lifetimes and performances have increased over the past years (Lawder et al., 2014), it still seems challenging to meet the financial objectives of battery owners and stimulate the substitution of fossil-based conventional flexibility resources with BESSs.

Of the various applications a battery can provide, frequency regulation is the most used application worldwide. This is probably due to the fact that this frequency regulation service is identified as one of the most suitable fields of applications for stationary battery systems (Oudalov et al., 2006). As described by Stephan et al. (2016), the primary frequency control or frequency containment reserve (FCR) is the frequency regulation service with the highest prospected net present value. In the article, however, it was also described that the use of batteries for FCR purposes only was not yet economically attractive.

The fact that the use of BESSs for FCR services alone is not always profitable over the lifetime of a battery, is also acknowledged by others. In an article by Fleer et al. (2016), it is shown that a battery, providing 1 MW FCR services in the German FCR market and having an energy capacity of 2 MWh, is not profitable over its lifetime. Other articles (Avendano-Mora and Camm (2015); Fares et al. (2014); Hollinger et al. (2018); Sigrist et al. (2013)) showed more mixed (both positive and negative) economic results.

This is also the main reason why Sioshansi et al. (2012) and Malhotra et al. (2016) suggested that a combination of different grid applications should be considered during BESS operation to increase its financial viability and accelerate its adoption in society. The overall profitability of a BESS is mainly determined by the value it can provide with the various battery applications the battery serves over its lifetime. Using the battery for various battery purposes can therefore potentially increase the overall battery's profitability.

Up until now, some studies have attempted to combine different grid applications for BESSs. Sigrist et al. (2013) and Shi et al. (2018) showed how a BESS could be used for both peak shaving and frequency control. They found that optimizing these two services could significantly improve the value of the BESS over its lifetime. A study by Stephan et al. (2016) even evaluated nine different combinations of two BESS applications, which all tend to increase battery investment attractiveness. These studies therefore provide evidence that combining different BESS services may increase the overall storage value and is favorable for storage economics.

Combining different grid applications is, however, not an easy task. Every application for BESSs needs a specific amount of power and a specific duration of power supply. The use of more applications by a BESS therefore requires an appropriate alignment of the power and energy requirements of each application with the available battery capacities. For batteries that provide FCR, in particular, this alignment is of importance, since this battery application serves a function that is critical for the continuity of electricity supply.

In the studies that were described previously, the methodologies the authors use to align the power and energy requirements of FCR and other battery applications is ambiguous and sometimes unclear. To be able to use a battery that is providing FCR services for other purposes, it seems therefore required to get more know-how about the way in which this FCR service is using the available energy and power capacities and what are the leftover capacities that could be used for other battery purposes and value

creation.

1.4. Research question and sub questions

Based upon the knowledge gap that has been identified and described in the previous section, the main research question (RQ) this thesis will answer is:

What are the opportunities to create added value in the utilization of a BESS that is providing FCR services in the European Union?

To be able to answer this research question, the following sub-question have been derived:

1. Which factors determine the activation of a BESS providing FCR services?

2. What is the activation profile of batteries providing FCR services in the European Union?

3. What are the degrees of freedom in the operation of a BESS that is providing FCR services which can be used for value stacking?

4. What is the practical usability of the degrees of freedom in the operation of a BESS that is providing FCR services which can be used for value stacking?

1.5. Research approach

The main research question that was posed earlier is of an exploratory character. This means that the goal of this thesis is to get a better understanding about the problem of using two various battery applications simultaneously (including FCR). Various research methodologies are available that can deal with problems that are of exploratory nature. Secondary data analysis, desk research, literature reviews, modeling, surveys, interviews and case studies are all examples that might be useful in answering exploratory research questions.

In this research, a case study design was chosen. As described by Collier (1993), this research methodology has several advantages over statistical methods and formal models. It can use heuristic methods for the identification of new variables and hypotheses and examine these variables and hypothesis to identify causal mechanisms. In this particular case, this methodology seems very useful for identifying and validating the opportunities that can be used value stacking.

Although this research method has the potential to consider the studied question from different perspectives and therefore gives the researcher the opportunity to get a complete understanding of the behavior of the system of interest, a case-study design does show some disadvantages. One of the main drawbacks of this research methodology is that the results that are obtained from these studies can often not be generalized (Wieringa, 2014). They use context specific data to generate results, which subsequently cannot be easily translated to a population level.

To deal with the problem of generalizability, this research does therefore not focus on one case study only. By selecting several cases in the European Union and studying them one by one, more insight into the relevant similarity between these cases can be obtained. This allows the improvement of the generalizability of the results and insights.

The approach of this research is structured based upon the design cycle that is described in Wieringa (2014). This cycle consists of 1) problem investigation, 2) treatment design and 3) treatment validation. In the problem investigation step, the phenomena (serving various battery applications simultaneously) that has to be improved is investigated. The treatment design step is used to identify potential degrees in freedom in the operation of battery in FCR that could be used for value stacking. In the treatment validation step, it is explored whether the identified degrees of freedom could treat the problem that was initially described.

1.6. Relevance of thesis to the COSEM master programme

This thesis is written to obtain the MSc. degree for the master programme Complex System Engineering and Management (COSEM) at the Delft University of Technology. This master is focused on the understanding of and design in complex socio-technical systems. Implementing changes in a socio-technical system is namely a trade-off between both the social and technical arrangements that are present in the system of interest.

The research that is conducted in this master thesis perfectly follows this way of system thinking. After all, the operation of frequency containment reserve assets is an interplay between the requirements of society (grid security and reliability), the interest of BESS owners (profitability) and the technical characteristics of the overall electricity system. This shows that knowledge and insight in all these various aspects is required to understand the real impact of the design and the results that are obtained in this thesis on the overarching electricity system.

The exploratory character of the research question that is used in this master thesis gives the opportunity to design and address these different system perspectives. The master thesis furthermore shows the strength of using a case study methodology in the design in socio-technical systems, since multiple bodies of knowledge could be included to identify the real impact of the design options that are extracted. It does also show that the discussion of the results of the individual research methodologies that are used in this master thesis is of real importance. It can show the dependencies and relationships between the various system perspectives and therefore, how the results and insights of this study fits in the overall socio-technical system that is of interest.

1.7. Master thesis outline

In Figure 1.3, a flow diagram is presented with that describes the overarching research methodology, underlying research methods and their connection to the various chapter in this master thesis. The introduction (Chapter 1) describes the motivation for this research and how this research fits into the existing literature. Chapter 2 provides an overview of the general concepts that are related to FCR activation, including background information on grid balancing and FCR provision. Chapter 3 discusses a literature review that is conducted to identify the various factors that influence the FCR activation of a BESS. Based upon these variables, potential degrees of freedom for value stacking in the operation of a BESS that is providing FCR services are identified. Chapter 4 and Chapter 5 are subsequently used to determine the usability of these degrees of freedom for value stacking. Chapter 4 does contain more quantitative information on the activation of a FCR asset. Chapter 5 is used to further analyze the value-stacking opportunities of batteries providing FCR service. In Chapter 6, the results that were obtained from these various chapters will be summarized and discussed. Chapter 7 concludes with answers to the research questions and provides recommendations for further research.
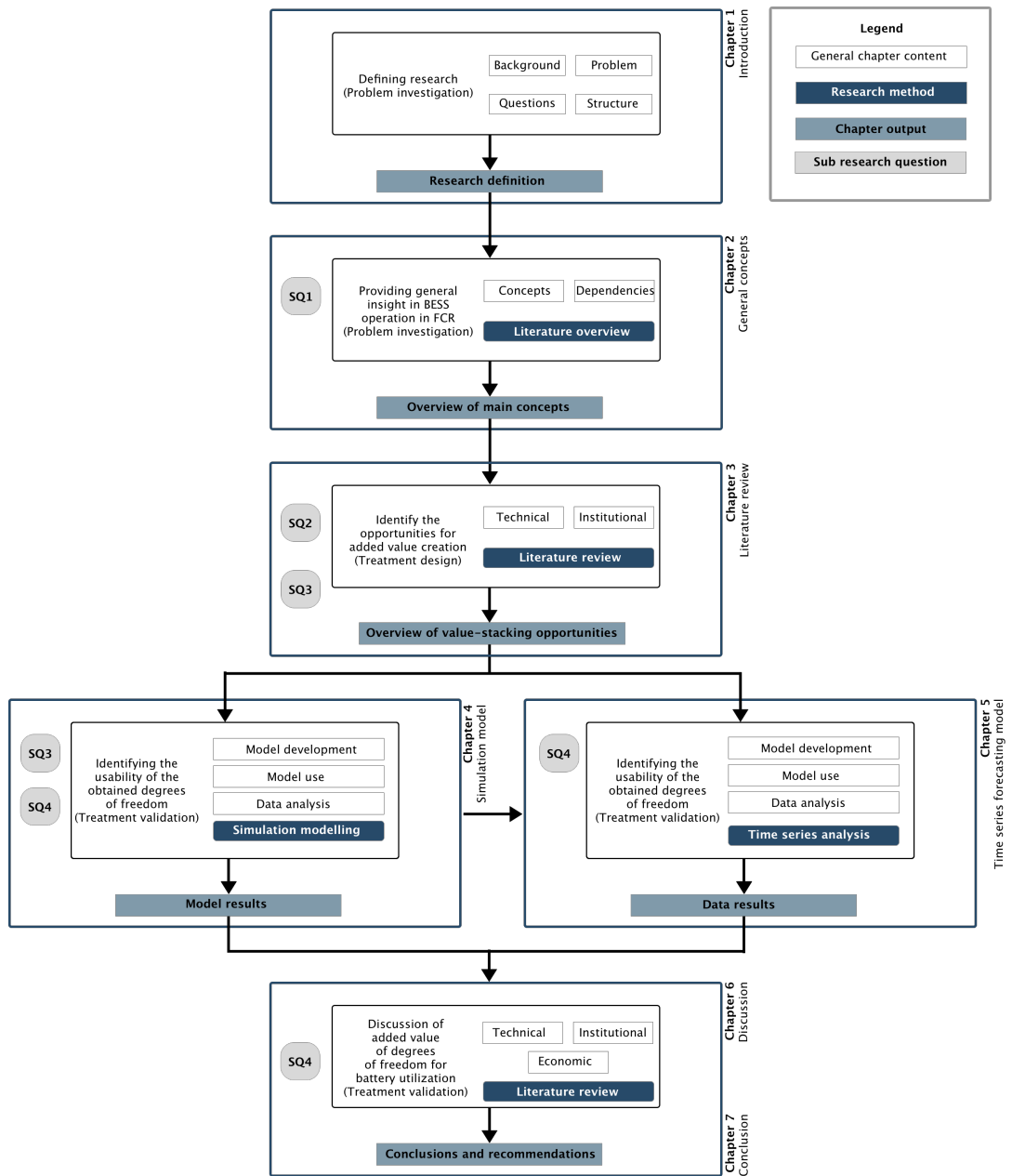
Figure 1.3: Thesis Methodology

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General Concepts

2.1. The electricity balancing act

In an electricity transmission grid, the balance between electricity demand and supply is essential for ensuring the security of supply of this commodity. In general, this balancing act is done by predicting the electricity demand of consumers and scheduling the electricity generation of assets based upon this load prediction. These load estimations are, however, not always perfectly accurate and do not reflect the real power demand at each time period. In addition, generation assets are not always capable to provide the scheduled amount of electricity to the grid (e.g. due to electricity power plant failures). These factors, along with other problems or failures that can might occur in the electricity network, can disturb the balance between electricity demand and supply and result in a power imbalance.

The power imbalance in the electricity network can change the overall grid frequency. In case of excess power demand, the grid frequency drops below the reference value. In case of excess power supply, the grid frequency increases above the reference value. The rate of change of the grid frequency is hereby directly correlated with the initial electricity demand and electricity supply mismatch.

To be able to restore the grid frequency and initial power imbalance as soon as possible, counteracting power that is equal to the initial power imbalance should either be supplied or extracted from the transmission grid. The electricity network itself already has one natural property that can counteract the power imbalance and can damp the resulting grid frequency deviation. As described by Tielens and Van Hertem (2016), rotating masses of generators and turbines that are synchronously connected to the transmission grid will instantaneously inject or absorb kinetic energy to or from the transmission grid respectively at the moments these power imbalances occur, thereby providing resistance to higher grid frequency deviations. This phenomenon, what is often referred to as system inertia, can therefore provide resilience to imbalances in the power system network.

The amount of rotating masses that are synchronized with the transmission grid determines the height of this system inertia and therefore, the resilient power of the transmission grid to power system imbalances. As described by Saleh Ebn Sharif (2017) a lot of the (small) power imbalances in the electricity system network can already be mitigated by this natural system inertia. Large imbalances between electricity demand and supply can, however, not only be solved by this system inertia and will therefore change the overall grid frequency.

Frequency deviations from the reference grid frequency can be very bad for overall electricity system functioning. Saleh Ebn Sharif (2017) describes that power generators are operating most efficient in grid frequencies that are close to the nominal value. Large frequency deviations from reference frequency can damage the generator functioning and therefore be harmful to power plants providing electricity to the grid. This is also the main reason that synchronous power plants have automatic protection systems that disconnect the power plant from the transmission grid at frequency levels above or below

a certain threshold.

The disconnection of a power plant from the transmission grid can, however, cause a snowball-effect that can eventually result in an electricity blackout. In case of excessive demand, the transmission grid frequency can drop below a certain threshold that triggers the automatic protection systems of power plants. When these power plants disconnect from the transmission grid, power system imbalances may become even larger due to a bigger mismatch between electricity demand and electricity supply. Furthermore, overall system inertia may decrease due to the disconnection of synchronous rotating masses, which will cause the grid frequency to drop further. Eventually, a widespread power outage could occur.

To guarantee the reliability and stability of the electricity network and to prevent (widespread) black-outs from happening, transmission system operators are required to reserve backup power that is able to counteract power imbalances caused by a mismatch of electricity demand and supply. These resources, that are referred to as frequency operating reserves, should be available whenever these power imbalances occur and provide the frequency reserve power that is required to restore these power imbalances.

2.2. Grid balancing within the European Union

In the European Union, the grid balancing services are controlled by the European Network of Transmission System Operators for Electricity (ENTSO-E). This entity, representing 43 transmission system operators (TSOs) from 35 countries across Europe, coordinates the stability and reliability of the European electricity network.

The European electricity network consists of two types of systems that are controlled by the ENTSO-E: a synchronous system and a balancing system (Hirth and Ziegenhagen, 2015). The synchronous system is a geographical region with an interconnected grid system and a shared steady-state frequency. In Europe, several synchronous systems can be identified. The continental synchronous area or Union for the Coordination of the Transmission of Electricity (UCTE), consisting of 24 countries, is the largest European synchronous system area. Other synchronous system areas include the Nordics, Baltics, Ireland, the United Kingdom and other small islands in Europe. The main role of the ENTSO-E for these synchronous system areas is to maintain the grid frequency at a nominal value of 50 Hertz (Hz) (see Figure 2.1).
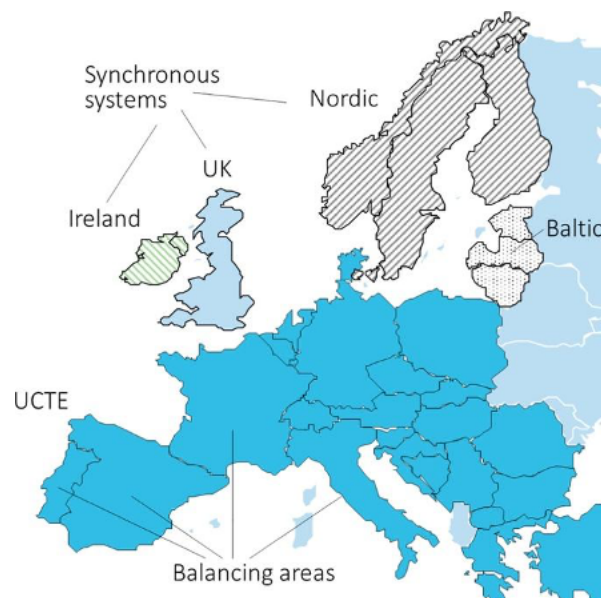

Figure 2.1: Synchronous systems and balancing areas in Europe. Source: Hirth and Ziegenhagen (2015)

The balancing system consists of several regions within a synchronous system, often the size of one specific country, and is meant to be functioning as a controlling entity for balancing the regional electricity network (Hirth and Ziegenhagen, 2015). One specific TSO of the ENTSO-E is responsible for balancing one specific balancing area. The main goal of the TSO is to maintain the net import balance of the balancing region at its scheduled level and the balancing system area error at zero.

2.3. Frequency operating reserves

As described before, the various synchronous system areas in the European electricity network are to be maintained at a system frequency of 50 Hz. Deviations from the system frequency above a certain threshold will activate the operating frequency control reserves. These reserves are used to restore the balance and nominal system frequency in the electricity network.

2.3.1. Reserve types

The various types of operating reserves can be differentiated by the type of events they respond to and their reaction time period (Milligan et al., 2010). A fast response (within seconds) is needed to compensate for direct disturbances in the power system network (e.g. due to contingency events). Power generation or storage assets that are synchronized with the electricity network should be able to serve or remove load from the power system almost instantaneously (Ela et al., 2010). For longer timescale events, such as large forecasting errors and net load ramps, additional generation and storage units are supposed to become available to up- and downregulate during the remaining disturbance recovery period.
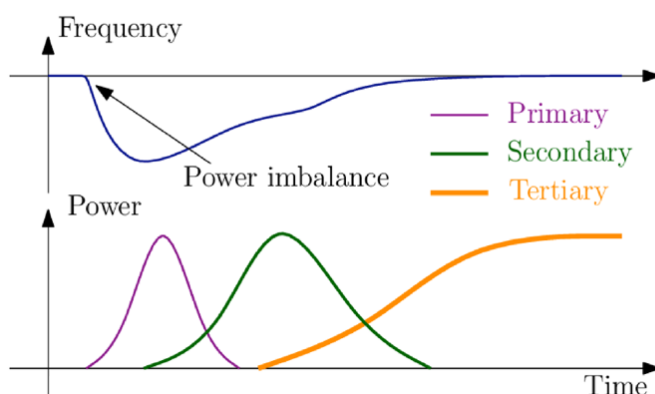
Figure 2.2: Primary, Secondary and Tertiary reserve types. Source: Ersdal et al. (2016)

In general, the operating reserves in Europe can be categorized into three different reserve types: primary, secondary and tertiary control (see Figure 2.2). In case of a specific frequency deviation or power imbalance, the primary control or frequency containment reserve is the first operating reserve that will be activated. Based upon the measured grid frequency, the activated power reservoirs will either provide or remove power from the grid to restore the original grid system frequency in the whole synchronous area.

If there is still a remaining imbalance in the power system network after a specific time period of FCR operation, the FCR is replaced by automatic frequency restoration reserves (aFRR). These 'secondary' reserves are used to restore system frequency and reduce the area control error in the balancing area where the power imbalance has been initiated (Ela et al., 2011). This secondary reserve mainly consists of units that can be controlled automatically and ramp up or down their power output relatively fast.

The tertiary control or manually activated frequency restoration reserve (mFRR) is the operating reserve that can support or substitute the secondary control reserve over a certain time (Hirth and Ziegenhagen, 2015). These systems are activated manually by the TSO controlling the balancing area

that is in imbalance and that lacks sufficient power provided by FCR and aFRR to restore the normal grid frequency in the balancing region. The mFRR systems, mainly consisting of stand-by power units, can start their operation in a relatively short amount of time.

2.3.2. Actors and responsibilities

Within the balancing market, three main actors can be defined: the TSO, the balancing service providers (BSPs) and the balance responsible parties (BRPs). All these parties have their own roles and responsibilities in balancing the transmission system network.

As described by the European Parliament (2009), the TSO is an entity that is responsible for the operation, maintenance and development of the transmission grid. Therefore, this entity has the responsibility of securing the availability and reliability of a transmission network system that is able to meet reasonable demands for electricity distribution. To ensure a secure and safe operation of the transmission grid, TSOs are responsible for procuring balancing services from balancing service providers.

BSPs are the balancing market participants. BSPs can offer reserve providing units or groups that are capable of providing balancing services to the TSO. These reserve providing units can, depending on existing regulations, include electricity generators, demand response facilities or electricity storage units (Jeriha et al., 2019).

As stated by the ENTSOE (2018), a BRP is an actor that has needs for the distribution of electricity over the transmission system network . A BRP generally has a portfolio of electricity generation and/or consumption units that require the transmission grid to distribute its generated or demanded electricity. BRPs are responsible for keeping the actual sum of generation and consumption of electricity in balance with the scheduled electricity generation and consumption. In case there is a mismatch between scheduled and actual electricity generation and consumption, BRPs are financially responsible for their portfolio's imbalances.

2.3.3. Balancing markets

The procurement of the primary, secondary and tertiary control reserve takes place in the balancing market. The products and arrangements by which these frequency control reserves are obtained vary between the different TSOs that are responsible for this procurement process. As described by Mott MacDonald (2013), this is mainly due to historical reasons. TSOs historically designed their own balancing market with regulations and procedures that were based upon national specificities. The portfolio of national generation assets, the presence of internal congestion and the number of interconnectors with neighboring countries determined the way in which the TSOs defined and procured their balancing products. Although nowadays there is a trend to internationalize and standardize the procurement of balancing products for one synchronous area, the historical influence is still affecting the way in which the balancing markets are organized.

Although the products and arrangements of procuring balancing reserves can be fundamentally different among various TSOs, the process of procuring and operating the balancing reserves has a lot of similarities. In general, the balancing market can be divided into three different phases: the balance planning phase, balancing service provision phase and the balance settlement phase (van der Veen and Hakvoort, 2016).

Within the balance planning phase, the BRPs submit their electricity generation and consumption schedule to the TSO. This schedule is based upon the predicted load and generation profile of their portfolio assets. The electricity generation and consumption schedule that is obtained by the TSO is subsequently used to predict and indicate the need for a specific amount of reserve power. The required amount of reserve power is then acquired from the prequalified BSPs. This can be done in the form of an open reserve market or by reserving reserve capacity from BSPs that are obliged to deliver these grid balancing services.

In the balancing service provision phase, the procured balancing reserve capacity should be available and operating based upon the real time frequency measurements of the transmission grid. BSPs

should hereby operate their procured balancing assets as prescribed in the requirements that are provided by the affiliated TSO. During the provision phase, the TSO will make sure that the real-time electricity demand and generation is in balance. It overlooks the automatic activation of the various primary and secondary control balancing assets and takes action when a long-lasting power imbalance occurs (e.g. by manually activating the mFRR).

In the balance settlement phase, the various market players will be rewarded or penalized for their market performance. BSPs that have properly provided reserve power will be rewarded based upon the pricing structure that is present in the specific reserve market in which it participated. BSPs that were unable to provide their control power, might be penalized. For BRPs, the same pricing structure is present. BRPs can hereby be penalized by having an imbalance between the scheduled power demand or generation profile and the real amount of power that is consumed or delivered respectively.

2.4. Frequency containment reserve

As described before, the FCR is the first operating reserve that is used by a TSO to restore the nominal grid frequency. The amount of FCR power a specific TSO or synchronous area acquires, is often dimensioned based upon the risk of a large imbalance to occur. In the UCTE region, for example, the FCR power at each moment in time is dimensioned at 3000 MW. This FCR power is sufficient to restore the nominal grid frequency in an event where two 1500 MW nuclear power plants fail instantaneously (De La Torre Rodriguez et al., 2014).

2.4.1. FCR provision with a battery energy storage system

In the introduction, it is stated that battery energy storage systems are, in theory, perfect candidates for providing this frequency containment reserve power. Li-ion batteries, for example, are characterized by their high efficiency, fast response time and long life time (Díaz-González et al., 2012). It is, however, also acknowledged that batteries have relatively high capital cost (Culver, 2010). Potential investors in battery energy storage systems should therefore carefully investigate how their BESS can and should be operated before they make their final investment decision.

2.4.2. FCR operation

The operation of batteries in the provision of FCR services seems, however, to be subject to constraints in both the technical and institutional domain. This can be illustrated by the use of the alignment scheme (see Figure 2.3), that is described by Ménard (2014). This alignment scheme is a very powerful framework in the identification of the interaction between technology and institutions. It shows how the technological architecture, formal and informal institutions, specific technical characteristics and specific rules are defining how technical assets are operated in a system of interest.
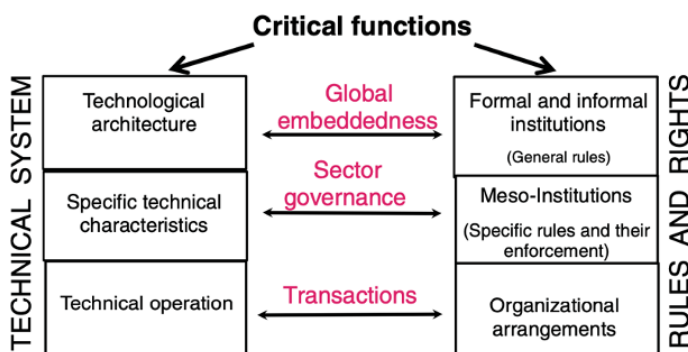

Figure 2.3: Alignment Scheme. Interaction between technology and institutions. Source: Ménard (2014)

Critical functions

One of the key concepts in this framework is the 'criticality' of the system that is of interest. As already described in the introduction of this master thesis, grid balancing is an essential controlling mechanism in the transmission of electricity from power generators to end consumers. Since the provision of FCR is crucial in the continuity of the technical operation of the energy system, it must be organized in such a way that it is always properly functioning.

Technological architecture

The technological architecture of the electricity system, including the power generation units, power consumption assets, transmission and distribution lines, transformation stations and balancing reserve assets, is the primary starting point that shows the need for balancing services. Electricity that is generated by power generation units and is transferred through the transmission and distribution lines has to be consumed directly by its consumer. When there is a mismatch between these electricity generation and demand, an imbalance in the power system network can occur and power generation assets could be damaged, potentially leading to electricity blackouts.

Formal and informal institutions

The need for balancing services is also determined by the people's perception of the provision of this energy commodity. Electricity is a form of energy that is crucial for economic growth, alleviation of poverty and the improvement of daily living standards (Ritchie and Roser, 2019). Energy security and reliability can therefore be seen as main general concepts that are embedded in society. Consequently, grid balancing is an essential mechanism of the electricity network, that has to be governed and operated in such a way that it can guarantee the continuity of electricity supply.

Specific technical characteristics

FCR is, as described, one of the controlling mechanisms that is used for maintaining the balance in the electricity network. The specific technical characteristics of the various balancing assets are determining the opportunities to use these assets for the delivery of FCR power (e.g. the possibility of thermal generators to adjust their power output (Carlini et al., 2019). For BESS, these technical capabilities are limited by several factors. First of all, batteries have a limited energy reservoir. FCR power that is delivered could therefore potentially use the total available energy capacity of a battery, completely emptying or filling the energy storage reservoir. If this situation occurs, batteries are not capable of providing any FCR services that requires a specific amount of battery energy capacity which is not physically available. Other limitations can be identified in the PCS of a BESS. The characteristics of this PCS limits the amount of power that a BESS can provide within one time unit and limits its use for FCR purposes.

Specific rules and their enforcement

Next to these specific technical characteristics, sector specific rules are also determining the way in which FCR can be acquired and operated to guarantee electricity system security and reliability. In general, the required frequency containment reserve capacity is acquired from authorized balancing service providers. To become an authorized balancing service provider, a potential market party is typically required to show that their balancing assets are capable of providing the FCR services in an appropriate way. As stated by van der Veen and Hakvoort (2016), the requirements that a market entrant should meet include technical pre-qualification tests of the FCR assets of interest and tests that examine the proper exchange of FCR activation data with the TSO. The existing institutional arrangements between the BSPs and TSOs are not only important for FCR market access, but also for the operation of a BESS providing FCR power. Regulations shape the way in which FCR assets are activated and therefore, how the battery is performing over time.

Technical operation

The various rules and technical characteristics of a BESS determine the way in which these batteries could and should be operating in the provision of FCR power. The operation of a battery providing FCR services is thus constrained by the combination of technical and institutional factors.

Organizational arrangements

The organizational arrangements are related to the way in which balancing service providers are structuring their activities, taking into account the rules that are defined at a broader, institutional level. These activities can include the development and use of BESS investment strategies, state of charge management strategies or other strategies that are related to the operation of a BESS in FCR provision.

2.4.3. BESS operation dependencies

The previous section has highlighted the interaction between technology and institutions in the operation of FCR assets. Regulations, on the one hand, are shaping the way in which FCR should respond to grid frequency imbalances. Technological limitations, on the other hand, are shaping the capabilities of the various technological assets to do so. The alignment of these two should, in the end, result in a system that is capable of performing the critical functions that are essential for grid security and reliability.

BSPs might, however, not only be interested in the security and reliability of the electricity network. The profitability of their balancing reserves can also be very important and may affect the way in which they want to operate their assets that are providing FCR power. To be able to comply with the overall system rules and to guarantee the continuity of electricity supply, it seems necessary to not only align the technological and institutional systems with each other, but also to include the other interests of the various actors that are involved in this grid balancing system.

One way of aligning these external interests is to find opportunities for profit maximization within the current technical and institutional systems. The identification of potential value-stacking opportunities in the current operation of a BESS can be the first step for optimizing the battery's utilization and hence, profitability. This does, however, require full insight into the current operation of a battery energy storage asset that is providing these grid balancing services. Knowledge about the FCR activation (the technical system) and the rules that determine this activation (the institutional system), is therefore required.

3

Prerequisites for FCR operation in the European Union

3.1. Literature review introduction

As described in the previous section, FCR is one of the controlling mechanisms of the ENTSO-E to secure the stability and reliability of the European electricity network. The use of energy reservoirs for maintaining the nominal value of 50 Hz is a shared goal among the TSOs that represent this European entity. Although there is an overall shared understanding about obtaining and activating these power reservoirs assets for frequency containment purposes, there are many differences in the market and technical design of acquiring and using these power reservoir assets. Chapter 2 described furthermore that various regulations seem to determine how potential balancing service providers can become authorized to deliver FCR services and how their reservoir assets should respond to certain grid frequency changes. These regulations will define the way the power conversion system and energy storage reservoir of a BESS should be used to counteract power imbalances in the electricity network.

Since these regulations can affect the direct operation of a battery that is providing FCR services, they can also indirectly affect the potential to use the battery for other battery purposes. This can be explained by the fact that a BESS has a limited power and energy capacity. Using a battery for multiple BESS applications simultaneously therefore requires the power and energy capacity requirements of the various applications to be aligned.

To be able to identify the value-stacking potential of a BESS that is providing FCR, a regulatory analysis and their consequences for battery behavior seems thus necessary. In this chapter, a literature review is described that is performed to obtain a general understanding of the FCR requirements of FCR markets that are present in the European Union. This analysis is used to identify the effect of FCR regulations on the battery's behavior. Based upon this, the opportunities for value creation of batteries that are providing FCR services in the European Union can be identified.

3.2. Literature review selection

For this literature review, studies have been collected that describe the regulations regarding the procurement and operation of energy resources in primary frequency control for European countries. The database Scopus was used to search for relevant studies. To obtain sufficient information about FCR market arrangements and FCR operation within Europe, a broad search string (see Appendix A) was used containing the key words *Energy/Power/electric**, *Europe** and *Frequency containment* (or other equivalent key words describing FCR such as *Balancing market*, *FCR*, *frequency reserve*, *frequency regulation* or *primary control*). Regulatory environments concerning energy markets are rapidly changing. To secure the quality an actuality of the regulations described in the literature review, the

literature search was limited to articles that were published in the year 2016 up until the day the literature search was conducted (20th April 2020). Using a search string with the keywords mentioned above and article publishing time constraints, 142 articles were collected from the Scopus database. Subsequently, a set of 58 potentially relevant studies was selected by title, excluding duplicate articles and articles that were not related to the field of energy science and balancing services in general. Based upon the abstracts of the remaining articles, the number of articles included in this literature review was further reduced. For this study, only articles focusing particularly on the market design or operation principles of FCR assets were included. The selection of articles based on the abstracts resulted in 18 remaining articles that were included in this review.

3.3. Literature review results

For the different articles that were extracted from Scopus and selected for this literature review, a differentiation can be made between articles that describe the operational requirements of specific power reservoirs that are used for FCR purposes and articles that describe other requirements that have to be fulfilled by the balancing service providers to enter and operate in the FCR market. In Table 3.1, an overview is given of the investigated studies and their classification based upon the aforementioned differentiation.

Table 3.1: Classification of studies in the literature review

Operational Requirements	Market Participation Requirements	Source
X		Aziz et al. (2018)
X	X	Barbero et al. (2020)
X		Benini et al. (2016)
	X	Bompard et al. (2018)
	X	Borne et al. (2018)
	X	Brijs et al. (2017)
X		Holttinen et al. (2016)
X		Hollinger et al. (2016)
X		Jomaux et al. (2017)
X	X	Koller et al. (2016)
X	X	Marchgraber et al. (2020)
X	X	Motte-Cortes and Eising (2019)
	X	Poplavskaya and De Vries (2018)
X	X	Poplavskaya and de Vries (2019)
X		Posma et al. (2019)
	X	Roben (2018)
	X	Schopfer et al. (2017)
X		Zeh et al. (2016)

3.3.1. FCR prerequisites: Operational requirements

The operational requirements of the power reservoirs that are used for FCR purposes are mainly related to the frequency measuring capabilities and the power delivery capabilities of the power reservoir assets over time. These operational requirements can be translated to different important variables for FCR provision, including the dead band, insensitivity range, power provision rate, power provision speed and power provision duration.

Dead band

The dead band can be described as a region around the nominal system frequency, wherein the control power provided by FCR assets is not required to react to frequency deviations (Zeh et al. (2016);Hollinger et al. (2016);Aziz et al. (2018)). This will result in a tolerated frequency deviation band, wherein a BSP can decide to not operate the power reservoir asset for FCR purposes.
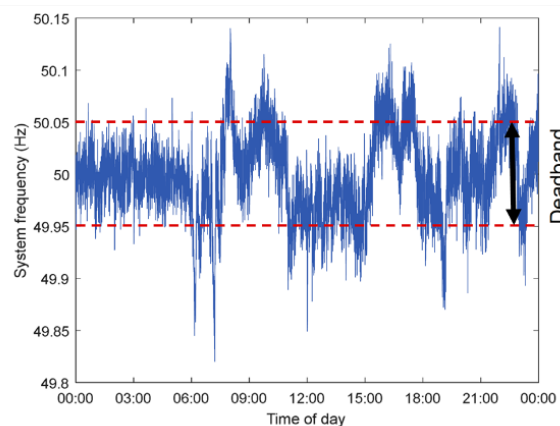

Figure 3.1: Example of a dead band region around the nominal system frequency (deadband of ±0.05 Hz). Source: Haakana et al. (2017)

In figure Figure 3.1, an example is shown of a deadband region of +0.05 Hz around the nominal grid frequency of 50.00 Hz. In this example, a tolerated frequency deviation band exist between 49.95 Hz and 50.05 Hz.BESSs that are providing FCR services will not be activated at the moments in time the measured grid frequency is within this frequency deviation band. The power capacity of the battery that is reserved for FCR power will therefore remain zero during these specific time moments.

Insensitivity range

Closely related to the dead band is the insensitivity range. As described by Posma et al. (2019), the insensitivity range can be described by the range of frequency deviation to which an FCR system is insensitive. This means that the power reservoir used for FCR purposes does not have to adjust its power output to frequency deviations within that insensitivity range (Posma et al., 2019). The dead-band region, as described in the previous section, is often derived from this insensitivity range, taking into account the technical limitations of measuring local grid frequencies (Benini et al., 2016) and therefore, the insensitivity measuring unit of an FCR asset. The dead band can thereby be seen as an insensitivity range around a specific value (e.g. at 50 Hz). An insensitivity range can, on the other hand, be around any value.

Power provision rate

The amount of control power that is to be provided by the power reservoir assets is often related to the height of the frequency deviation from its reference value and the contracted amount of FCR power by the BSP. Various power-frequency characteristics, determined by an individual or group of TSO(s), exist within Europe and describe the way in which a FCR unit should adjust its power output according to the change of measured grid frequencies (Holttinen et al. (2016);Aziz et al. (2018)).

Figure 3.2 shows, as an example, the specific power-frequency characteristics of power reservoir units that are providing FCR in Germany. The FCR assets in Germany are not required to react to frequency deviations within the dead band range (49.99 Hz – 50.01 Hz). For frequency deviations between 10 mHz and 200 mHz from nominal system frequency (50 Hz), the power output provided by the FCR units are supposed to increase linearly to 100% of the contracted amount of FCR power (Zeh et al., 2016). Frequency deviations above 200 mHz should fully activate the contracted amount of FCR power (Zeh et al., 2016). The power output of an FCR unit can hereby be seen as positive in case of under-frequency (Δf < 49.99 Hz), which means that power is injected from the FCR unit to the grid (discharging of a BESS). Negative power output is considered in case of over-frequency (Δf > 50.01 Hz), having power absorbed from the grid (charging of a BESS).
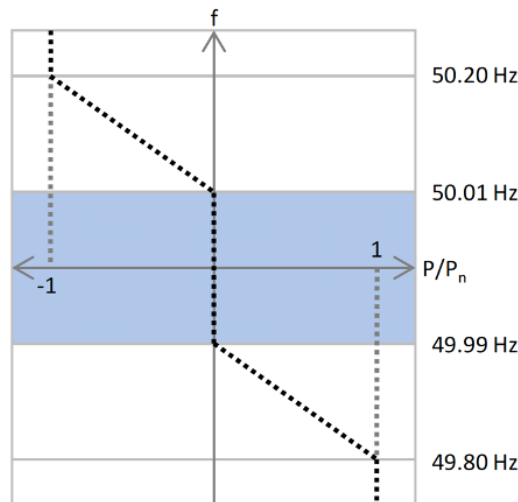

Figure 3.2: Power-frequency characteristics of power reservoir units that provide FCR in Germany. The x-axis shows the relative amount of power P (W) from the total reserved FCR power Pn (W) that should be provided at a specific frequency deviation. the y-axis shows the grid frequency. Source: Zeh et al. (2016)

Power provision speed

Next to the amount of power that has to be delivered by the contracted FCR units based upon the frequency deviation of the grid, the speed in which this contracted amount of FCR power has to be delivered is often part of the operational requirements that are set by the different European TSOs. This provision speed can hereby be defined as the time (often in seconds) in which an FCR unit should provide a specific amount of contracted power output (either positive of negative) to or from the grid after a certain deviation in grid frequency is detected (Hollinger et al. (2016);Jomaux et al. (2017);Poplavskaya and de Vries (2019);Motte-Cortes and Eising (2019);Barbero et al. (2020)).

The power output responses of FCR units to frequency deviations are generally within a matter of seconds. Since BESS can ramp up and ramp down their power output relatively fast, they are normally able to react to these frequency deviations in an appropriate way (Hollinger et al., 2016).

Power provision duration

The length of the power output response of FCR units to frequency deviations is another requirement that is often described by TSOs in their regulations concerning the operation of the contracted FCR power reservoirs. These regulations mainly describe the minimal amount of time that a FCR unit should be able to provide the contracted amount of control power at specific frequency deviations. Various articles (Barbero et al. (2020); Jomaux et al. (2017); Koller et al. (2016); Marchgraber et al. (2020); Poplavskaya and de Vries (2019)) provide information on the length of these power provision periods for different countries within Europe, ranging from a 20-second to 30-minute period. After this period,

BESS often have a certain recovery period in which the battery is not required to react to frequency deviations and remains idle.

3.3.2. FCR prerequisites: Market participation requirements

To be able to use a BESS for FCR purposes, BSPs are supposed to comply with all market requirements. These market requirements do not only include the operational requirements of the FCR assets that have been described previously, but also include other requirements, such as FCR market access restrictions and bid-related FCR market requirements. The market access restrictions, FCR contracting period, bid symmetry, bid size and unit pooling requirements and prerequisites are all factors influencing the way in which BSPs can operate in the FCR market and therefore operate their FCR assets.

Market access restrictions

Various countries within Europe have different regulations concerning the way in which the primary reserve is procured. For some countries, the total required FCR power is procured in a public market, accessible for all types of providers (Poplavskaya and de Vries, 2019) *(Open FCR market)*. The reserve capacity of these countries is hereby increasingly procured on an international level (Koller et al., 2016). In other countries, as described by Borne et al. (2018), part of the required FCR capacity is provided by large producers of electricity *(Restricted FCR market)*. They are obliged to deliver a specific amount of FCR power, based upon their energy production. Some European countries do not even have an FCR market implemented on a national scale. In the Baltic synchronous area, including Estonia, Latvia and Lithuania, the FCR power market is totally controlled and provided by Russia (Bompard et al., 2018) *(No FCR market)*. To be able to provide FCR power within these Baltic states, BSPs must therefore have access to the Russian FCR market and follow the Russian procurement guidelines.

FCR contracting period

The power that is required for frequency containment is mainly procured in the form of FCR provision contracts for specific time periods. BSPss that get into a provision contract with a TSOs are supposed to deliver FCR power during this particular time period according to the operational requirements that are prescribed. The duration of these FCR contracts can vary among the different TSOs and FCR markets. FCR capacity can hereby be contracted on an hourly, daily or weekly basis (Brijs et al. (2017);Barbero et al. (2020);Koller et al. (2016)).

Bid symmetry

In FCR markets, two types of products can be sold: a positive reserve and a negative reserve (Roben, 2018). The positive reserve is a product that is activated upon specific frequency deviations below the reference value and is therefore used to increase the amount of power that is provided to the grid. The negative reserve is activated at specific frequency deviations above the reference value, which will increase the amount of power extracted from the grid. Within some countries, these two products (upward and downward regulation) are procured separately (Roben, 2018). BSPs can hereby make an offer to provide FCR power by their FCR assets in either the positive or negative direction or in both directions.

Other countries, however, have specific regulations that require BSPs to provide the entire amount of reserve power in both the positive and negative direction (Roben, 2018). Having a symmetrical FCR product can constrain various BSPs to enter or participate in the FCR market since this symmetrical bidding process requires BSPs to have FCR units available that are able to deliver the same amount of upward and downward FCR power simultaneously (Borne et al., 2018).

Bid size

In general, the different TSOs provide a minimum bid size for BSPs to participate in the FCR market (Barbero et al., 2020). This bid size will describe the minimal amount of power (in MW) that a BSP can offer and the FCR asset should be able to deliver during the period of contract. For the various countries in the European union, the minimal bid size for the specified period of contract can be between

0.1 MW and 1 MW of FCR power (Motte-Cortes and Eising (2019);Schopfer et al. (2017);Poplavskaya and de Vries (2019);Marchgraber et al. (2020)).

Unit pooling

As described in the previous sections, BSPs are often required to offer a minimal amount of FCR power in the balancing market for a specific contracting period. For some countries, these offers even have to be symmetrical. These requirements can be a burden for small sized energy resources to participate in the FCR market, since they might not be capable of delivering the amount of required FCR power in the required amount of time in both the positive and negative direction (Borne et al., 2018). For these small energy resources, there is a need for aggregation or pooling, allowing different flexibility assets to participate in the balancing market (Poplavskaya and de Vries, 2019).

The regulations concerning the opportunity to pool resources affect the possibility of BSPs to integrate the capacities and capabilities of their reserve unit portfolio (Poplavskaya and de Vries, 2019). The allowance of aggregators and pooling of FCR unites in a balancing market can therefore have a huge impact on the number of potential participants and the installed FCR capacity.

For various countries within Europe, such as Germany and the Netherlands, steps have been taken to allow aggregation and pooling in the FCR market (Motte-Cortes and Eising, 2019). The TSOs in the Nordic synchronous area and the United Kingdom have also showed actions to open up their balancing markets to aggregators (Motte-Cortes and Eising, 2019). Other countries in Europe, however, are lacking behind in their market opening to all potential aggregator entities (Barbero et al., 2020). This can restrict certain parties to pool their flexible energy resources and participate in the FCR bidding process.

3.4. Literature review discussion

The results show that various regulations and market access restrictions exist for the synchronous areas that are present in the European Union. These regulations affect the participation of reserve assets in the provision of FCR power and thereby the behavior of battery energy storage systems. This can, in the end, affect the potential use of battery energy storage capacity for added value creation. In this section it is described how the different regulations can affect overall battery performance and how these regulations can either contribute or restrict potential balancing service providers in using their battery for FCR and for other battery purposes.

3.4.1. Idle moments

As described in the results, FCR assets are not required to provide FCR power within the tolerated frequency deviation band. This will result in time periods where the state of charge of the energy storage reservoir is stable over time (idle periods) and where the power conversion system is not used for FCR power (see Figure 3.3). BSPs can therefore decide to use the battery for other purposes in the time periods the measured grid frequency is within this dead band region. Hollinger et al. (2016), as an example, poses that a BESS that is providing FCR power can use this dead band region for battery management purposes. By discharging and charging the battery during the idle time periods, BSPs can still comply with the regulations that prescribe how much power output (in either the positive or negative direction) a battery should deliver in the periods the measured grid frequencies are not within this dead band region. In Tan et al. (2020), it is stated that this state of charge management strategy can be beneficial to reduce deep charge and discharge of a BESS, thereby prolonging its lifetime and overall profitability.

Since FCR assets are not required to react on frequency changes within the insensitivity range, BESSs could, in theory, also use this insensitivity range for properly managing the state of charge of a battery or serving other battery purposes. In practice, however, it can be questioned whether the availability of an insensitivity range would genuinely increase the opportunities for value stacking. The insensitivity range is, as described by Benini et al. (2016) often based upon the technical limitations of grid frequency measuring units. Frequency deviations within the insensitivity range might therefore be difficult to detect by the frequency measuring units of a BESS, which makes it impossible for power reservoir assets to operate properly within this region for other purposes than FCR.
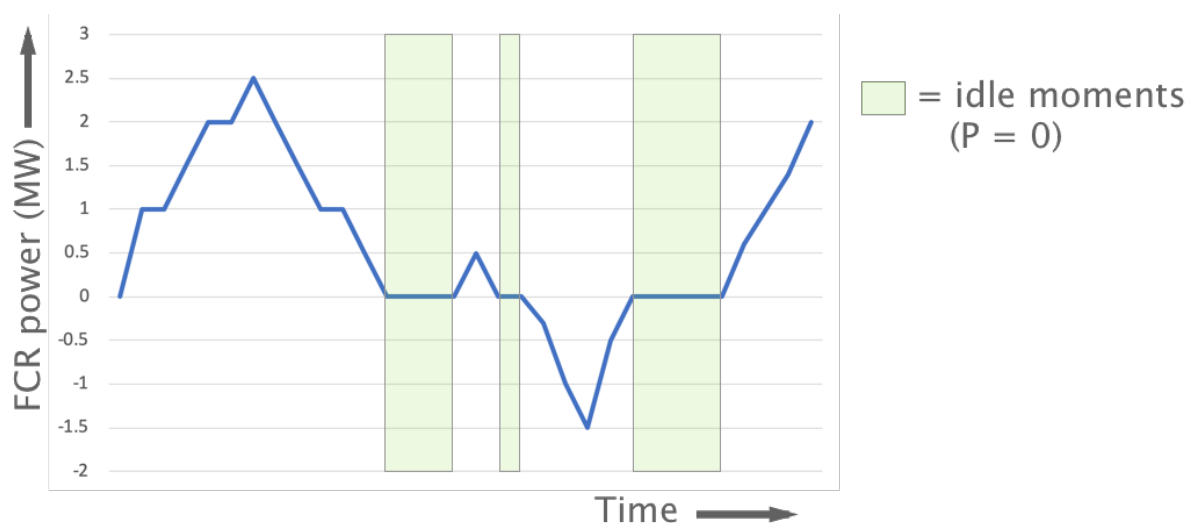

Figure 3.3: Idle moment identification of a BESSs. These idle moments (at moments where the power conversion system is not used and P=0) could potentially be used to serve other battery purposes.

3.4.2. Underutilized battery energy capacity

The regulations that prescribe the power frequency characteristics of a battery providing FCR services are also limiting the value stacking opportunities of these storage systems. For batteries, the power provision rate, power provision speed and power provision duration do not only give constraints to the power output (of the grid-connected wire) of a battery at a certain timepoint, but also to the size or the state of charge limits of the energy storage reservoir of a battery that is providing FCR services. As the operational requirements in the results section of this literature review prescribe, BESSs that are used for FCR should be able to maintain the fully contracted power output for the given provision time period, which in fact means that the energy capacity of the battery should also be big enough to be able to provide this control power (in either the positive or negative direction) over the total length of FCR provision. To guarantee that the contracted FCR power can be delivered at any timepoint, the battery should therefore either be big enough to provide the required FCR power over the specified time horizon (Engels et al., 2019) or have a proper state of charge management strategy implemented (Iurilli et al., 2019).

For both of these cases, it could be possible that part of the battery energy capacity remains un(der)utilized. First, a BESS could have a bigger size than required for providing the contracted amount of FCR power (see Figure 3.4) over the maximal provision period prescribed (Thien et al., 2017). This would result in a 'valid' operating range of the state of charge of the battery system that could be used for other battery purposes. Secondly, the required FCR power over a specific time period could be less than the amount that the balancing service provider is contracted for. This could, in theory, give an additional operating range for balancing service providers that are participating in a FCR market and want to use part of their battery capacity for other applications.
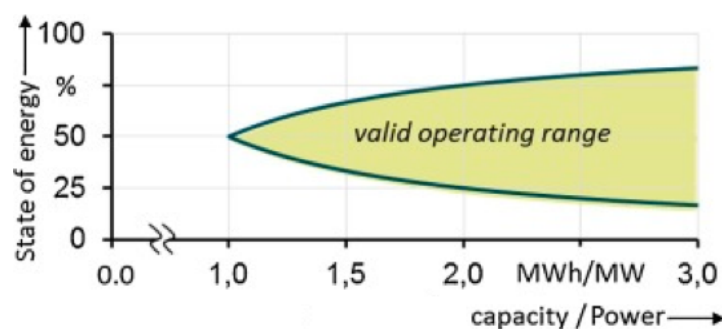

Figure 3.4: Valid operating range of a BESS. Batteries that are providing FCR services are required to deliver a certain amount of power over a certain time period (as a response to frequency deviations). If the amount of power (in either the positive or negative direction) that is required over a certain time period is equal to the total capacity of the battery (capacity/Power = 1.0), no energy capacity is left for serving other battery purposes. If the required amount of FCR power over a certain period is lower than the total energy capacity of a battery, part of the energy capacity of a battery will not be used. This underutilized energy capacity (here described by a valid operating range of the state of charge of the BESS) might be used for serving other batter purposes. Adopted from: Thien et al. (2017)

Next to the power frequency characteristics (power provision rate, -speed and -duration), other regulations also affect the way in which a specific amount of energy capacity of a battery is used and the affiliated state of charge is evolving over time. Providing FCR within an asymmetrical market will, for example, only change the state of charge of the battery in one specific direction (the battery will either be charged or discharged) (Hollinger et al., 2018). The addition of a battery application that requires energy or power in the opposite direction could therefore be a good additive to add value to the overall battery system.

The regulations concerning bid size and unit pooling are directly correlated to the amount of FCR capacity a balancing service provider can bid in a FCR market. This will have consequences for the minimal and maximal contracted FCR power and the battery energy capacity that is needed to deliver the required FCR power over a particular time period. These regulations can thus affect the ratio between the energy capacity of the battery and the prequalified FCR power (as shown in Figure 3.4)

and thereby indirectly affect the battery state of charge behavior and the amount of energy that can be used for other battery applications.

Although the FCR contracting period does not give direct insight in the opportunities of using FCR with other battery applications simultaneously, it does influence the value-stacking opportunities indirectly. This can be explained by the fact that a balancing service provider could better determine their bidding and operational strategy in FCR markets that have relatively short FCR contracting periods. As described by Brijs et al. (2017), BSPs that are participating in FCR markets that have shorter contracting periods are able to make a better estimation of the profitability to use specific parts of their storage assets installed capacity for FCR purposes. Based upon the current or predicted market conditions and the battery's state of charge evolvement, BSPs can adjust their FCR bidding size and choose the preferred state of energy operating range.

3.4.3. Optimal BESS management and utilization

The previous sections have shown that an optimal utilization and value creation of a battery providing FCR power might only be achieved if BSPs are optimally using the idle moments and total energy capacity of their batteries. To optimize the use of these idle moments and (underutilized) battery energy storage capacity over a specific time period, it seems necessary to have perfect knowledge about future FCR activation and state of charge developments. This information can be used to prevent the noncompliance to FCR provision and the technical state of charge limitations (Angenendt et al. (2020); Claessens et al. (2019)).

It can, however, be questioned whether these idle moments periods and state of charge developments can be (properly) predicted. In Chapter 2, it was already stated that the operating reserves are mainly required for electricity system imbalances that cannot be restored by the natural system inertia (Saleh Ebn Sharif, 2017). Larger system imbalances, resulting in frequency deviations that trigger the FCR activation can be seen as the initial cause of battery state of charge fluctuations (of batteries that are providing FCR services). From this perspective, it can be concluded that the behavior of a BESS is the result of the probability of a certain power imbalance to occur and FCR regulations that determine how an FCR asset should respond to this power imbalance. To be able to perfectly predict the idle moment periods and state of charge developments, it seems necessary to have knowledge about the predictability of power system imbalances in combination with the information on the FCR asset responses to these power imbalances.

3.4.4. Literature review limitations

Although this literature review identifies two potential degrees of freedom (using idle moments and underutilized battery energy capacity) that can be used for added value creation of a BESS providing FCR services, the real potential and benefit of using these degrees of freedom for added value creation can be constrained or expanded by other regional regulations that are present in the area of interest and potential future changes in the existing regulations.

Specific regulations

For some synchronous or balancing areas, FCR regulations might be subject to even more regulations that can contribute or restrict the value stacking opportunities. As an example, the existence of a regulation that allows for FCR power overfullfillment (which in fact means that you can provide or extract more FCR power than required) will give the BSP the opportunity to not only use the idle moments of a battery for other purposes (that require PCS that is connected to the grid), but also the moments where the FCR asset is actively providing FCR power (Schlund and German, 2017).

Change in existing regulations

FCR regulations are initially implemented to guarantee that the power system is able to withstand larger system imbalances and thereby, prevent blackouts from happening. Regulations for FCR provision that

are used in one specific synchronous area can, however, change or evolve over time based upon the historical performance of these FCR assets or an overall changing environment.

The TSOs that are controlling the grid stability and reliability might, as an example, need to change their FCR regulations as a result of renewable energy penetration. Since these intermittent energy resources are generally not contributing to the natural system inertia (Tielens and Van Hertem, 2016), renewable energy resources that are used in electricity generation tend to increase the amount and heights of frequency deviations from the nominal grid frequency level. To compensate for this lower system inertia, TSOs might need to procure higher FCR volumes or change the operational requirement of the available reserves (or add new ones).

Another example that might require the TSOs to adjust their regulations is the European market integration and market opening. To decrease electricity prices and increase power system security, the European Union tends to integrate various electricity markets (of different synchronous areas and balancing areas) with each other and open up these markets for third parties (Newbery et al., 2016). To be able to integrate the various markets with each other, it is necessary that all the institutional arrangements are aligned. This includes the prequalification requirements of potential BSP to enter and participate in the integrated FCR markets.

3.5. Literature review conclusion

In this literature review, it is showed that frequency containment reserve regulations determine the way in which FCR assets are activated and should respond to specific grid frequency deviations. Since this FCR activation is directly correlated to the state of charge of the battery, FCR regulations are indirectly defining the overall battery's behavior and performance.

The regulations that are described in this review seem to affect the battery's behavior in roughly two ways. First of all, some of these regulations define the moments that a battery should provide or not provide FCR power, which can result in a battery that is 'idle' over particular time periods. Secondly, some regulations determine the height and direction of the FCR activation, which can directly reflect the battery's state of charge development over time and the utilization of energy storage capacity for FCR services.

Batteries could potentially use the un(der)utilized energy storage capacity and, in particular, the idle moments of a battery to perform other battery services. In this literature review, it is suggested that optimizing the use of these idle moment periods and underutilized energy storage capacity could potentially increase the overall profitability of a BESS.

To be able to identify the full potential of using these idle moments and underutilized energy storage capacity for serving other battery purposes, it is necessary to determine the practical usability of these two degrees of freedom for value-stacking opportunities. In the next two chapters, the usability of both these degrees of freedom will be further analyzed.

In Chapter 4, more insight will be obtained in the usability of the idle moments (moments at which the power conversion system of a battery is not used) for value-stacking in the operation of a battery providing FCR services. In Chapter 5, the potential of using un(der)utilized energy storage capacity (periods in which the energy storage reservoir is not fully used for FCR power) for serving other battery services will be discussed in greater depth.

4
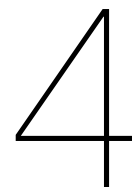
Modelling the activation profile of batteries providing FCR services for three synchronous areas within Europe

4.1. Simulation model introduction

The previous chapter shows that there are several important variables that determine the way in which the FCR assets are activated for FCR controlling areas within Europe. The different operational requirements that are set by the TSOs responsible for controlling these synchronous areas influences the behaviour of battery energy storage systems that are providing FCR services. As stated in the literature review, battery energy storage systems should be capable of providing or extracting the required amount of FCR power to or from the grid based upon these regulations. These regulations determine at what time a battery should actively provide FCR power and at what time the battery is not needed for FCR purposes.

This chapter describes the research that is conducted to get a better understanding of the FCR activation of a BESS providing FCR services. A simulation model is constructed and is used to determine the FCR activation, the occurrence of idle moments and the length of the idle moment periods. Based upon this information, more insight is created in the usability of idle moments for battery value-stacking.

4.2. Simulation model methodology

4.2.1. General model description

In this section, the simulation model that is constructed to analyze the activation of assets providing FCR services is elaborated. The activation of the BESSs is determined by the operational requirements that are set by the TSOs that are acquiring these FCR assets for an FCR market within a specific synchronous area.

Model scope

As been described in Chapter 2, there are several synchronous areas within Europe that all have their own grid characteristics. Although the reference value of the synchronous areas within Europe is the same (= 50.0 Hz) for all regions, grid frequency profiles can differ among the synchronous regions depending on electricity demand and supply profiles, weather conditions and the overall electricity grid architecture. The requirements to operate BESSs in the different synchronous areas might moreover vary, as described in Chapter 3. The requirements that are described in the literature review will therefore be used as a starting point (model variables) for this simulation model.

Since the UCTE, Nordic and United Kingdom synchronous areas are the largest synchronous areas within Europe (see Figure 2.1), these three regions have been selected as the cases of interest for this study. Properly balancing these synchronous areas seem to be of most interest, since imbalances in these electricity networks might result in the most widespread blackouts of all synchronous areas that are present in the European Union. Although the Baltic countries are also part of a very large synchronous area, grid balancing services are completely provided by Russia (Bompard et al., 2018). Since there is no European FCR market for this synchronous system area, this region was not included in this study.

For this model, it is assumed that the energy storage system that is providing the FCR services is always available and thus, accepted for the entire simulation period by the TSO for providing primary frequency control. This is done for the reason that the bidding prices of FCR capacity can vary among the different balancing service providers and the results of these market processes are often not publicly available. As a consequence, the results of this study might underestimate the total amount of time the battery is not used for FCR purposes. The present study can, however, still be used to gain an preliminary and rough understanding about the value-stacking opportunities of batteries in the time the battery is used for FCR purposes. The maintenance periods of battery energy storage systems are also not taken into account in the model. It seems that, in the case of a Li-ion battery, this is not a significant concern, since this battery type has the property of being very reliable and having low operation and maintenance requirements (Zubi et al., 2018). Maintenance periods will thus have only little to no effect on the total availability of a battery for all different BESSs services.

As described in Chapter 3, both regulations, measured grid frequencies and the prequalified FCR power determine how much FCR power a BESSs should deliver at each time moment. This activation does therefore not directly depend on the technological characteristics of a BESSs. The technical properties of a battery, including the total energy storage capacity, conversion efficiencies and daily self-discharge rates, are therefore not in the scope of this research.

Time resolution

In general, assets that are providing FCR services should be capable of delivering the required amount of FCR power almost instantaneously (Ela et al., 2010). This means that these assets should be able to respond correctly to all 'significant' grid frequency deviations. Since frequency deviations are measured on a second scale basis, the response of the FCR assets to these frequency deviations should also take place on the same time level. Although this detailed time granularity makes the simulations very time-consuming, it seems necessary to use this level of detail to clearly understand the frequency and periods in which an FCR asset is activated.

Time horizon

To be able to get a good estimation of the required activation power and activation periods of the FCR assets, the time horizon was set to one year. This was done to make sure that all daily, weekly and seasonal effects are taken into account in the analysis. The use of this yearly time horizon could be helpful to include the seasonal variation in renewable (wind and solar) energy output (Klein et al., 2017), which tend to influence the need for grid balancing ancillary services (Chuang and Schwaegerl, 2009). Yearly trends, such as an increasing penetration of renewable energy resources in the electricity mix (Mehedintu et al., 2018) can, however, not be identified with the chosen time horizon. Although these yearly trends could potentially influence the need for ancillary services in general, the inclusion of more years in the simulation model would drastically increase the computational time required to execute the simulation.

Model input

To determine the activation of assets providing FCR services, several input variables are needed. Since the activation of FCR assets depends on grid frequency deviations, one of the main input variables is the grid frequency profile of a specific synchronous region. Another important input variable is the amount of FCR power that is available and contracted for FCR purposes, since this can also influence

the height of the response to frequency deviations. Finally, area specific regulations concerning FCR activation are required to simulate the activation of the assets that are providing the primary control services.

The area specific regulations or operational requirements of the FCR assets that are included in the simulation model are all based upon the literature review that has been described in Chapter 3. The various operational variables that have been described in this literature review and that have a direct impact on the activation of FCR assets, are included in this simulation model. This includes the frequency dead band, power provision rate, power provision duration and bid symmetry concepts. The regulations concerning the power provision speed is not implemented in the simulation model, since the interpretation of these regulations can be different among the various BSPs and its implementation often depends on the technical limitations of the FCR asset. In this model, therefore, it is assumed that the battery energy storage system is instantaneously providing the required FCR power, which is a realistic assumption due to the fact that these BESSs are able to react to grid demand within a matter of milliseconds (Helwig, 2016). The insensitivity range of the BESSs for the various FCR markets was determined indirectly. This insensitivity range was based upon the decimal place accuracy of the grid frequencies that were present and measured in the synchronous area of interest. These historical grid frequencies are also measured with a frequency measuring unit, which is assumed to have the same characteristics as the frequency measuring units that are present in a BESSs.

Model output

The model generates information on the activation of an FCR asset, the height of this activation and the direction in which the FCR power is flowing. These results indicate at each moment in time whether the battery should have been providing electricity from the energy reservoir to the grid (discharging the battery) or extracting electricity from the grid to the energy reservoir (charging the battery). From these results, the idle moments of a battery for each FCR market can be identified and discussed. Moreover, the total length of these idle moment periods can be examined. Based upon this information, insight can be obtained in the predictability of these idle moments and the potential of using these idle moment for using the battery for other purposes.

4.2.2. Mathematical model

Based upon the general model description that is elaborated in the previous section, a mathematical model has been developed. In this section, the mathematical formulation of the simulation model is provided.

Frequency deviation

The amount of FCR power that the FCR asset should deliver at each time step depends on the height of the frequency deviation from its reference value. This frequency deviation $\Delta f(t)$ (Hz) can be derived with the formula

$$\Delta f(t) = f(t) - f_N \quad \forall t \in T \tag{4.1}$$

In this formula, $f(t)$ (Hz) is the locally measured grid frequency at timepoint t ($\forall t \in T$), wherein T is the set of all timesteps of the year 2019 (in seconds). The f_N (Hz) variable is the reference frequency value of the electricity grid. For all the synchronous areas within Europe, this reference value has been set to 50 Hz.

Power frequency characteristics

Depending on the measured frequency deviation from reference frequency at timepoint t ($\forall t \in T$), the asset that has a specific amount of FCR power P_{FCR}^{max} (W) reserved for FCR purposes will either be (partially or fully) activated or not. The amount of FCR power that the FCR asset should provide or extract from the electricity grid is dependent on the power frequency characteristics that have been described in the regulations provided by the TSOs controlling the synchronous area of interest. The

amount of FCR power P_{FCR} (W) that the FCR asset should deliver at timepoint t ($\forall t \in T$) can be described by the function

$$P_{FCR}(t) = \begin{cases} P_{FCR}^{max} & , |\Delta f(t)| \geq \Delta f_{FCR}^{start} + \Delta f_{max} \\ P_{FCR}^{max}(\frac{\Delta f}{\Delta f_{max}}) & , \Delta f_{FCR}^{start} < |\Delta f(t)| < \Delta f_{FCR}^{start} + \Delta f_{max} \quad \wedge \quad \Delta f_{max} \neq 0 \\ P_{FCR}^{max} & , \Delta f_{FCR}^{start} < |\Delta f(t)| < \Delta f_{FCR}^{start} + \Delta f_{max} \quad \wedge \quad \Delta f_{max} = 0 \\ 0 & , |\Delta f(t)| < \Delta f_{FCR}^{start} \end{cases} \quad (4.2)$$

The variable Δf_{FCR}^{start} (Hz) denotes the threshold, described by a frequency deviation from the reference frequency value, from which a minimal activation of the FCR asset is required. The Δf_{max} (Hz) variable describes the frequency deviation from Δf_{FCR}^{start}, where a maximal activation of the FCR asset is required.

Although the function above can already describe whether FCR is activated at a certain time point, it does not yet include the direction of the power flow. The FCR variable $P_{FCR-result}$ (W) that includes this power direction, can be described by the function

$$P_{FCR-result}(t) = \begin{cases} P_{FCR}(t) & , f(t) \geq f_N \\ -P_{FCR}(t) & , f(t) \leq f_N \\ 0 & , P_{FCR} = 0 \end{cases} \quad (4.3)$$

A positive value of $P_{FCR-result}$ corresponds to an electricity influx (extracting electricity from the grid, thereby charging the battery). A negative value of $P_{FCR-result}$ corresponds to an electricity efflux (providing electricity to the grid, thereby discharging the battery).

The real activation of the FCR assets can also be subject to several other conditions influencing the behavior of these FCR units. This includes the existence of a frequency dead band, the presence of a(n) (a)symmetrical FCR market and the power provision duration of FCR delivery.

Frequency dead band

The presence of a frequency dead band around the reference grid frequency value denotes that there is a region of grid frequencies in which the FCR asset is not required to deliver FCR power. This dead band region can be described by the variable $\Delta f_{deadband}$ (Hz), which is defined as the frequency deviation from nominal grid frequency wherein no FCR power has to be delivered. As a result, a tolerated frequency deviation band (without FCR activation) can be created between the values $f_N + \Delta f_{deadband}$ and $f_N - \Delta f_{deadband}$.

In the case that there is a frequency dead band present in a particular synchronous area, the real activation power of the FCR asset $P_{FCR-real}$ (W) can be calculated with the function

$$P_{FCR-real}(t) = \begin{cases} P_{FCR-result}(t) & , |\Delta f(t)| \geq |\Delta f_{deadband}| \\ 0 & , |\Delta f(t)| < |\Delta f_{deadband}| \end{cases} \quad (4.4)$$

The FCR asset will only be activated if the measured grid frequency is above the tolerated frequency deviation band.

(A)symmetrical FCR market

The presence of a symmetrical or asymmetrical FCR product does also influence the activation of the acquired FCR assets. As described in the literature review in Chapter 3, a symmetrical FCR product includes both a positive and negative reserve. The FCR can therefore both be activated for frequency deviations above and below the reference value. In an FCR market where only a negative reserve is procured, FCR assets can only be active if the frequency is above the reference value. In an FCR market where only a positive reserve is procured, the FCR assets can be activated at measured grid frequencies below the reference value. The real activation power of the asset providing FCR $P_{FCR-real}$ will therefore be subject to the presence of an (a)symmetrical FCR market, described by the function

$$P_{FCR-real}(t) = \begin{cases} P_{FCR-result}(t) & , FCR_{negative} = True \quad \wedge \quad f(t) > f_N \\ P_{FCR-result}(t) & , FCR_{positive} = True \quad \wedge \quad f(t) < f_N \\ 0 & , FCR_{negative} = False \quad \wedge \quad f(t) > f_N \\ 0 & , FCR_{positive} = False \quad \wedge \quad f(t) < f_N \\ 0 & , P_{FCR-result}(t) = 0 \end{cases} \quad (4.5)$$

where $FCR_{negative}$ is a Boolean that describes the presence of a negative reserve and $FCR_{positive}$ is a Boolean that describes the presence of a positive reserve.

Power provision duration

For the various FCR markets in Europe, the ENTSO-E have described guidelines on the minimal duration of the FCR activation of FCR providing assets. These guidelines generally include a minimal duration t_{min}^{fcr} (sec) that an FCR asset should be able to provide FCR power in either the positive or negative direction. This t_{min}^{fcr} is often described as the minimal amount of time that an FCR asset should be able to provide the maximal amount of contracted FCR power (P_{fcr}^{max}).

Making use of the function

$$E_{min}^{fcr} = P_{FCR}^{max} \times t_{min}^{fcr} \quad (4.6)$$

the minimal amount of energy capacity E_{min}^{fcr} (Joule/sec) that an FCR asset should be able to use for FCR purposes can be calculated. To take into account the possibility that an FCR asset is not always using the full contracted FCR capacity at each time point, FCR assets in the European Union are mainly obliged to deliver the required amount of FCR power for a duration t_{req}^{fcr} (sec) that is proportional to t_{min}^{fcr}. By using the real FCR power $P_{FCR-real}$ at timepoint t ($\forall t \in T$) as a percentage of the maximum amount of contracted FCR power (P_{FCR}^{max}), the amount of energy E_{req}^{fcr} (Joule/sec) that is required for a specific period an FCR unit is activated (idle time period n) can thereafter be derived with the function

$$E_{req}^{fcr}(n) = \sum_{t}^{t=t_{req}^{fcr}} \frac{P_{FCR-real}}{P_{FCR}^{max}} \quad (4.7)$$

This E_{req}^{fcr} variable thus describes the amount of battery energy capacity that is needed to provide the required amount of FCR power over the period that the FCR power is asked for.

Some of the synchronous regions do also take into account the state of charge limitations of battery energy storage systems that are providing frequency containment reserve services. At the specific time moments that E_{req}^{fcr} (n) is equal to E_{min}^{fcr}, they therefore allow a period of recovery of length t_{rcv}^{fcr}, in which the FCR asset does not have to be used for FCR purposes. The $P_{FCR-real}$ in that particular recovery period will thus remain zero (which has also been adopted in this model).

4.2.3. Model implementation

The mathematical model that has been developed in the previous section has been implemented in a Python environment (Visual Studio Code), making use of the SimSES (Simulation of stationary energy storage systems) open source modeling framework that has been developed by Maik Naumann, Nam Truong, Marc Moeller and Daniel Kucevic from the Institute for Electrical Energy Storage Technology at the Technical University of Munich (Naumann et al., 2017). This modeling framework has already proven to be useful for analyzing lithium-ion based battery energy storage systems and optimizing the utilization of battery energy storage capacity for different applications, including FCR (Kucevic et al. (2020); Naumann et al. (2015); Truong et al. (2016)). A great advantage of using this modeling framework to simulate the activation behavior of FCR assets for different FCR markets is the fact that other aspects influencing the behavior of battery energy storage systems, such as battery

degradation, conversion efficiencies and state of charge management systems can easily be added in future research.

4.2.4. Case selection

As described in the general model description section, the activation behavior of an FCR asset providing FCR services within three different synchronous regions in Europe is examined; the UCTE region, the Nordic region and the United Kingdom. For these three synchronous regions, five FCR markets have been identified and included in this study. All these markets have their own regulatory characteristics that determine the activation of FCR assets. In Table 4.1, an overview is shown of the regulations of the various FCR markets that have been used in this study to simulate the activation behavior of FCR providing assets.

Information of these regulations have mainly been received by analyzing various documents (see Table 4.1 literature) provided by the TSOs that are controlling the different synchronous areas. In this study, the regulations that are described by the Belgium TSO Elia (UCTE region), Finnish TSO Fingrid (Nordic region) and the British TSO National Grid ESO (United Kingdom region) have been adopted in the model. The reason for this is that these TSOs have defined the most clear and complete information on the operational requirements of FCR assets. Although some small variations in the operational requirements have been identified between TSOs operating in the same synchronous area (Elia (2019);Fingrid (2019a);National Grid ESO (2017);Smethurst et al. (2017);TenneT (2019);50hertz et al. (2020);Merlo and Falabretti (2016);SVK (2020);Statnett (2019)), most of the operational requirements are the same. This is mainly due to the fact that there are international guidelines on the provision of FCR (European Parliament, 2017), which constrain the individual TSOs of one specific synchronous area in the regulations they can set up and use concerning the provision of FCR by balancing service providers.

Synchronous region and FCR market	Reference frequency	Dead band	Power provision rate	Power provision duration	Recovery time period	Bid symmetry	Literature
UCTE Belgium	50 Hz	±10 mHz	linear increase 0% at Δf = 0 mHz 100% at Δf = 200 mHz	≥ 25 min	2 hours	Yes	Elia (2019)
Nordic Finland FCR-N	50 Hz	±10 mHz	linear increase 0% at Δf = 0 mHz 100% at Δf = 100 mHz	≥ 30 min	2 hours	Yes	Fingrid (2019a)
Nordic Finland FCR-D	50 Hz	±10 mHz	linear increase 0% at Δf = 100 mHz 100% at Δf = 500 mHz	≥ 30 min	2 hours	No (only neg.)	Fingrid (2019a)
UK United Kingdom Non-Dynamic	50 Hz	±15 mHz	100% at Δf = 300 mHz	Indefinitely	-	Yes	National Grid ESO (2017) Smethurst et al. (2017)
UK United Kingdom Dynamic	50 Hz	±15 mHz	linear increase 0% at Δf = 0 mHz 100% at Δf = 500 mHz	Indefinitely	-	Yes	National Grid ESO (2017) Smethurst et al. (2017)

Table 4.1: Overview of regulations of the various FCR markets

Historical grid frequency data of the different synchronous regions of interest was collected from various databases. For all synchronous areas, the measured grid frequency for the whole year in 2019 was collected. The Frequency information of the Nordic region was collected from the Fingrid TSO (Fingrid, 2019b). Frequency information of the UCTE region was obtained from the Réseau de Transport d'Électricité (RTE) TSO (RTE, 2019). Historical frequency information of the United Kingdom region has been collected from the database of the National Grid ESO TSO (National Grid ESO, 2019). For the UCTE region, frequency data could only be obtained with a time interval of 10 seconds per observation. To be able to compute the FCR activation on a second basis, a forward filling method has been used. In the Nordic region, frequency data for the period '04/05/2019 10:48:07 - 09/05/2019 14:35:24' could not be obtained. Therefore, this particular time period has been excluded in the numerical data analysis part of this research.

In this research, a BESS with a prequalified FCR power rating of 1 MW has been used to compare the various synchronous areas and FCR markets. This power rating is based upon the minimal bidding

size of a BESS in the UCTE, United Kingdom dynamic, United Kingdom non-dynamic and Nordic FCR-N markets. Although higher or smaller bids might be possible for a battery with a different energy storage capacity, this can only directly influence the height of the FCR activation (the required FCR power is always proportional to the bidding size).

4.2.5. Model verification

To guarantee the correct implementation of the mathematical model in the Python environment, all the different variables that have been described in the previous section were implemented, used and checked by hand. This was done by creating a test sample of grid frequency deviations, simulating the FCR activation based upon the various regulations individually and jointly and checking the outcomes of the model with the expected ones. Errors that were identified were removed and additional model verification simulations were performed until no further errors could be identified.

4.3. Simulation model results

In this section, the simulation results of a battery energy storage system with a prequalified FCR power rating of 1 MW providing FCR services in three different synchronous regions (United Kingdom region, UCTE region, Nordic region) and five different FCR markets are elaborated. The results include observations on the activation, idle times and the length of idle time periods of the battery energy storage system.

4.3.1. Continental Europe (UCTE region)

Figure 4.1 shows a heatmap with the height and direction of the activation of a battery energy storage system providing FCR services in the UCTE synchronous area over the period of one year (in the year 2019). In this graph, a power influx (FCR power that is extracted from the grid and charges the battery) is described with values that are positive (P > 0 W). The efflux of FCR power (power that is provided to the grid and discharges the battery) is described with values that are negative (P < 0 W). The variation in color (color gradient) is explaining the relative intensity of the height of FCR activation. Higher power influx or efflux is hereby described with colors that are darker. In periods that the FCR asset is not providing FCR power, the color in the heatmap is completely white.
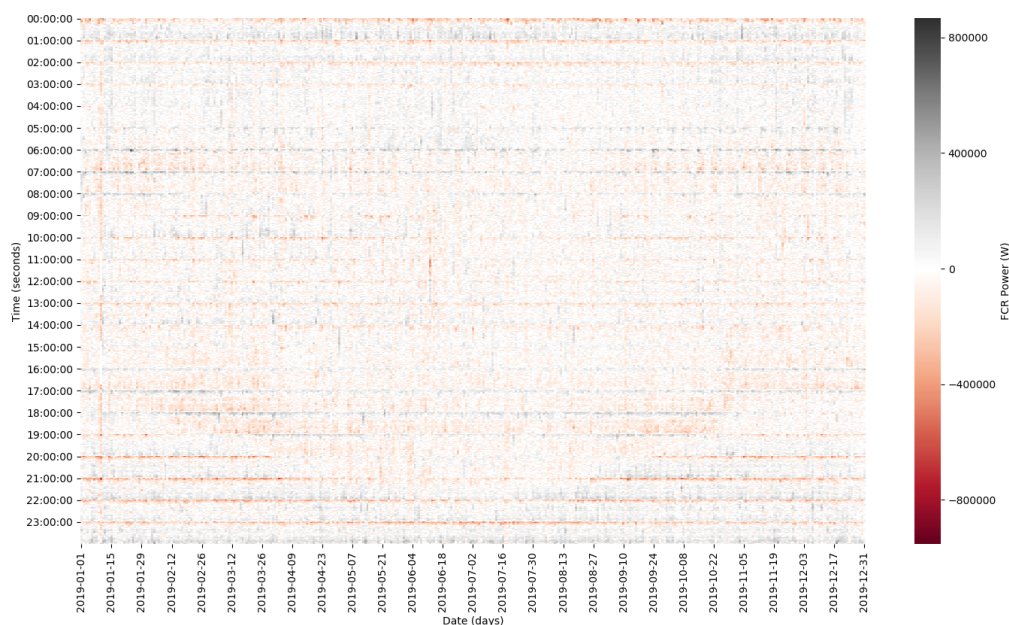

Figure 4.1: Heat map of the frequency containment reserve activation of a battery (1MW prequalified FCR power) for the UCTE FCR market in 2019.

As illustrated in Figure 4.1, BESSs that are providing FCR services in the UCTE region show FCR activation in both the positive and negative direction and varying heights of FCR activation over time. In the year 2019, the total amount of FCR that should have been delivered by the FCR asset is 305.18 MWh in the positive direction (battery charging) and 305.46 MWh in the negative direction (battery discharging).

In the examined time period, the BESS was not providing any FCR power for 8.98 ± 1.08 hours a day, resulting in an average percentage of battery idle time of 37.42 ± 4.51% per day. Over the year 2019, the battery was idle for a total of 3277.8 hours. In Figure 4.2, the mean and 95% confidence intervals of the FCR power a battery energy storage system delivered over a daytime for the year 2019 is shown. The variation (mean and 95% confidence intervals) in FCR activation over the day shows that the specific time moments in which a battery is 'idle' cannot be perfectly predicted.
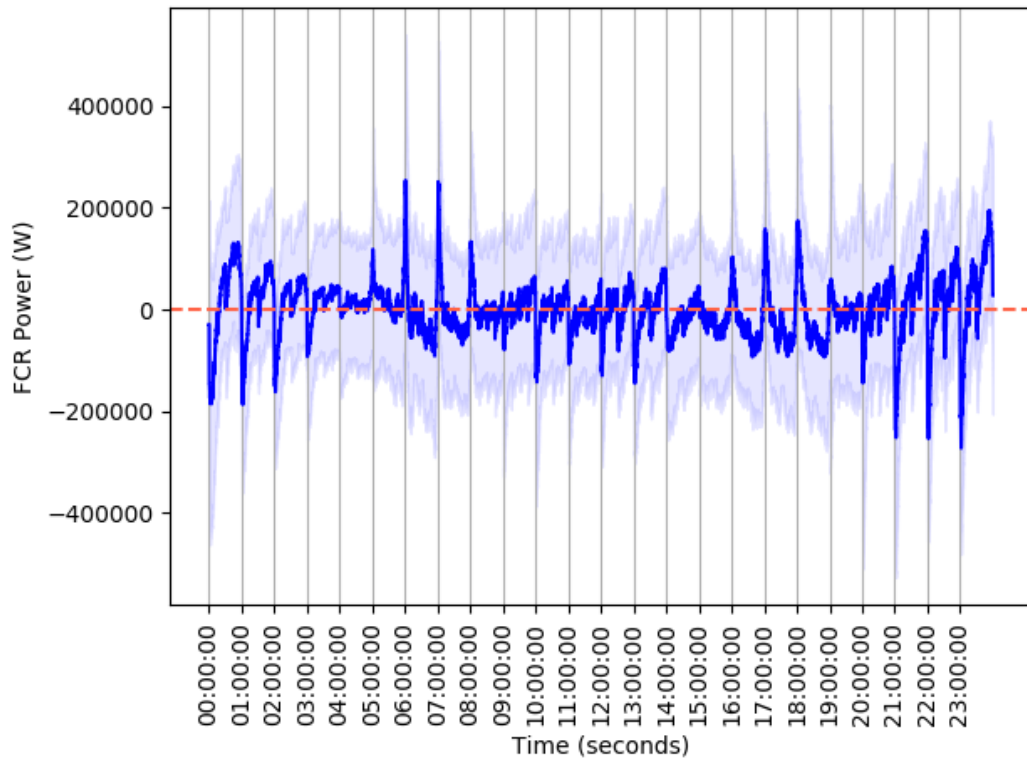

Figure 4.2: Average amount of FCR power output (W) with 95 percent confidence intervals of a battery in the UCTE FCR market over the day.

Figure 4.3 shows the distribution of the lengths of the idle time periods in the UCTE synchronous area. As shown in the figure, the amount of idle moments that were identified in the year 2019 seems to decrease exponentially with increasing idle time period length. In the case that the BESS was idle, the length of idle time was on average 57.52 ± 121.73 seconds. The minimal length of these idle periods was 10 seconds, the maximum length was 4880 seconds.
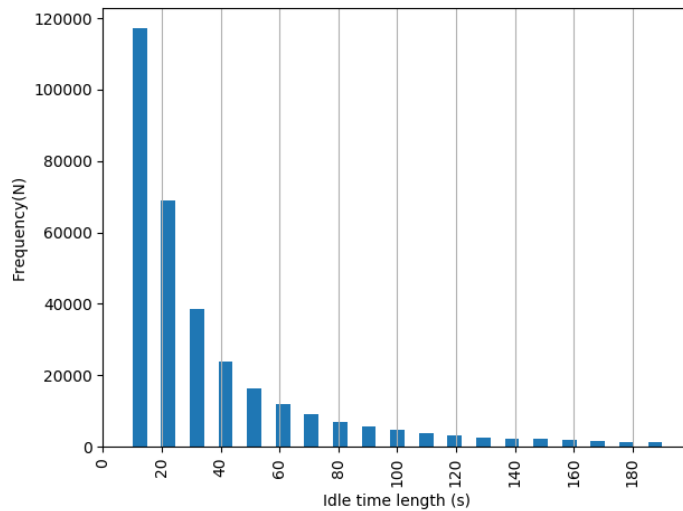
Figure 4.3: Frequency of the idle time period lenghts for the UCTE FCR market.

4.3.2. Nordic region – FCR-N

In the Nordics, battery energy storage systems show other FCR activation characteristics. In Figure 4.4, the heatmap describing the activation of a BESS that is participating in the Nordic FCR-N market is shown. Based upon this figure, several things could be noted. First of all, the missing data in the period '04/05/2019 10:48:07 - 09/05/2019 14:35:24'. Since frequency data of this particular time period is missing (as described in the methodology section), no clear FCR activation estimation could be made within this time period. As seen from the intensity of the colors in the heatmap, the amount of FCR activation of assets that are delivering FCR in the Nordic FCR-N market is relatively high. Over the whole time period, a total of 1475.66 MWh of FCR has been delivered in the positive direction (battery charges) and a total of 1443.32 MWh in the negative direction (battery discharges).
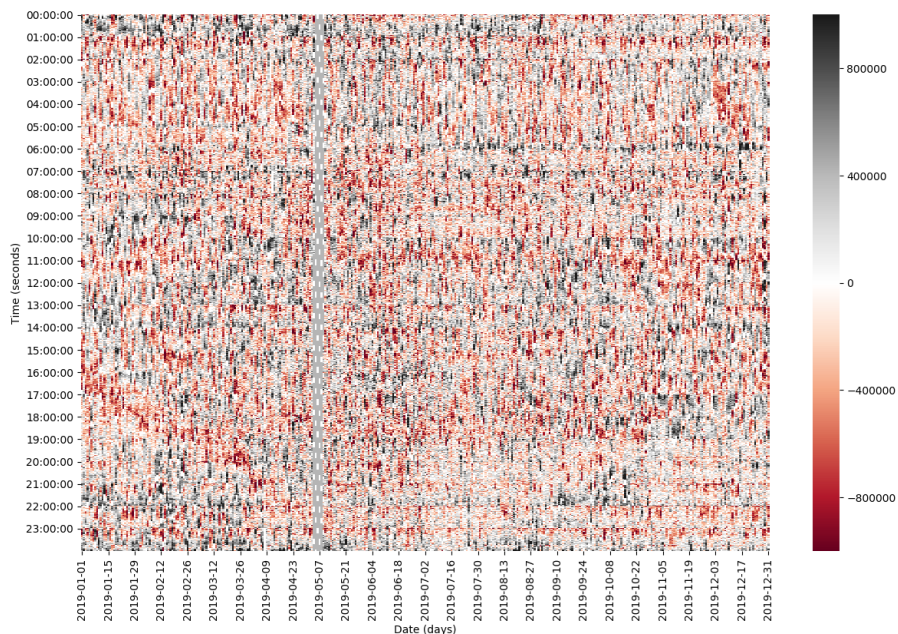

Figure 4.4: Heat map of the frequency containment reserve activation of a battery (1MW prequalified FCR power) for the Nordic FCR-N market in 2019.

For a battery providing FCR-N power, the average idle time over the year 2019 was 4.62 ± 0.58 hours per day. This corresponds to an average daily idle time percentage of 19.26 ± 2.42%. Over the whole time period, the battery was considered idle for a total time of 1669.1 hours.

The plot that visualizes the mean and 95% confidence intervals of the FCR reserve activation of a BESS over a twenty-four-hour period in the Nordic FCR-N market (see Figure 4.5) shows that the variation in FCR activation during the day is relatively high. The 95% confidence intervals are broad, and the limits of these intervals are relatively close to the maximal contracted FCR power of the BESS (±1 MW FCR). This thus indicates that there are no specific time moments over the day where the battery is always considered idle.

The histogram that is presented in Figure 4.6 shows that the total length of the idle time periods of a battery providing FCR-N power follows a similar pattern as a battery providing FCR power in the UCTE region. The amount of idle moments that were identified in the year 2019 decreases with an increasing length of the idle time period. On average, the idle time period was 42.57 ± 121.90 seconds, with an observed minimum idle time period of 1 second and an observed maximum idle time period of 3219 seconds.
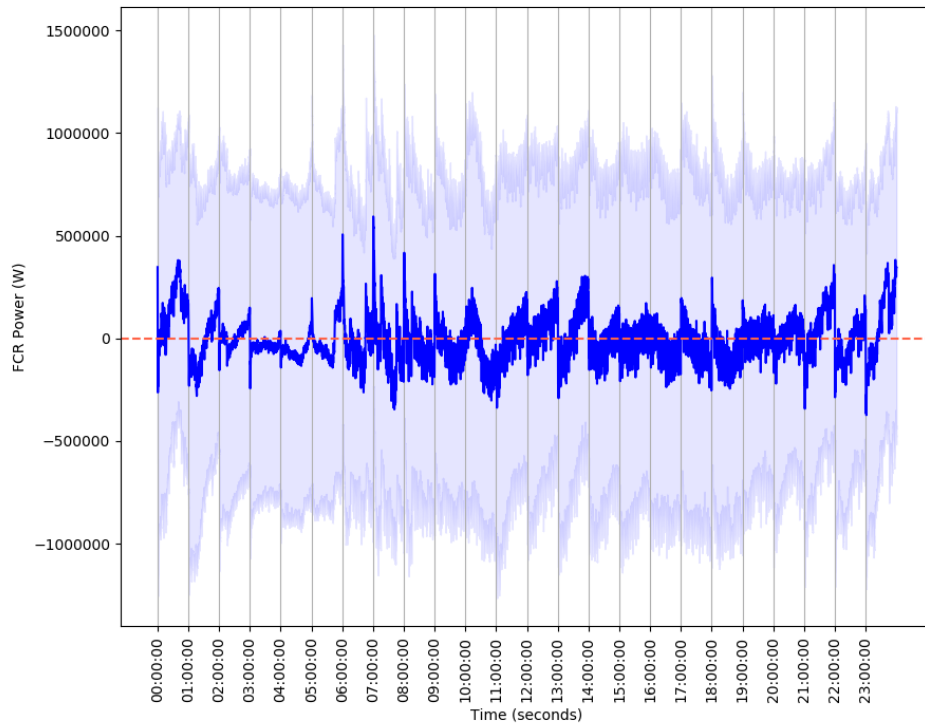

Figure 4.5: Average amount of FCR power output (W) with 95 percent confidence intervals of a battery in the Nordic FCR-N market over the day.
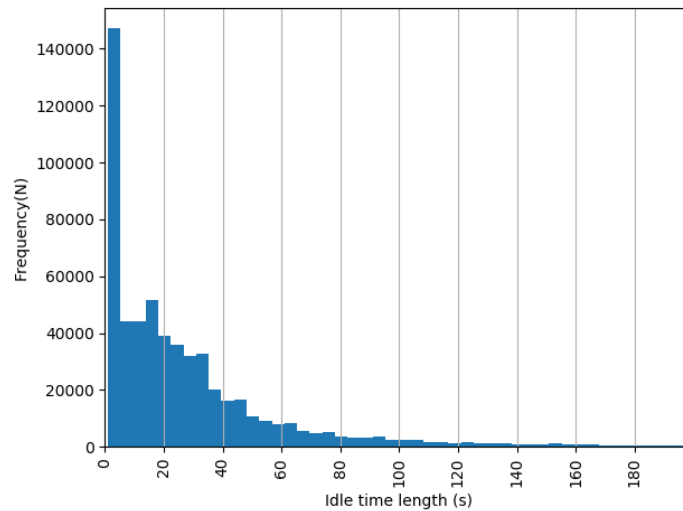
Figure 4.6: Frequency of the idle time period lenghts for the Nordic FCR-N market.

4.3.3. United Kingdom region – Dynamic FCR

In Figure 4.7, the activation of a battery providing FCR services for the dynamic FCR market of the United Kingdom is presented. This FCR power was delivered in the year 2019 for a total of 452.10 MWh in the positive direction (battery charging) and for a total of 459.04 MWh in the negative direction. In the examined time period, the battery energy storage system was not providing frequency containment reserve power for a total of 1238.82 hours. On average, the idle time period per day was 3.39 ± 0.40 hours, corresponding to an idle time percentage of 14.14 ± 1.67%.
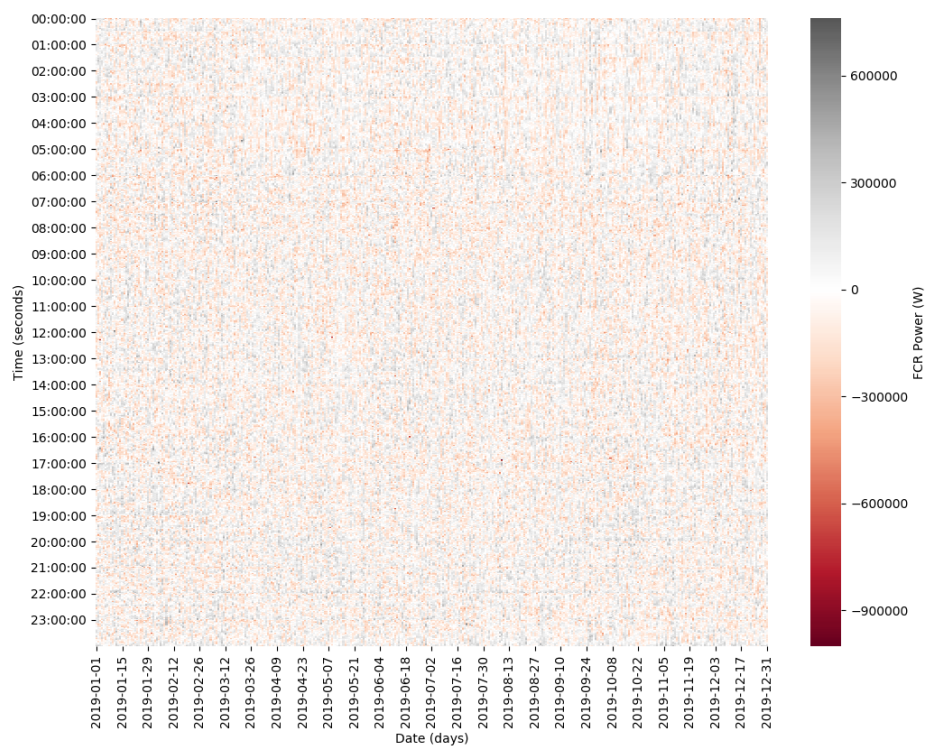

Figure 4.7: Heat map of the frequency containment reserve activation of a battery (1MW prequalified FCR power) for the United Kingdom dynamic FCR market in 2019.

The plot (see Figure 4.8) that shows the mean and 95% confidence intervals of the FCR reserve activation of a BESS providing dynamic FCR power in the United Kingdom region shows that for this FCR market, also no perfect prediction can be made when these idle moments occur. Over the year 2019, batteries were actively providing frequency containment reserve power for each time moment of the day for at least a few days per year.

Figure 4.9 shows a histogram of the total length of the idle time periods of a battery providing dynamic FCR power in the UK synchronous area. The average length of these idle time periods is 83.34 ± 226 seconds. The observed minimum length of these idle time periods was 1 second. The observed maximal length of the idle time periods was 6748 seconds.
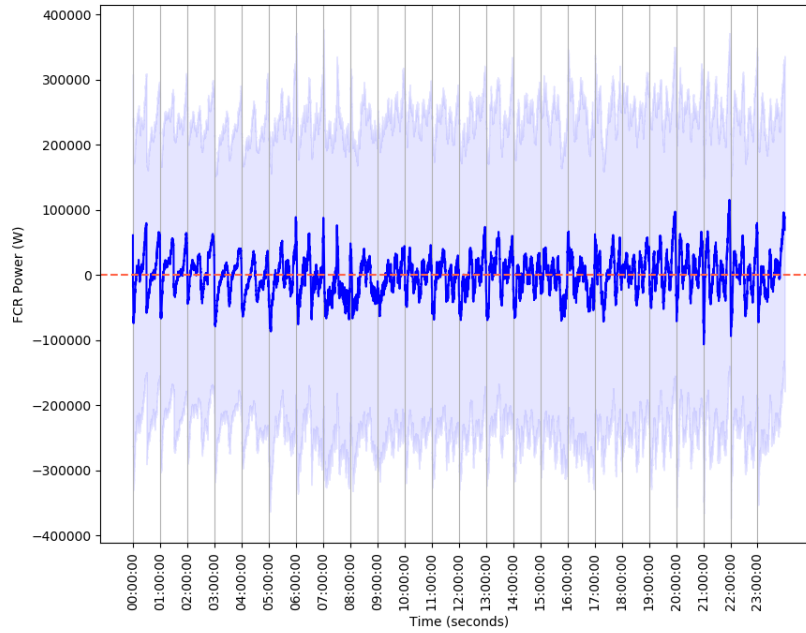

Figure 4.8: Average amount of FCR power output (W) with 95 percent confidence intervals of a battery in the United Kingdom dynamic FCR market over the day.
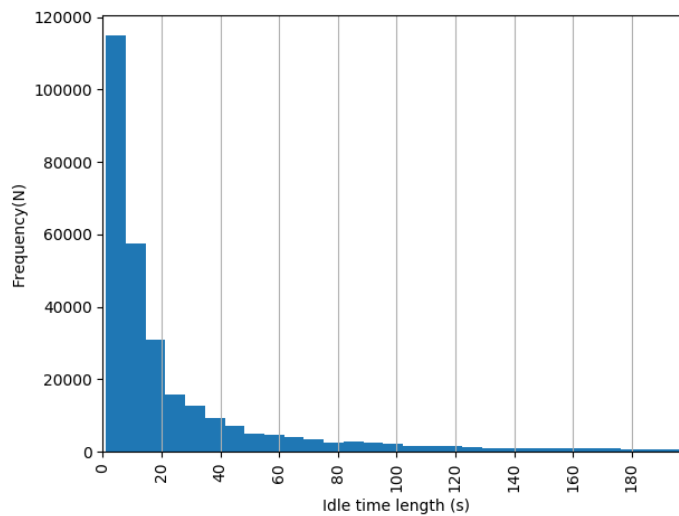

Figure 4.9: Frequency of the idle time period lenghts for the United Kingdom dynamic FCR market.

4.3.4. Other FCR markets

In both the UK Non-dynamic FCR market and the Nordic FCR-D market, total FCR activation was relatively low (for the affiliated heatmaps, see Appendix B). Batteries that were providing FCR services in the Nordic FCR-D market are only required to provide negative reserve power. This has resulted in a net total battery energy efflux of 3.72 MWh over the year 2019. Batteries providing FCR services in the UK Non-Dynamic FCR market (which is a symmetrical FCR market), delivered 0.12 MWh of FCR in the positive direction and 0.11 MWh of FCR in the negative direction over the year 2019.

For both the UK Non-Dynamic (24.00 - 0.07 hours per day) and the Nordic FCR-D (23.72 ± 0.20 hours per day) markets, the amount of idle time per day was relatively high, corresponding to an idle time percentage of 100.00 - 0.31% and 98.83 ± 0.84% and a total idle time of 8759.65 and 8657.74 hours over the year 2019 respectively.

Due to the relatively small amount of time the battery was required for FCR purposes over the year (as shown in the heatmaps in Appendix B), the length of the idle time periods between two FCR activations for these two FCR markets could become relatively large. In the United Kingdom Non-dynamic FCR market, a maximal observed idle time period of 218.45 hours was observed for the year 2019. For the Nordic FCR-D market, a maximal idle time period of 125.03 hours. Due to the relatively small amount of active data samples, however, no proper estimation could be made about the predictability of these idle moments and their mean idle period lengths.

4.4. Simulation model discussion

The results in the previous section show that the FCR activation of a battery with a prequalified FCR power rating of 1 MW can be very different for the various synchronous regions and FCR markets. Both the height of total FCR delivery, direction of FCR activation, total idle time and idle time lengths are showing various behaviour based upon the grid frequency input and regulations that are present within the specific synchronous areas.

4.4.1. Frequency containment reserve activation

For the different synchronous regions that were examined, various FCR activations of battery energy storage systems providing FCR services were identified. In the synchronous regions Continental Europe and the United Kingdom, a relatively lower FCR power was required (for the UCTE FCR market and dynamic FCR market) over the year 2019 compared to the Nordic region (FCR-N market). These results are in line with the results obtained by Hollinger et al. (2018). They showed that the amount of FCR power that batteries were providing in the Nordic FCR-N market was of a factor three times higher compared to the equivalent UCTE and dynamic UK FCR markets (with frequency data that was obtained in the years 2012-2015). Several explanations can be given for this difference.

First of all, the overall grid frequencies and electricity grid architectures of these synchronous areas are not similar. Deviations from the nominal reference frequency of 50 Hz are, as shown in Figure 4.10, relatively higher in the Nordics compared to the UCTE synchronous area. This reflects that the electricity system of the Nordic synchronous areas is less stable with larger imbalances between electricity generation and demand. To compensate these larger system imbalances, FCRs are required more actively provide balancing services (Hollinger et al. (2018); Maurer et al. (2017)).

The grid frequency characteristics that are shown in Figure 4.10 do not yet explain the relatively high difference in FCR activation between the FCR-N market of the Nordic synchronous area and the Dynamic FCR market of the United Kingdom. The deviations in grid frequencies from the reference frequency seem rather similar between these two synchronous areas. Moreover, it does also not explain the differences in FCR activation between the Nordic FCR-N and Nordic FCR-D or the United Kingdom dynamic and United Kingdom Non-Dynamic FCR markets. The reason for the difference in FCR activation between these synchronous areas and FCR markets can, however, be explained by the variance in regulations that are affecting the operation of the FCR assets.

The dead band that is used in the United Kingdom is, for instance, ± 0.15 mHz (Smethurst et al.,

2017) compared to the dead band that is used in the Nordic synchronous area (± 0.10 mHz) (Fingrid, 2019a). This shows that batteries providing FCR power in the Nordic FCR-N market are already required to provide FCR services at smaller frequency deviations from the reference frequency compared to the United Kingdom region.

Other regulations that heavily affect the activation of FCR assets are the power-frequency characteristics, as described in the literature review in Chapter 3. Batteries providing FCR services in the Nordic FCR-N market are required to deliver their full contracted FCR capacity at a frequency deviation of ±100 mHz (linearly increasing from ±0 mHz) from reference frequency, whereas the dynamic FCR market in the United Kingdom requires the full contracted FCR capacity at a frequency deviation of ±500 mHz (linearly increasing from ±0 mHz). In the UCTE FCR market, the requirement of full FCR provision is at ±200 mHz (linearly increasing from ±0 mHz). This shows that the variance in FCR activation is both the result of varying grid frequencies and varying regulations in the different synchronous areas and FCR markets.
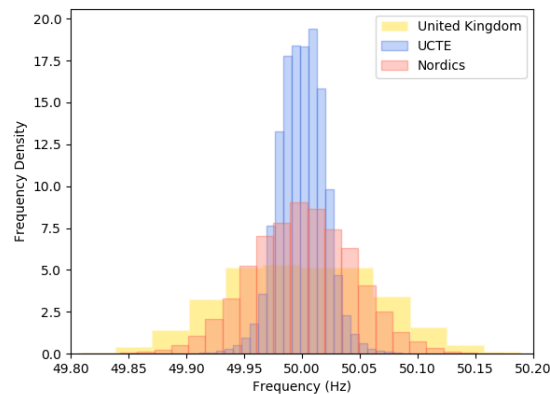

Figure 4.10: Deviations from the nominal reference frequency of 50 Hz for the UCTE, Nordic and United Kingdom regions.

4.4.2. Total idle time

In the results section, it is shown that for the various FCR markets, batteries were not providing frequency containment reserve power for a relatively high number of hours per day. For the UCTE FCR market (8.98 ± 1.08 hours of idle time per day), Nordic FCR-N market (4.62 ± 0.58 hours of idle time per day) and United Kingdom dynamic FCR market (3.39 ± 0.40 hours of idle time per day), the total percentage of idle time of a battery providing FCR power per day reached up to 37.42 ± 4.51% on average. For the Nordic FCR-D and United Kingdom Non-Dynamic FCR markets, the average idle time percentage is even higher (up to 100.00%). These numbers show that the energy storage reservoir and the power conversion system of a BESS is not fully utilized over the lifespan of a battery providing primary control power and that there is a big opportunity for battery utilization optimization, especially in the markets where the battery is rarely used.

Although the total idle time of batteries providing FCR services is relatively high, the actual amount of time that the battery is not used for FCR related charging and discharging purposes is supposed to be lower. In various articles (Brivio et al. (2016); Divshali and Evens (2020); Sanchez et al. (2018); Stroe et al. (2017); Tan et al. (2020)), it is described that some of these idle moments must be used to maintain the energy reservoirs state of energy within its state of charge limits. Depending on the state of charge management strategy of the BSP, the size of the battery and the state of charge evolution over time, a specific amount of idle time should, as described in these articles, be reserved for battery charging and discharging, thereby obtaining a preferred state of charge level for complying with future FCR power requirements.

4.4.3. Idle time period lengths

The results show that the number of occurrences of idle time periods seem to be exponentially decaying with an increased idle period length for the UCTE FCR market, Nordic FCR-N market and United Kingdom dynamic FCR market. This indicates that the majority of the idle time periods only last for a small amount of time (in the range of seconds to one minute).

Since a battery is generally able to react to grid frequency changes in a matter of milliseconds (Helwig, 2016), they might, in theory, be capable of using these small time periods for other battery purposes. This, however, also requires that these alternative battery services are beneficial to use on this relatively small timescale. Apart from reactive power control (Aminzadeh et al., 2020) or state of charge management (Divshali and Evens, 2020), no other battery service is known that could be properly performed within this seconds timescale.

For the Nordic FCR-D and United Kingdom Non-Dynamic FCR markets, the time periods between two FCR activations could be very long. This might, in theory, be beneficial for using the battery for other purposes. The Nordic FCR-D market seems the market of most interest. This market does not only have a long overall idle time and long-lasting idle time periods between two FCR activations, it is also a market that only requires FCR power within one specific direction (providing negative reserve power). This thus opens up the opportunity to use the battery for purposes that require power or battery capacity in the opposite direction.

4.5. Simulation model conclusion

This simulation model has demonstrated that the activation of a BESS that is providing FCR services varies among the synchronous regions and FCR markets. Both the frequency characteristics of the specific synchronous areas and the regulations that define the operational requirements of a BESS participating in one specific FCR market seem to determine the height and direction of FCR activation.

The result of the different model simulations showed that the total amount of idle time of batteries participating in primary control reserve can be very high for some FCR markets. This indicates that there are many moments in time where the power conversion system of a battery is not used and the state of charge of the batteries is not changing. This information (in particular for the Nordic FCR-D and United Kingdom Non-Dynamic FCR market) gives the indication that there might be a huge potential in using these idle moments for other battery purposes.

The potential to use these idle moments for other battery purposes can partially to fully be negated by the fact that the idle time periods are relatively small for some of the FCR markets. Since most of the idle moment periods only last for some seconds to minutes, no clear potential for using these moments for other battery purposes, apart from reactive power control and state of charge management, could be identified.

For the Nordic FCR-D and United Kingdom Non-Dynamic FCR market, the potential of using the battery for other purposes seems of most interest. These markets have an overall relatively long idle time and the affiliated idle time periods could be relatively large. For these markets, however, the question remains whether a proper prediction could be made about the periods in which these idle moments occur.

<div style="text-align: right; font-size: 3em;">5</div>

Forecasting the behavior of batteries providing FCR services for different FCR markets

5.1. Time series model introduction

Analyzing the behavior and value-stacking opportunities of batteries providing FCR services is not only constrained to the question whether a battery is actively providing FCR power at a certain time moment or not. The use of a battery for a specific purpose does require both insight into the available power capacity and energy capacity of a battery. Next to the question at what time moments a battery is using its power conversion system (available power capacity, as examined in Chapter 4), it is therefore necessary to identify what is the available energy capacity of the energy reservoir of a battery over time. The direction and height of the power flow, and thereby the consequences for the state of charge of the battery (available energy capacity of a battery), can be very helpful in determining the required energy capacity of a battery for FCR purposes and the leftover energy storage capacity for other battery applications.

In this chapter, time series forecasting models for all the examined FCR markets of the previous chapter where time series analysis was possible to conduct were constructed and used to determine the predictability of the FCR activation of a BESS. Using simulated time series data of a battery that is providing FCR power in three various synchronous regions and markets in the European Union, it is attempted to identify whether the BESS FCR activation can be predicted from historical values. This information can, in the end, be useful for balancing service providers in analyzing and optimizing their batteries utilization and profitability.

5.2. Time series model methodology

To perform the time series analysis and generate the forecasting model, the forecast process research framework described by Montgomery et al. (2015) was used. This research framework describes the activities, including the 1) problem definition, 2) data collection, 3) data analysis, 4) model selection and fitting and 5) model validation steps, that should be performed to do proper time series analysis and forecasting.

5.2.1. Problem definition

The general goal of this time series analysis is to get a better understanding of the height and direction of the activation of battery energy storage systems providing FCR and to get a rough estimation of

the predictability of this charging and discharging behavior. Although all information on each time granularity might have an added value for understanding FCR activation and behavior, most added value is seen in a time series analysis for a minute to several hours forecast. Time series analysis for a seconds forecast does not seem to be of much importance, since the capacity of batteries that are providing FCR services are generally so large that the power that is extracted from or stored in the energy reservoir of these FCR assets on a second's timescale is almost neglectable. Weekly, monthly or yearly forecasts seem also less informative. Although these forecasts might be able to capture long-term trends in grid frequency volatility and FCR activation, they do not generally provide insight into the charging or discharging behavior of a battery within one battery cycle.

Although a high forecast accuracy can better estimate the future behavior of BESS providing FCR, no specific forecast accuracy levels are included in this study. The height of the forecast accuracy level mainly depends on the specific requirements that are set by the BESS owner, which can vary on risk aversion and the forecast application. In this study, it was therefore only relevant to identify whether the constructed time series forecasting model could better predict the FCR activation of a BESS than the mean of the whole time series dataset.

5.2.2. Data collection

For the time series analysis and forecasting process, data on the height and direction of the FCR services provided in the three most used FCR markets in the synchronous regions UCTE, Nordics (FCR-N) and United Kingdom (Dynamic) in 2019 has been derived from the results of the simulation model described in Chapter 4. The Nordic FCR-D market and United Kingdom Non-Dynamic FCR market have not been included in this time series research, since the FCR assets participating in these two markets, were rarely activated. It is therefore not possible to do proper time series analysis for these two FCR markets.

The data obtained from the three FCR markets that were included in this study is aggregated from a one second level to a five-minute period. This has been done to be able to make a forecast that can capture both hourly and daily seasonality. Furthermore, the data set was divided into two subclasses to do both time series analysis and model building and time series forecasting. The training set, which has been used for the time series analysis and model building part, included the FCR activation data of the first two weeks of January 2019. It was assumed that this training set could contain enough data to do proper data analysis and was not too big to include the monthly or seasonal patterns that could be present in the time series. The forecasting set included FCR data of the first hour (15-01-2019 00:00:00 up to 15-01-2019 00:55:00) after the training set.

5.2.3. Data analysis

In the data analysis step, the FCR data that was collected was visualized and checked for normality. Potential trends and other abnormalities in the dataset, including seasonal components and outliers, were flagged. The insights that were obtained in the potential seasonality's and outliers were subsequently used in the model fitting process and the discussion section of this time series analysis.

5.2.4. Model selection and fitting

In literature, a wide variety of quantitative forecasting methods have been described (Montgomery et al., 2015). All these methods have their own properties and limitations. As described by Hyndman and Athanasopoulos (2018), exponential smoothing and Autoregressive Integrated Moving Average (ARIMA) models are the most widely used approaches for time series forecasting. The strength of exponential smoothing methods can be found in its capacity to describe trends and seasonality in time series data. ARIMA models are more aimed at describing the auto-correlations (the correlation between a time series and a lagged version of itself) that are present within the time series.

For understanding the behavior of batteries providing FCR services, both information on trends and seasonality as well as information on the similarity between the given time series and a lagged version

of itself seems of interest. The identification of seasonal trends can give information on the availability of charging or discharging patterns as a response to FCR activation for batteries providing FCR. The autocorrelation of a time series could give information on the near term prospected FCR requirement of an FCR providing asset. This shows the relevance of using a model that can both capture seasonality and the autocorrelation of the collected time series.

A time series forecasting method that can be used for identifying both autocorrelation and seasonal patterns is the Seasonal ARIMA (SARIMA) model, initially presented by Box and Jenkins (1976). This model is able to describe time series that exhibit non-stationary behavior within and across certain defined seasons. It has some additional, seasonal components compared to the standard ARIMA model, which is a model that is built upon the combination of an auto-regression model (AR), differentiation or 'integrated' (I) time series and a moving average (MA) model.

Autoregressive (AR) model

An autoregressive model is a model that uses past observations to predict the current observation (Hyndman and Athanasopoulos, 2018). It uses the linear association between the past values of the variable and the current value. An autoregressive process that depends on p past observations is described as an autoregressive model of degree p, or AR(p). For an autoregressive model, the outcome y_t at time t of the autoregressive process of an order p can be described by the function

$$y_t = \phi_1 y_{t-1} + \phi_2 y_{t-2} + \cdots + \phi_p y_{t-p} + \varepsilon_t \tag{5.1}$$

The predicted value of the observation at a particular timepoint therefore depends on the lagged values of y_t, their regression coefficient ϕ_p and an error term ε_t.

Integrated (I)

Many of the time series that are found in practice are non-stationary, which means that the statistical properties of the time series are dependent on time (e.g. due to trends or seasonality). The problem with this non-stationarity is, however, that analytical tools, tests and forecasting models rely on the assumption that the data is stationary, as described by Manuca and Savit (1996). Without stationary data, the interpretation of the results of a times series analysis and forecasting model can therefore become problematic.

The way in which Box et al. (1994) cope with this non-stationary data for time series analysis and forecasting is the use of time series differencing. This method computes the differences between consecutive observations, thereby attempting to remove the non-stationary elements of a time series. A difference-stationary process or integrated process with an order d (d-th-degree differencing operator) and outcome y_t can hereby be written as

$$y_t' = y_t - y_{t-1} \tag{5.2}$$

In this function, y_t' represents the value of the first-degree difference of the time series dataset. For this differenced series, the first observation cannot be differenced. The total amount of observations will therefore become T-1.

Moving average (MA) model

The moving average model is a model that uses past forecast errors as predictors for future outcomes (Hyndman and Athanasopoulos, 2018). It thus incorporates the dependencies between an observation and the residual errors from a moving average model that is applied to the lagged or past observations. In general, the outcome of a moving average model y_t at time t for a moving average process of an order q or MA(q) that uses q past observations can be described by the function

$$y_t = \mu + \varepsilon_t + \theta_1 \varepsilon_{t-1} + \theta_2 \varepsilon_{t-2} + \cdots + \theta_q \varepsilon_{t-q} \tag{5.3}$$

where mu is the mean of the data series, ε_t the white noise at time t and θ_q the regression coefficient of the previous error term q. The value of the outcome of this moving average process can be described as a weighted moving average of the q past forecast errors.

Autoregressive integrated moving average (ARIMA) model
An ARIMA model can be defined as a model that combines an autoregressive model, a 'differenced' time series and a moving average model. This model can thus generate predictions of a time series that is integrated or differenced with an order d and based upon the lagged values (obtained from the autoregressive part) and lagged errors (obtained from the moving average part) of y_t (Hyndman and Athanasopoulos, 2018). The full model can be written as

$$y_t' = \mu + \phi_1 y_{t-1}' + \cdots + \phi_p y_{t-p}' + \theta_1 \varepsilon_{t-1} + \cdots + \theta_q \varepsilon_{t-q} + \varepsilon_t \tag{5.4}$$

This model can also be denoted as an ARIMA(p, d, q) model, wherein p describes the order of the autoregressive part of the model, d describes the degree of differencing and q describes the order of the moving average part of the model.

Seasonal autoregressive integrated moving average (SARIMA) model
The ARIMA model that have been described in the previous paragraph could be further extended by the addition of a seasonal part. The seasonal part of a SARIMA model (as shown in Figure 5.1) consists of some seasonal terms that can be used to better predict the value of the current observation by also taking into account the seasonal variation in the time series dataset (Hyndman and Athanasopoulos, 2018).
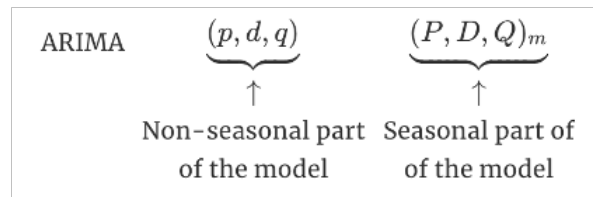

Figure 5.1: overview of the seasonal autoregressive moving average (SARIMA) model terms.

The part that describes the seasonal influences consists of terms that are similar to the terms used in a normal ARIMA model; an autoregressive component (with order P), a differencing component (with order D) and a moving average component (with order Q). The only difference in the computation of the terms in the seasonal part compared to the non-seasonal part of the SARIMA model is that the seasonal terms are based upon the correlation of the current observation y_t with the lagged values and errors of $y_{(t-1)m}$, where m is the seasonal period.

Parameter order determination
In general, the order of the autoregressive, differencing and moving average terms can be determined by an extensive analysis of the raw time series dataset. The order of the differencing component (d, D) can often be derived by looking at the level of stationarity of the time series. To check the data for stationarity, this study has used the augmented Dickey-Fuller (ADF) test (Mushtaq, 2012). This ADF test is used for testing the null hypothesis that a specific time series is non-stationary. If a certain time series dataset cannot reject this null hypothesis, the order of the differencing operators (d, D) is changed by a value of one. Subsequently, the ADF testing procedure is repeated until stationarity of the dataset is achieved.

The estimation of the (p, q) and $(P, Q)m$ terms of the SARIMA model is primarily done by analyzing the autocorrelation function (ACF) and partial autocorrelation function (PACF) of the time series. The ACF is a function that can describe how different points in time are correlated to each other in a way that can be explained by temporal distance (Ramanathan et al., 2017). Within time series analysis, this

particular function is often used to get a rough first estimation of the degree of the moving average terms (q and Q). The PACF, as described by Ramanathan et al. (2017), is a function that can give insight into the partial correlation of a time series with its lagged values, thereby controlling for all values of the time series that have shorter time lags. The use of this function can give a first rough estimation of the order of the autoregressive terms (p and P).

The selection of the preliminary order of the autoregressive and moving average terms of the non-seasonal part of the model is done by looking at the presence of a significant correlation ($\alpha = 0.05$) of the first few time lags with the current observation. The order of the terms is hereby estimated at the amount of significant correlations that can be identified in a consecutive order and do not increase over the time lags (since this indicates the presence of seasonality). For the preliminary selection of the order of the autoregressive and moving average terms of the seasonal part of the model, the ACF and PACF were analyzed on the (re)occurrence of a significant correlation with a time lag of period m.

As stated by Wang et al. (2013), the use of the described methods (the analysis of the ACF and PACF) is often not sufficient to get the parameters that are needed for an optimal model fit. Further SARIMA model parameter determination can be done by trial-and-error, varying the order of the non-seasonal and seasonal autoregressive and moving average terms and by comparing the different model fits with each other. In this study, the Akaike information criterion (AIC), which is a technique developed by that is used to estimate the likelihood of a model to estimate future values (Akaike, 1974), is used as an estimator for the quality of the model fit. The preferred model is the one with the minimum AIC (Wang et al., 2013).

5.2.5. Model validation

The time series analysis forecasting models that were developed in this research have been validated by evaluating the fit of the model to the historical data set. Based upon a Q-Q plot, the residual errors of the model were analyzed and examined on their normality. The fit of the model to the historical dataset and the forecasting dataset have also been evaluated by calculating the root-mean-square error (RMSE). For the historical dataset, the calculated RMSE was compared with the RMSE of a model that was only representing the overall mean of the historical data time series. In this way, preliminary insight could be obtained about the strength of using time series forecasting in the prediction of FCR activation.

5.3. Time series model results

This section describes the results of the SARIMA time series analysis and forecasting models that are constructed and used to identify the predictability of the FCR activation of a BESS, providing FCR services in the UCTE FCR market, Nordic FCR-N market and United Kingdom Dynamic FCR market. Since the activation of a BESS providing 1 MW FCR power is based on the regulations and grid frequency profiles that are present in each of these synchronous regions (which varies, as shown in Chapter 4), an individual time series and forecasting model has been constructed for each synchronous area.

5.3.1. UCTE region

In Figure 5.2, the time series and corresponding histogram of the FCR activation of a battery, providing 1 MW prequalified FCR power in the UCTE market, is shown for the first two weeks of January. Based upon the Dickey-Fuller test that has been performed, stationarity of the dataset could be assumed ($p < 0.001$). This indicates that the time series data does not show a significant trend over its time horizon. Time series differencing for this particular dataset was therefore not needed ($d = 0$ and $D = 0$).
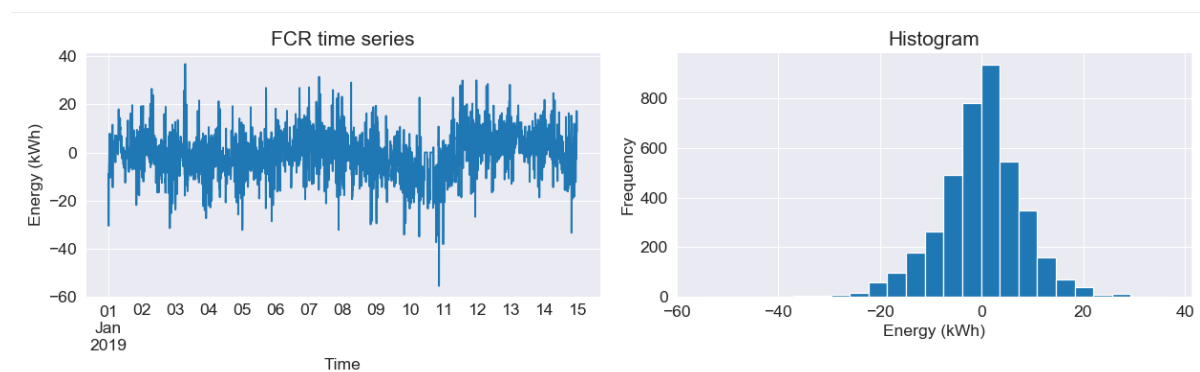

Figure 5.2: Time series overview (left) an histogram (right) for the FCR activation (kWh) in the UCTE FCR market.

Figure 5.3 shows the graphs for the autocorrelation function and partial autocorrelation function of the UCTE time series dataset. The autocorrelation of each time lag with an observed value at timepoint t ($\forall t \in T$) can hereby be analyzed. Based upon the ACF and PACF shapes, the preliminary values of the SARIMA (p, q) and (P, Q) can be identified.

The shape of the ACF in this figure shows a high seasonal correlation with a period of $m = 12$. Since each time series lag corresponds to a 5-minute window, a seasonality therefore seams to occur on an hourly basis. This pattern has been observed for at least three lagging periods, which suggests that the seasonal MA (P) order should be equal to 3 or 4. The PACF also shows a high correlation at time lag 12. This seasonal correlation, however, seem to diminish for the longer time lags. This indicates that the seasonal AR (Q) term should be of an order 1.

The preliminary orders of the MA and AR terms of the non-seasonal part of the model were estimated by looking at the first few time lags of the AC and PAC functions respectively. The ACF shows a declining significant correlation up to time lag 3 or 4, whereas the PAC function shows significant correlations for around 3 time lags (higher time lags will give an autocovariance that is close to zero). This indicates that the q should be equal to 3 or 4 and the p should be equal to 3.
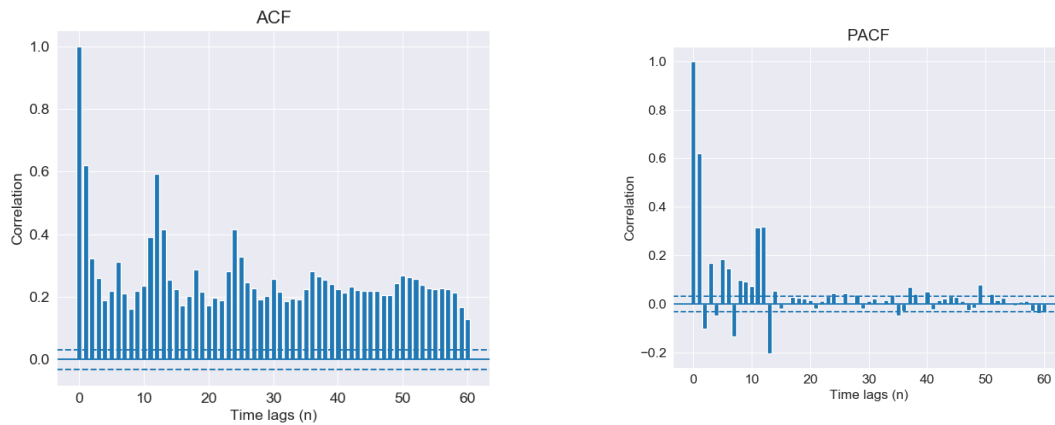
Figure 5.3: Autocorrelation function (left) and partial autocorrelation function (right) of the time series of the UCTE region.

The SARIMA model was thus estimated to have a degree (p, d, q) $(P, D, Q)m$ of $(3, 0, 3)$ $(1, 0, 3)12$. Fitting this model with the original time series dataset, an AIC value of 25025.710 was found, which is a relative measure of model parsimony. Further SARIMA model parameter estimations and model comparisons were done to get a model that could best fit the time series data. The model with a lower AIC score is hereby expected to have a superior balance between its goodness-of-fit and its ability to avoid over-fitting the time series dataset by including to many parameters. The model with model parameter terms $(1, 0, 4)$ $(2, 0, 4)12$ showed the optimal fit with the original dataset, with an observed AIC value of 24938.674 (which is lower then the preliminary AIC value).

In Figure 5.4, the original dataset (blue) and the constructed SARIMA model fit are plotted. For the time series training set (first two weeks of January), the RMSE of the SARIMA model has a value of 5.32. Compared with the RMSE of the mean of the whole dataset (RMSE = 8.32), the SARIMA model seems to perform better in estimating the FCR activation of an FCR asset. The RMSE for the predicted FCR activation for the defined forecasting period (15-01-2019 00:00:00 up to 15-01-2019 00:55:00) had a value of 7.49.
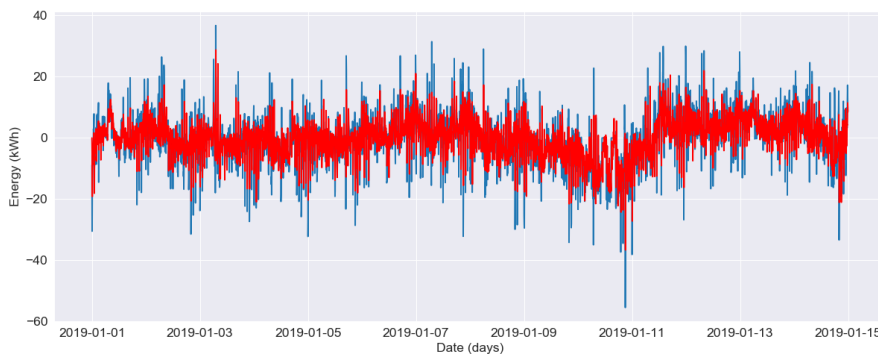

Figure 5.4: Model fit of SARIMA (1,0,4) (2,0,4)12 (red) for time series data of FCR activation of the first two weeks of January 2019 (blue) in the UCTE FCR market.

In Figure 5.5, the residuals of the predicted values of the SARIMA model with the observed values of the data training set are presented in a normal Q-Q-plot. This Q-Q-plot shows that the residuals of the fitted model are generally following a normal distribution. It is, however, also shown that the residuals have more extreme values than expected in a normal distribution. This could give the indication that the model that is constructed is not able to fully capture the extreme values that are present in the data training set.
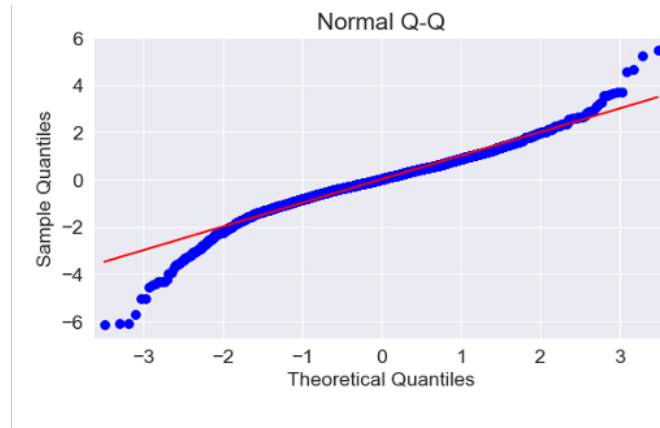
Figure 5.5: Plot of model fit residuals for the UCTE Seasonal autoregressive integrated moving average (SARIMA) model.

5.3.2. Nordic region

The time series data of the activation of a battery with a prequalified power rating of 1 MW in the Nordic FCR-N market is shown in Figure 5.6a and the corresponding histogram in Figure 5.6b. The results of the Dickey-Fuller test showed that time series is stationary ($p < 0.001$). Differencing was therefore not needed for the construction of the time series forecasting model ($d = 0$ and $D = 0$).
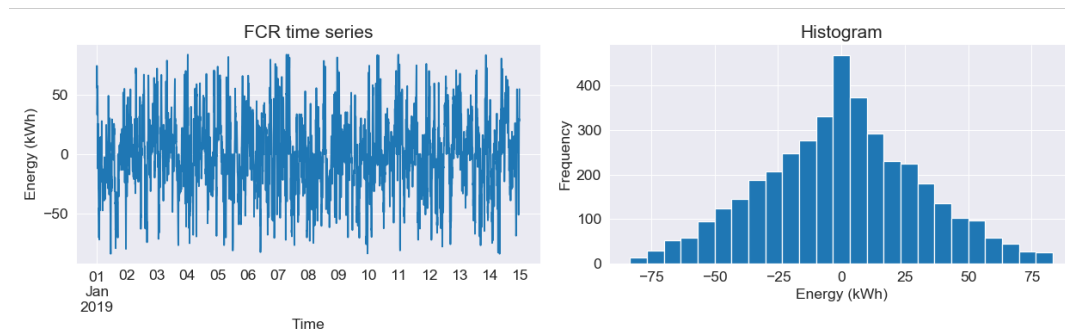

Figure 5.6: Time series overview (left) an histogram (right) for the FCR activation (kWh) in the Nordic FCR-N market.

In Figure 5.7, the graphs of the ACF and PACF of the Nordic FCR-N dataset are presented. Although the shape of the ACF shows a high probability of the presence of a seasonal component (due to trend in time lag correlation), it did not give direct insight into the specific period in which this seasonality occurs. The PACF graph, on the other hand, did show some seasonality. Both time lag 12, 24 and 36 showed a significant autocovariance. Therefore, it was preliminary assumed that a seasonality exists for a period $m = 12$ with an MA (Q) and AR (P) order of 0 and 3 respectively.

Based upon the ACF and PACF plots, the MA and AR degrees of the non-seasonal component were estimated at 8 and 3 respectively. This resulted in a SARIMA model with parameters (p, d, q) $(P, D, Q)m$ of $(3, 0, 8)$ $(3, 0, 0)12$ with an AIC value of 33862.443. After trial-and-error of other parameter values, a model that was slightly better fitting the data training set was found. The SARIMA model with model parameter $(3, 0, 4)$ $(2, 0, 0)12$ resulted in an AIC of 33858.058, describing the data slightly better with less model coefficients.

In Figure 5.8, the constructed SARIMA model (red) has been plotted along with the original time series dataset (blue). The RMSE of the model that has been constructed (RMSE = 16.09) seems to be a lot better than the RMSE that has been calculated based upon the mean of the whole dataset (RMSE = 31.28). The model thus seems to be able to better follow the real FCR of an asset providing FCR-N services in the Nordic synchronous area compared to a model that is only based upon the historical mean of FCR activation. The RMSE of the forecasting dataset was 25.75.
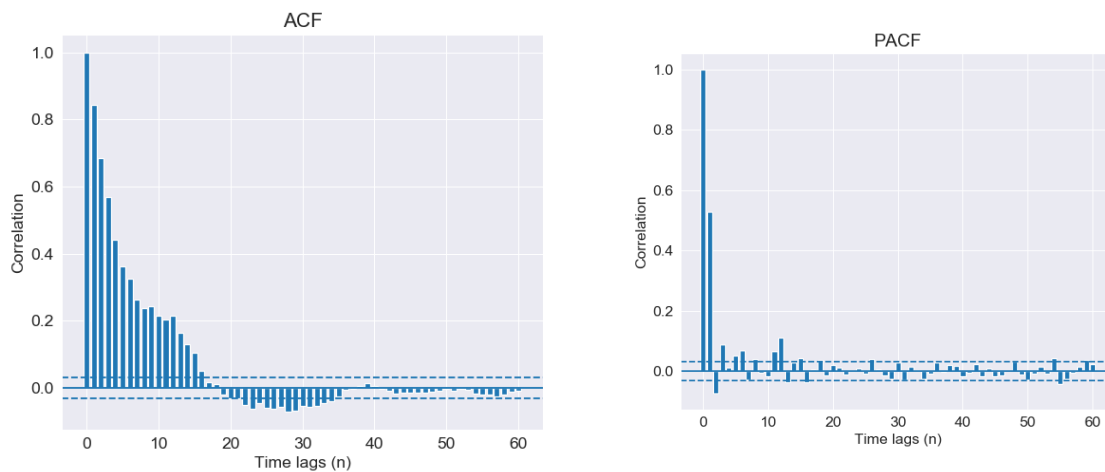
Figure 5.7: Autocorrelation function (left) and partial autocorrelation function (right) of the time series of the Nordic region.

Figure 5.8: Model fit of SARIMA (3,0,4) (2,0,0)12 (red) for time series data of FCR activation of the first two weeks of January 2019 (blue) in the Nordic FCR-N market.

In Figure 5.9, a Q-Q-plot is presented that shows the residuals of the predicted values of the SARIMA model and the observed values of the data training set. The Q-Q-plot shows that the model that is fitted to time series dataset has residuals that more or less follow a normal distribution (with some observed extreme values).
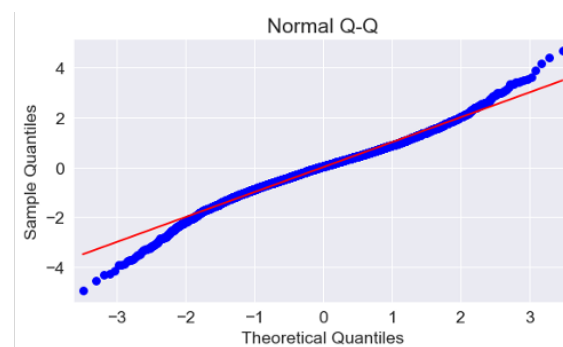
Figure 5.9: Plot of model fit residuals for the Nordic Seasonal autoregressive integrated moving average (SARIMA) model.

5.3.3. United Kingdom region

Figure 5.10a and the histogram in Figure 5.10b shows the activation of a battery with a prequalified power rating of 1 MW for the United Kingdom Dynamic FCR market. The lack of an overall trend and therefore, the stationary of the dataset has been confirmed by the Dickey-Fuller test (p<0.001). The order of the differencing components (d,D) of this data time series set that has been used for creating the forecasting model are therefore equal to zero.
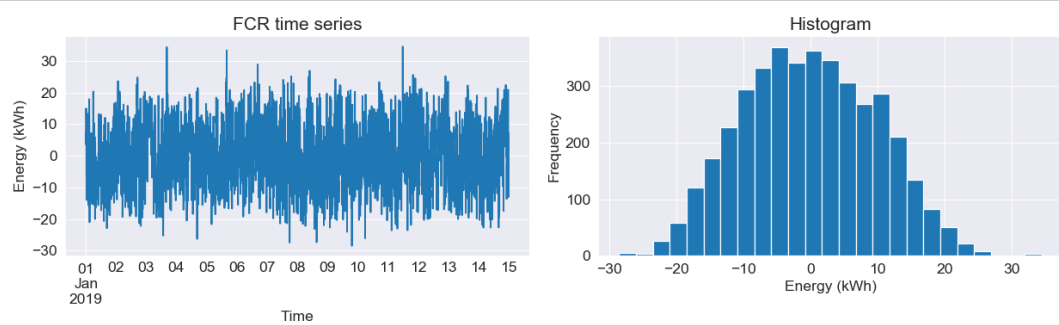
Figure 5.10: Time series overview (left) an histogram (right) for the FCR activation (kWh) in the UK dynamic FCR market.

Figure 5.11 shows the autocorrelation function and partial autocorrelation function of the United Kingdom FCR activation time series. Seasonality in this timeseries dataset has been identified for the periods $m = 6$ or $m = 12$, based upon the observed patterns of significant autocovariance in the ACF function. Since time lags 6, 12, 18 and 24 show a higher significant correlation compared to the time lags around these values, a period of $m = 6$ is assumed with an MA (Q) order of 4 and AR (P) order of 2.

Preliminary orders of the MA term and AR term of the non-seasonal part were estimated at $q = 5$ and $p = 3$ respectively. The corresponding SARIMA model $(3, 0, 5)$ $(2, 0, 4)6$ was fitted with the original data set and showed a model fit with an AIC value of 28432.540. By using other model parameters and comparing various models with each other, a better model fit with model parameters $(1, 0, 3)$ $(1, 0, 3)6$ and an AIC value of 28430.750 was found.

The results of the fit of the model (red) and the original time series dataset (blue) are plotted in Figure 5.12. In overall, the SARIMA model that has been constructed to model the FCR activation seems to perform a little bit better (RMSE = 8.20) compared to the mean of the whole dataset (RMSE = 9.95). For the forecasting dataset, the RMS was 9.60.

Figure 5.11: Autocorrelation function (left) and partial autocorrelation function (right) of the time series of the United Kingdom region.
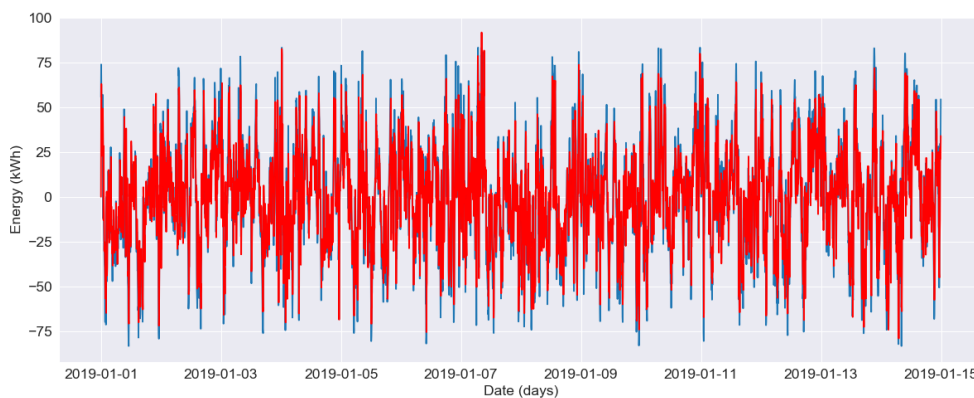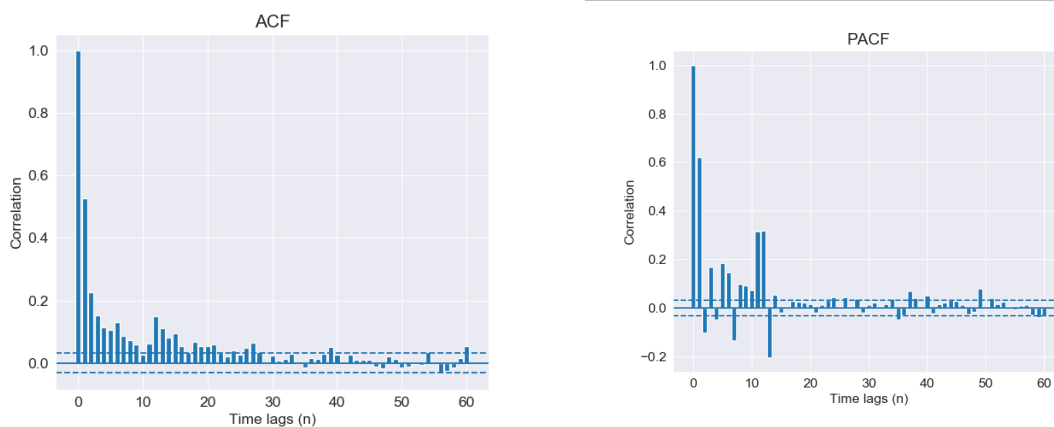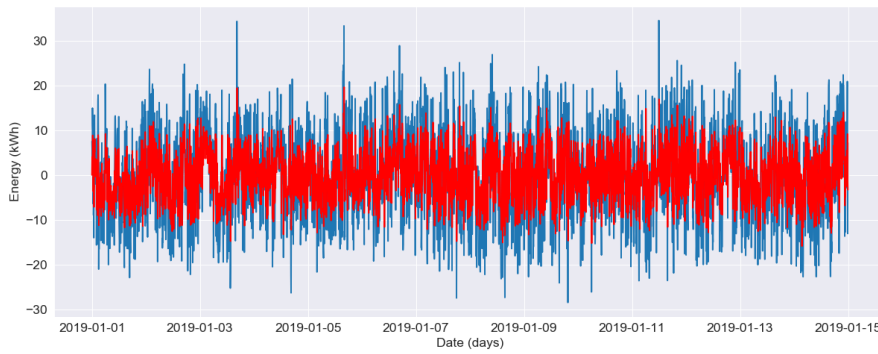
Figure 5.12: Model fit of SARIMA (1,0,3) (1,0,3)6 (red) for time series data of FCR activation of the first two weeks of January 2019 (blue) in the UK dynamic FCR market.

In Figure 5.13, a Q-Q-plot is presented that shows the residuals of the SARIMA model that is fitted with the data time series of the FCR activation of an asset providing FCR services in the United Kingdom Dynamic market. The Q-Q-plot shows that the residuals of the SARIMA model are almost normally distributed. This indicates that there are almost no extreme outliers in the residuals of the fitted model.
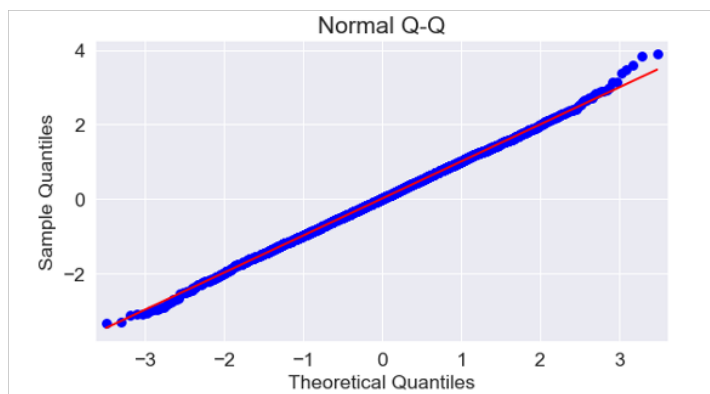
Figure 5.13: Plot of model fit residuals for the United Kingdom Seasonal autoregressive integrated moving average (SARIMA) model.

5.4. Time series model discussion

The results showed that SARIMA models that include both non-seasonal and seasonal components can be used to fairly estimate the battery's behavior in response to grid frequency deviations. This indicates that the height and direction of FCR activation and the future state of charge development of a battery could be predicted by using historical FCR data that has been aggregated to a 5-minute period window. The information that is needed to predict future FCR activation of a BESS does, however, vary among the synchronous areas and FCR markets.

5.4.1. Time series autocorrelation

The moving average terms of the non-seasonal component of the various SARIMA models show that all the synchronous regions use historical moving average values and errors for predicting the value of the current observation (with values that were obtained up to 20 minutes in history). This could therefore give the indication that there might be a change in upward and downward trends in FCR activation in a period of 15 - 20 minutes. This means that the battery might have predictable periods of power influx ('charging') or periods of power efflux ('discharging') for around 15-20 minutes. The autoregressive terms of the various SARIMA models show that the observed values of FCR activation

were also dependent upon the values of the lagged observations. This gives the indication that near-term FCR activation could be predicted based upon historical values.

5.4.2. Time series seasonality

In the results section of the various time series analysis performed, seasonalities in FCR activation were observed in the FCR-N market and UCTE market for time lags with a period of m = 12. This indicates that there is a pattern in the FCR activation that is repeated every hour (since every time lag corresponds to a 5-minute window). First indications of this pattern could also be observed in the plots of the FCR activation over a daytime for the year 2019, that were obtained in the previous chapter (e.g. power fluctuations in FCR activation in the UCTE region, as shown in Figure 5.14). In these plots, on the hour spikes in the FCR activation (both in the positive and negative direction) of an FCR asset can been observed for both the UCTE and Nordic FCR-N market for almost all hours, which might be referring to the existence of an hourly seasonality. For the United Kingdom, these fast power fluctuations seem to occur on a half-hourly basis (see Figure 4.8).
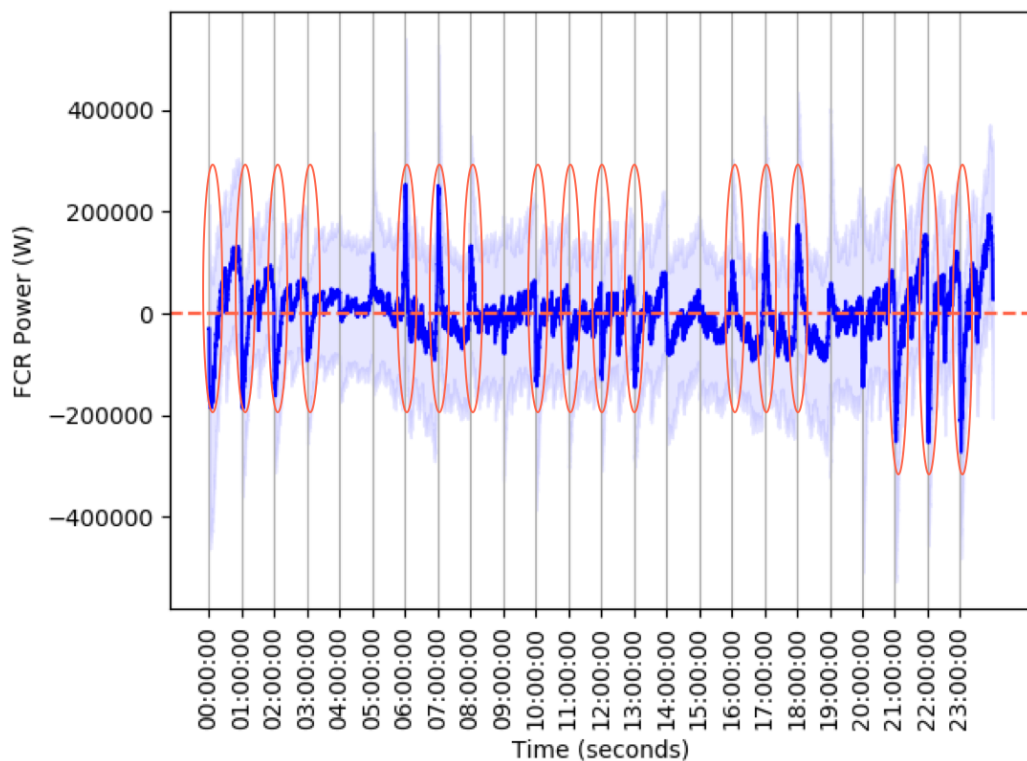
Figure 5.14: Average amount of FCR power output (W) with 95 percent confidence intervals of a battery in the UCTE FCR market over the day. Seasonal peaks were observed around each market scheduling point (on the hour).

The clear spikes in FCR activation seem to be the result of deterministic frequency deviations. These deterministic frequency deviations are defined as frequency deviations that have a typical moment of occurrence, durations and value. As described in (Weissbach et al., 2018), the root cause of these specific deterministic frequency deviations (and affiliated FCR activation) can be found in the changes in power plant schedules that are ramping up or down their power output as a result of electricity market scheduling. In their article, they describe that electricity market scheduling, which is based upon hourly products (or half hourly in the case of the United Kingdom (Hagfors et al., 2016)), is causing deterministic power imbalances in the electricity system network. While electricity demand shows a relatively smooth daily load curve (due to the fact that electricity demand is continuously changing over time), daily electricity generation profiles are more the result of stepwise scheduled

power program changes. The stepwise change in power output of power plants is caused by the fact that these power plants are not perfectly following the load evolution over the (half) hour, but rather change their power output based upon the products that are procured in the electricity market (which are based upon the average electricity demand for a specific (half) hour). This results in a relatively high fluctuation in power output of various power plants in a small period of time (close to the (half-) hourly market scheduling point), thereby causing system imbalances, higher frequency deviations and a higher FCR activation in the same time period.

In literature, more articles were found that describe the interaction between hourly market scheduling and deterministic frequency deviations in the UCTE (Weissbach and Welfonder, 2009) and Nordic (Li et al. (2011); Persson and Chen (2017); Xu et al. (2008)) synchronous areas. All these articles show that more system imbalances and higher frequency deviations from the reference frequency are more likely to occur around the market scheduling point.

In Weissbach and Welfonder (2009), it is even shown that the magnitude and direction of these deterministic frequency deviations are directly dependent on the specific load gradient and time of day (as shown in Figure 5.15). This suggests that there might be a highly correlated daily seasonality in FCR activation (which could also be observed in the heatmap of the UCTE region in the results section of Chapter 4 and which could also explain the high extreme values in the Q-Q plot of the SARIMA that are fitted to the time series of the UCTE and Nordic region). Further investigation in these daily seasonality's should be done to identify new prediction opportunities of FCR activation and the affiliated state of charge developments.
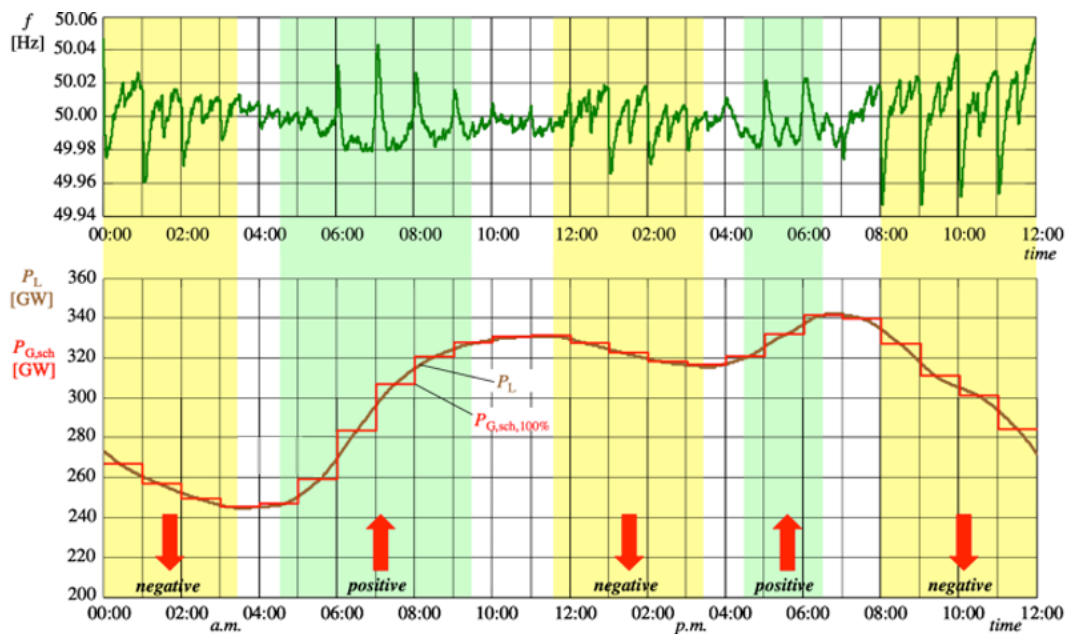
Figure 5.15: Power generation and load and grid frequencies. Scheduled electricity generation (Pg (GW)) and electricity consumption (Pl (GW)) shows to be interconnected with the observed frequency deviations (deterministic) for the UCTE region. Source: Weissbach and Welfonder (2009).

5.5. Time series model conclusion

In this chapter, it is demonstrated that the height of FCR activation of a battery that is providing FCR services in the UCTE FCR market, Nordic FCR-N market and United Kingdom dynamic FCR market, can be predicted with the use of a seasonal autoregressive integrated moving average model. Results show that historical data that is aggregated to a five-minute period can be a useful source in the prediction of future batteries behavior.

For all markets, a seasonal pattern in FCR activation has been found for periods with lengths that are equal to the lengths of the contracting periods of the power exchange markets that are present within

the various synchronous areas. For the Nordic FCR-N and UCTE FCR markets, an hourly seasonality was observed. For the United Kingdom dynamic FCR market, a half-hourly seasonality was observed.

Although the time series analysis and forecasting models that have been constructed in this research show the strength of using historical data to predict future changes in FCR activation and thereby, the batteries behavior, further research that includes other seasonality's should be conducted to get a better estimation of the predictability of FCR activation. This can, in the end, be helpful to determine the full potential of using historical data for future FCR activation predictions.

6

Discussion

In this chapter, the results that were obtained from the literature review, simulation model and forecasting model and their implication for the operation of BESSs providing FCR, will be discussed. First, the overall findings of the various chapters will be elaborated. Second, the overall limitations of the master thesis research approach will be discussed. Third, the implications of these research findings for the operation of BESSs in FCR markets will be considered. In the end, suggestions for further research will be provided.

6.1. Overall research findings

The results of the literature review, simulation model and forecasting model show the complexity and various dependencies in FCR activation and the affiliated charging and discharging behavior of batteries. Both technical, economic and regulatory factors seem to play a determining role in the operation of primary control assets and to shape the boundaries for additional value creation of batteries that provide this grid service.

First of all, in Chapter 2 it is shown that the battery's response to power system imbalances is partially determined by the regulations of the specific synchronous region or balancing area. Regulations, set by the various transmission system operators that are controlling these regions, define how balancing service operators can act within a specific balancing market and how their control assets should respond to certain frequency deviations (as described in Chapter 3).

The real operation of a battery that is providing FCR power does, however, not rely on these regulations only. The occurrences and heights of grid frequency deviations from the nominal reference value are an important indication of FCR activation as well (as shown in Chapter 4). The combination of these two factors determine the power and energy demand of a battery for each time unit throughout the period a battery is performing FCR services.

In Chapter 4, it is demonstrated that the power conversion system of a BESS is not always running at its full (reserved) capacity. For the various synchronous regions and FCR markets that have been examined in this research, simulation results show that there are a lot of moments a battery is not even using the power conversion system and thus remains idle. These moments are referred to as idle moments. In some cases, this total idle time reaches up to around 100% of the time period the battery is available for FCR purposes.

The same applies to the FCR reserved capacity of the energy reservoir of a BESS. As described in Chapter 3, a BESS should be able to deliver the maximal amount of FCR power for a specific time period. In theory, BSPs should reserve a particular amount of battery energy storage capacity to be able to deliver this FCR power at any time. Due to the fact that a battery is idle for a long amount of time and is not always providing its full contracted FCR power (as demonstrated in Chapter 4), the

percentage of time periods in which the whole battery energy storage capacity that is reserved for FCR is needed, seems to be less then 100%.

The differences in the theoretical amount of battery power and energy reservoir capacity that is required for FCR purposes and the real amount of battery power and energy capacity that is needed in response to grid imbalances leaves room for optimizing the battery's utilization. In Chapter 3, it is illustrated that both the idle moments and underutilized storage capacity (energy storage capacity that is not used within a particular time period) could be a useful source for added value creation.

The results of the simulation model in Chapter 4 show that the usability of the idle moments for added value creation is, however, limited. The moments in which a battery is not used for delivering FCR power cannot be perfectly predicted for the UCTE, Nordic FCR-N and the United Kingdom dynamic FCR markets. Additionally, the results show that the batteries in these markets that are providing FCR services are most often only idle for a short period of time (second-minutes). Consequently, these idle moments can only be used for battery purposes that are able to use an irregular power output over a longer time period.

The results of the time series forecasting study in Chapter 5 showed that there are opportunities in determining the required battery energy storage capacity that is required for FCR. It is demonstrated that FCR activation and the affiliated change in state of charge can be predicted based upon historical FCR activation data. This indicates that the future need for battery energy storage capacity for FCR purposes can be estimated. Storage capacity, reserved for FCR purposes but not needed for future FCR delivery, (as estimated by a forecasting model) could therefore be used to serve other battery purposes.

The combination insights that were obtained from the FCR activation simulation study and time series forecasting study shows that the capability of using reserved and underutilized FCR battery power capacity and energy storage capacity for other purposes is very limited. No clear prediction can be made of the behavior of a BESS in response to grid system imbalances. To comply with both the power conversion limits of a BESS in the short term (at a second level) and the energy reservoir state of charge limits in the medium to long term (at a 15 to 30-minute basis) seems to remain a very challenging task.

6.2. Research limitations

In this master thesis research, various limitations were identified. In this section, the limitations of the model assumptions, modelling methods, used data and the obtained results are elaborated.

6.2.1. Model assumptions

The various models that have been developed and used in this study have several simplifications. First of all, information on the technical characteristics of the BESSs was not included. The overall size of the energy storage reservoir and the power conversion system does, however, constrain the opportunities to use a BESS for FCR purposes and influences the overall battery's behavior. The size of the power conversion system is directly related to the maximal power output of a battery that is providing FCR services and therefore, the maximal amount of FCR power a BSP can contract. In this study, it is assumed that the battery has a prequalified power rating of 1 MW (in both the upward and downward direction), which corresponds to the minimal bid size for some of the FCR markets examined in this thesis. Since the total FCR output of a battery is directly related to the maximal contracted amount of FCR power, the results of this study can, however, easily be transformed for balancing service providers that want to contract higher amounts of FCR power.

The size of the energy reservoir of a BESS is also influencing the battery's behavior in response to FCR activation. The developments in the state of charge of a battery and the range in which a battery can be used for other battery purposes is directly dependent on this battery size. Having a smaller battery requires the BSP to do more state of charge management in order to comply with the technical and operational requirements of FCR delivery (Thien et al., 2017).

The daily self-discharge rate, energy conversion efficiencies and battery degradation factors are other technical properties that can influence the state of charge of the battery (Dunn et al., 2011) and therefore, the need for intermediate battery charging or discharging. This indicates that the real potential of using the un(der)utilized battery's power and energy capacity is very case specific and dependent on the technical characteristics of the battery of interest.

Another main assumption in the simulation model, is that the BESS is assumed always to be contracted for FCR services. In reality, this might not always be the case. In most of the European countries, balancing services are procured in an open market. BSPs can hereby make offers on the provision of FCR services and the offers are selected on a merit order basis (Borne et al., 2018). This might result in a FCR offer of a specific BSP that is not accepted and therefore, the BSP is not required to deliver FCR power for the contracting period that has been procured. Consequently, the BSP can decide to use the battery for other battery purposes during the contracting period it is not providing FCR services.

6.2.2. Model limitations

Although the seasonal autoregressive integrated moving average model that has been used in this study is capable of including a time series seasonality, the model does have some limitations. One of the biggest limitations of the use of this SARIMA model is that it can include only one seasonal component in its original form. This limits the forecasting model to the use of an hourly seasonality only, whereas the data showed that there might also be a daily seasonality in the time series. Future research could focus on the inclusion of external regressors (Fourier terms) to take into account the daily seasonality in the prediction of FCR activation, as shown in (Murat et al., 2018).

Both the simulation model and time series forecasting model could not be validated by the use of real FCR activation data of a BESS that was providing FCR power. It can, however, be questioned to what extend this would have impacted the results. FCR activation is, in general, directly related to the institutions that are defining the way in which BESS should respond to certain grid frequency deviations. This indicates that in the normal operation of a BESS in FCR provision, no real deviation from this theoretical value is possible. The validation of these models with real FCR activation data could however identify the impact of the market bidding and state of charge management processes on FCR activation.

6.2.3. Data limitations

In the simulation model of this master thesis, grid frequency data of the various synchronous regions (UCTE, Nordics, United Kingdom) was collected from different TSO databases. The raw grid frequency data that was obtained for the UCTE region had a time interval of 10 seconds per observation. To be able to make an estimation of the BESS FCR activation on a 1 second interval, a forward filling method has been applied. This forward filling method does have consequences for FCR activation and the idle time moments and periods of a battery providing FCR services in this region (it can either over- or underestimate the amount of idle time moments and idle time periods). This is also the case for the Nordic FCR-N market. Missing data values of the period (04/05/2019 10:48:07 - 09/05/2019 14:35:24) affect the results of the overall total FCR reserve activation and total idle time of a battery performing FCR services in this particular region.

Although these data problems have been acknowledged, it does not change the overall insights that were obtained in this study. In this master thesis research, it was not the intention to find the exact values of FCR activation and the total amount of idle time. Gaining meaningful insights into the operation of an FCR asset and the usability of idle moments for other purposes were still possible.

6.2.4. Result limitations

The results that were obtained in this study show that there are many factors directly or indirectly involved in FCR activation. Regulations, grid frequency characteristics and battery characteristics all

seem to influence the overall activation of a FCR asset. The dependencies of the results on these factors also reveal the vulnerabilities of the results to (future) changes in these specific variables. Grid frequency characteristics could, as an example, change due to the penetration of RES. Since these RES are not contributing to the system inertia of the electricity network, (higher) grid frequency deviations are more likely to occur (Kroposki et al., 2017). Changes in regulation or the substitution of specific balancing products could also influence the FCR requirements and FCR activation (Gundogdu et al., 2017). The institutions and technical limitations of a battery do also affect the possibilities to use the un(der)utilized power and energy capacities for other battery applications. First of all, the results do not take into account the recharging strategy of a battery that is required to control the state of charge of a battery within its limits. The risk of FCR non-compliance could also impose penalties, which can restrict balancing service providers that are risk-averse to use the available battery capacities (Engels et al., 2019). Consequently, actual information on the FCR operational requirements and grid frequency characteristics, taking into account the characteristics of the battery, seems essential for identifying the real FCR operation and predictability of the state of charge development.

One other limitation of the results that were obtained from this study is the fact that no clear estimation could be made of the profitability of using the identified degrees of freedom for other battery purposes. Making estimations of the profitability of a certain other application, requires not only insight into the profitability of this other application, but also insight into its required battery energy storage and power capacities and the overall effect of this battery service on the batteries state of charge.

6.3. Research implications

Although this research showed that there is only a limited opportunity for added value creation in the operation of batteries that are preliminary used for FCR purposes, the knowledge that is obtained in this study can still be very useful for BSPs in determining the operational strategies of their battery energy storage assets.

The ability to predict the future state of charge evolution of a BESS could, for example, be used to make better choices on the state of charge management strategies of batteries that are oversized for the delivery of FCR services. By predicting the development of the state of charge of a battery over time, BSPs might be able to identify a future need for battery's charging or discharging on an earlier notice (see Figure 6.1). This information could be used to buy or sell electricity in the intraday electricity market, hereby changing the state of charge of the battery to a preferred state of charge level.
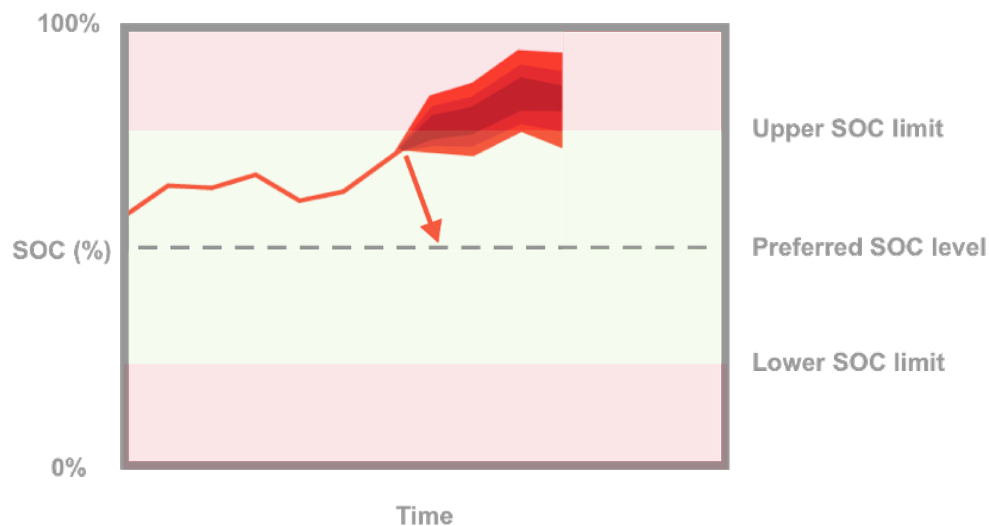

Figure 6.1: State of charge (SOC) development over time (red) due to battery usage. By predicting the future state of charge, more insight can be obtained in the moments that a battery has to be charged or discharged to the preferred SOC level.

Transmission system operators could also use the information obtained in this study for the attraction of new reserve capacity. By providing more transparent and clear information on the operational requirements of their existing FCR products and the predictability of FCR activation, balancing service providers are more able to estimate their profitability and operational strategies. This might attract new market players in the FCR market which can lead to more installed reserve capacity and more competitive FCR pricing.

The results of this master thesis study also highlight the complexity and interdependencies in the determination of an optimal battery's utilization and operation (as also shown in the alignment scheme in Chapter 2). The technical characteristics of a battery are important in defining the state of charge and power output limits of a BESS. The institutional arrangements that are present in the area in which the BESS is deployed and operated, define part of the battery's behavior in response to grid frequency deviations. These grid frequency deviations are, partially the result of deterministic system imbalances. These deterministic power system imbalances seem to be correlated with the products that are procured in the electricity market, which are, again, based upon regulations that are set by the TSO. Finally, all the various regulations are dedicated to guarantee a stable and reliable electricity transmission between power system generators and power consumers, which is the critical function of this grid balancing system.

All the aforementioned relationships show the sociotechnical character of this problem and its designed solutions. The use of a battery for two applications simultaneously, and in particular, applications where more than one actor is involved, requires compatibility of both the technical and social arrangements in the system of interest. From the results that are obtained in this master thesis, this seems to be not bounded to one specific system level only. Technical and institutional arrangements on various system levels seem to affect the operation of a battery in FCR provision and the profitability of a battery over its lifetime. Research that is conducted in this particular research field should therefore take into account the impact of the institutions and technical architectures that are present in other system levels on their results. New causal relations and potential improvements of the system of interest might be more easily identified, designed and implemented.

7

Conclusion

In this chapter, the answer to the main research question is provided. Furthermore, the sub research questions that have been used to answer this research question are elaborated. Finally, recommendations for further research will be given based on the results of this study.

7.1. Main research question
What are the opportunities to create added value in the utilization of a battery energy storage system that is providing frequency containment reserve services in the European Union?

The results and insights that were obtained in this study showed that the opportunities of added value creation in the operation of a battery that is providing FCR services in the European Union are limited.

Batteries that contracted their full power capacity for FCR purposes are constrained in the use of their power conversion system and energy reservoir by compliance with existing FCR regulations. These regulations define the activation profile of batteries that provide FCR services. Meaning that the regulations also define how much storage capacity and power capacity of a battery is required and used over time. However, the historical activation profile of such battery suggests that this does not always have to result in a full utilization of the reserved FCR power capacity and energy storage capacity of a battery. For various FCR markets in Europe, moments were identified where the power conversion system was not used and time periods were identified where the total reserved energy storage capacity of a battery was underutilized. Theoretically, these idle moments and the underutilized energy storage capacity of a battery could therefore be opportunities for added value creation. In practice, the use of these degrees of freedom for added value creation seems, however, limited. Although the results of this research suggest that there is a possibility to predict the future utilization of the energy storage capacity of a battery for some of the FCR markets in Europe, the moments and length of the periods in which a battery is not using its power conversion system for FCR purposes seems not perfectly predictable. This indicates that there is only a possibility to use these degrees of freedom for other battery applications that require an irregular (grid) power output over a certain time period.

7.1.1. Sub research questions
In the research process, several sub research questions were answered to motivate the answer to the main research question. The section summarizes and elaborates on these research questions.

Which factors determine the activation of a BESS providing FCR services?
FCR is the first controlling mechanism that is used by a transmission system operator to counteract imbalances between electricity demand and electricity supply in the power supply chain. It is used

to stabilize frequency deviations from its nominal value in the entire connected high voltage transmission network and is critical for normal grid functioning. It includes power reserve assets that are synchronized with the electricity network and increase or reduce their power output to restore a system imbalance, regardless of its cause and location.

In general, the activation of a BESS providing FCR is dependent on the grid frequency profile, contracted amount of FCR power and regulations that are present in the synchronous region where the battery is deployed. Grid frequency profiles and the affiliated grid frequency deviations are region specific and related to the overall characteristics of the electricity network infrastructure in the synchronous area of interest. The amount of FCR power that a BSPs can contract depends on two factors. Firstly, the technical limitations of the BESS define the size of the power conversion system and energy reservoir. Secondly, the regulations (including the market access restrictions, FCR contracting period, bid symmetry, bid size and unit pooling requirements) prescribe how a BSPs can participate in the FCR market.

Other regulations, including the frequency dead band, insensitivity range, power provision rate, power provision speed and power provision duration, determine the operational requirements and FCR activation of a BESS providing frequency containment reserve services.

What is the activation profile of batteries providing FCR services in the European Union?
Based upon the regulations and grid frequency profiles of the various synchronous regions in Europe, a varying (simulated) activation profile of batteries providing FCR services for the different FCR markets that were examined in this study was observed. Both the amount-, time-, height- and direction of FCR activation was different for the various FCR markets that were included in this research. The activation profiles showed that in all markets, time periods were observed in which the battery was not used for FCR purposes. This indicated that there are moments when the battery is 'idle' as well as periods when not all of the reserved battery capacity for FCR was utilized.

What are the degrees of freedom in the operation of a BESS that is providing FCR services which can be used for value stacking?
The FCR activation profiles of the BESS for the various synchronous areas showed that the battery does not always use its full power capacity and energy capacity that was initially reserved for FCR purposes. The presence of idle moments and periods in which not all of the reserved energy capacity of a battery is used show that there might be opportunities to use these degrees of freedom for serving other battery purposes and therefore, add value to the overall battery's operation.

What is the practical usability of the degrees of freedom in the operation of a BESS that is providing FCR services which can be used for value stacking?
The practical usability of the identified degrees of freedom for value stacking opportunities is limited. No clear prediction can be made of the various moments a battery is used for FCR and the length of the periods in which the battery is idle. The results of this study do, however, suggest that the state of charge development of a battery that is providing FCR services might be predictable. Patterns in FCR activation and direction have been identified for various FCR markets in Europe and could therefore be useful in predicting the state of charge development over time and identifying the periods in time in which a certain storage capacity is underutilized. The question remains whether the combination of these two degrees of freedom gives enough room for value creation. More insight into the required power and energy storage capacities for state of charge management and other battery applications is required to identify the full potential of the identified degrees of freedom and the potential impact on a battery's profitability.

7.2. Scientific relevance
In the presented master thesis, various research methods have been used to explore the value-stacking opportunities of batteries that are providing FCR services in the European Union. A literature review

was performed, a simulation model was built, and a time series analysis and forecasting model was developed to understand the theoretical and practical value-stacking opportunities of a BESS. In general, the master thesis that was performed opened new research directions for identifying value-stacking opportunities of batteries providing services that are subject to operational constraints set by external parties (such as TSOs). Up until now, most research that was found in literature focused on the combination of battery services based upon the 'theoretical' activation of batteries rather than its real activation profile.

In the case of a battery that is providing FCR services, the regulations that determine the activation of batteries seem to be somewhat 'over-cautious' to be able to secure the critical functionality (stable and reliable electricity supply) of the system of interest (electricity system). These regulations are determined and sized in such a way that the electricity system is able to withstand very high system imbalances that have an extreme low probability to occur. As a consequence, there is a discrepancy between the battery capacity that is reserved for FCR (based upon the 'theoretical' activation of batteries) and the real battery capacity that is used for FCR. This research does therefore suggest that the full value-stacking potential of batteries could only be identified by analyzing and evaluating the real activation profile of batteries that are operated in a certain context.

7.3. Societal relevance

The information that is obtained in this master thesis study is also societal relevant. As described in this thesis, BESS are seen as important assets to provide the required flexibility and stability of the future electricity supply chain. BESS are, however, extremely capital intensive. Investors in batteries are therefore trying to identify the best methods to obtain the most value in the lifetime of a battery. This includes the identification of the best operating strategy (which application to serve at each time moment) and best state of charge management strategy (at what moment to charge or discharge your battery to the preferred state of charge level).

The insights that are obtained in this research can contribute to the knowledge that is necessary to make these strategic operating choices. The information of the required power capacity and energy capacity of a battery for FCR purposes can determine the profitability of using a battery for the provision of FCR services. This can subsequently be used to make better strategic bidding choices in a certain FCR market. Additionally, the information obtained in this study can give insight into the benefit-stacking opportunities of batteries that are providing FCR services (making use of the idle moments and underutilized energy storage capacity of the battery). Consequently, BSPs might be able to better decide upon their state of charge management choices and operating strategy. This could, in the end, result in added value creation and make the investment in BESS more economically attractive.

7.4. Research suggestions

Based upon the results and insight that were obtained in this study, various recommendations for further research could be made. First of all, additional battery properties could be added in the (SimSES) simulation model to get a better prediction of the battery's behavior to grid frequencies deviations. The addition of the size of the battery energy storage reservoir could give more insight in the need for state of charge management and the amount of 'idle' time that is required to control this state of charge. Including the self-discharge rate, energy conversion efficiencies and battery degradation rates could further show the need for this state of charge management and the impact on the battery's power and energy storage capacity usage.

Other research could focus on the predictability of the FCR activation in the UCTE FCR, Nordic FCR-N and United Kingdom dynamic FCR market. By adding other seasonal terms to the SARIMA models that were developed and used in this study (e.g. the daily seasonality that has also been observed in this research), potential improvements in the predictability of future state of charge developments of batteries providing FCR services could be made. This information could be useful in the determination of the future battery's behavior, which could improve the operational strategies of BSPs.

By further investigating the factors (size, efficiency, self-discharge rate) that influence the need for a specific amount of power capacity and energy capacity of a BESS that is providing FCR services, more insight could be gained in the opportunities to use these batteries for other battery purposes simultaneously. To use a battery for two applications simultaneously does require insight into the power and energy capacity requirements of each battery application that is used. In particular, it is needed to obtain information about the time constraints and regularity in which a specific battery application requires power and energy capacity of a battery. This can help to understand the real potential and benefit of using these various applications simultaneously.

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A
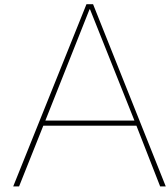
Literature Review Search String

TITLE-ABS-KEY ((energy OR power OR electric*) AND europe* AND ("Balancing market" OR "FCR" OR "Frequency containment" OR "Frequency regulation" OR "Frequency* reserves*" OR "primary control")) AND (LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016))

B

Results FCR Activation

B.1. Heatmap of Nordic FCR-D market
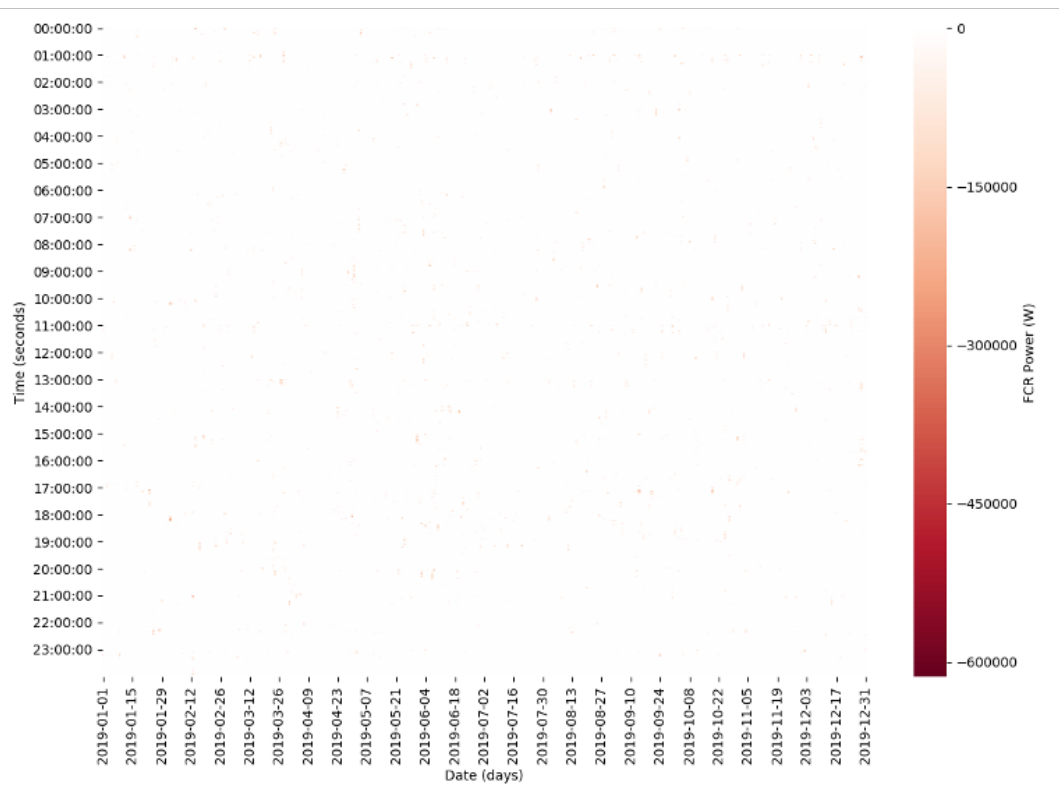
B.2. Heatmap of UK Non-Dynamic FCR market