



APPLICATION OF A BESS OPTIMISATION ALGORITHM FOR FREQUENCY CONTROL IN SPAIN AND GERMANY

Master's in Sustainability Science and Technology
Universitat Politècnica de Catalunya

CLARA LANDARIBAR

Supervisor: Jose Lopez Lopez

Co-supervisor: Luka Smajila

September 2023

Acknowledgments

Firstly, I would like to thank my supervisors Luka Smajila and Jose López López for their support and guidance throughout the development of the thesis.

I would also like to thank Professor Mikael Amelin, as it was his course in KTH Royal Institute of Technology that first introduced me to various of the topics covered in this research project.

To the people I have met within the Heat and Power department, with whom I have shared a space to work.

To the friends in Stockholm that made the process that much more enjoyable every day.

To my family and friends back home, for their constant support through my studies.

To Ben, for his patience and support.

Lo más hermoso se aprende enseguida y lo hermoso nos cuesta la vida

-Silvio Rodríguez

Keywords

AS. Ancillary Services

BESSs. Battery Energy Storage Systems

CO₂. Carbon dioxide

CPP. Coal Power Plant

DB. Deadband utilization

DoD. Depth of Discharge

EoL. End of Life

EU. European Union

FCR. Frequency Containment Reserves

GWP. Global Warming Potential

kWh. Kilowatt-hour

LCA. Life Cycle Assessment

LIB. Lithium-ion Batteries

MW. Megawatt

MWh. Megawatt-hour

OTC. Over-the-counter

OF. Overfulfilment

PCP. Primary Control Provision

PV- Photovoltaic

REE. Red Eléctrica Española

SoC. State of Charge

ST. Scheduled transaction

TSO. Transmission System Operator

Abstract

The energy transition, particularly in the electricity sector, has led to the inclusion of a higher share of renewable sources in the grid. The intermittent nature of renewable sources and their lower inertia has increased in the need for regulatory mechanisms. Battery energy storage systems are considered a potential solution for frequency regulation, being particularly well suited for primary frequency control due to their fast response. In that line, the project explores the global warming potential of the utilisation of this technology in the deployment of primary frequency control in Germany and Spain.

The analysis is conducted with the development of three different models. Firstly, the deviation and frequency model allows for the statistical analysis of the German grid's frequency. Secondly, a dispatch model is utilised to obtain the energy dispatched by the battery system for primary frequency control and for state of charge management in its use phase. Lastly, the environmental model calculates the global warming potential of the battery system throughout its lifespan. With a life-cycle approach, the project accounts for the production and use phases, excluding the end-of-life stage.

For the German market, the analysis is conducted for the year 2021 deploying a battery system of 1 MWh of usable storage capacity. The considered prequalified power is 1 MW and the lifespan of the system is established at 20 years. Moreover, it is assumed that all bids placed are accepted. The global warming potential associated with the deployment of primary frequency control in Germany under the previously listed conditions amounts to 288.1 g CO₂/kWh of energy deployed for primary frequency control. This result showcases a reduction of 75% when compared the use of coal and of 50% when compared to the use of natural gas. The sensitivity analysis increases the usable storage capacity to 3 MWh which translates to a further reduction of 9% in the global warming potential compared to the base case scenario.

The Spanish market is analysed with the German frequency dataset and regulatory base, due to significant limitations to available information and to current the non-existent market for primary frequency control. The global warming potential is calculated for a battery system of 1 MWh of usable storage capacity, obtaining 115.12 g CO₂/kWh. It entails a reduction of 90% compared to coal and 80% compared to natural gas.

The results, consistent with academic research, emphasise the relevance of the use-phase in the determination of battery energy storage systems environmental impacts. In particular, the electricity mix of the grid is found to be a driver of emissions in the use-phase of the battery system. With this consideration, the utilisation of battery systems for primary frequency control provision can play an increasingly valuable role with the continuous reduction of the grid's carbon intensity. In line with the previous considerations, the inclusion of a regulatory framework and market for primary frequency control is recommended in Spain.

Key words

Battery Energy Storage Systems, Primary Frequency Regulation, Global Warming Potential, Balancing Markets.

Abstract - Spanish

La transición energética, sobre todo en el sector eléctrico, ha llevado a la inclusión de una mayor proporción de fuentes renovables en la red. El carácter intermitente de las fuentes renovables y su menor inercia han aumentado la necesidad de mecanismos de regulación. Los sistemas de almacenamiento de energía en baterías se consideran una solución potencial para la regulación de la frecuencia, siendo particularmente adecuados para el control de la frecuencia primaria debido a su rápida respuesta. En esta línea, el proyecto explora el potencial de calentamiento global de la utilización de esta tecnología en el control primario de frecuencia en Alemania y España.

El análisis se lleva a cabo con el desarrollo de tres modelos diferentes. En primer lugar, el modelo de *deviation and frequency* permite el análisis estadístico de la frecuencia de la red alemana. En segundo lugar, se utiliza un modelo de *dispatch* para obtener la energía utilizada por el sistema de baterías para el control primario de frecuencia y para la gestión del estado de carga en su fase de uso. Por último, el modelo medioambiental calcula el potencial de calentamiento global del sistema de baterías a lo largo de su vida útil. Con un enfoque de ciclo de vida, el proyecto tiene en cuenta las fases de producción y uso, excluyendo la etapa de fin de vida.

Para el mercado alemán, el análisis se ha realizado para el año 2021 empleando un sistema de baterías de 1 MWh de capacidad de almacenamiento útil. La potencia precualificada considerada es de 1 MW y la vida útil del sistema se establece en 20 años. Además, se asume que todas las ofertas realizadas son aceptadas. El potencial de calentamiento global asociado al despliegue del control primario de frecuencia en Alemania en las condiciones anteriormente enumeradas asciende a 288,1 g CO₂/kWh de energía utilizada para el control primario de frecuencia. Este resultado muestra una reducción del 75% en comparación con el uso de carbón y del 50% en comparación con el uso de gas natural. El análisis de sensibilidad aumenta la capacidad de almacenamiento utilizable a 3 MWh, lo que se traduce en una reducción adicional del 9% del potencial de calentamiento global en comparación con la hipótesis de base. El mercado español se analiza con el conjunto de datos de frecuencia y la base reguladora alemanes, debido a las importantes limitaciones de la información disponible y a la inexistencia actual de un mercado para el control primario de la frecuencia. El potencial de calentamiento global se calcula para un sistema de baterías de 1 MWh de capacidad de almacenamiento utilizable, obteniendo 115,12 g CO₂/kWh. Supone una reducción del 90% respecto al carbón y del 80% respecto al gas natural.

Los resultados, en línea con la investigación académica, subrayan la importancia de la fase de uso en la determinación del impacto ambiental de los sistemas de almacenamiento de energía mediante baterías. En particular, el mix eléctrico de la red resulta ser un factor determinante en las emisiones de la fase de uso del sistema de baterías. Teniendo esto en cuenta, la utilización de sistemas de baterías para el suministro de control de frecuencia primaria puede desempeñar un papel cada vez más valioso con la reducción continua de la intensidad de carbono de la red. En línea con las consideraciones anteriores, se recomienda la inclusión de un marco regulatorio y un mercado para el control primario de frecuencia en España.

Palabras clave

Sistemas de Almacenamiento Energético de Baterías, Control de Frecuencia Primario, Potencial de Calentamiento Global, Mercados de Balance.

Abstract – Catalan

La transició energètica, sobretot en el sector elèctric, ha portat a la inclusió d'una major proporció de fonts renovables a la xarxa. El caràcter intermitent de les fonts renovables i la seva menor inèrcia han augmentat la necessitat de mecanismes de regulació. Els sistemes d'emmagatzematge d'energia en bateries es consideren una solució potencial per a la regulació de la freqüència, sent particularment adequats per al control de freqüència primària a causa de la seva ràpida resposta. En aquest sentit, el projecte explora el potencial d'escalfament global de la utilització d'aquesta tecnologia en el control primari de freqüència a Alemanya i Espanya.

L'anàlisi es duu a terme amb el desenvolupament de tres models diferents. En primer lloc, el model de *deviation and frequency* permet l'anàlisi estadístic de la freqüència de la xarxa alemanya. En segon lloc, s'utilitza un model de *dispatch* per obtenir l'energia utilitzada pel sistema de bateries per al control primari de freqüència i per a la gestió de l'estat de càrrega en la seva fase d'ús. Finalment, el model mediambiental calcula el potencial d'escalfament global del sistema de bateries al llarg de la seva vida útil. Amb un enfocament de cicle de vida, el projecte té en compte les fases de producció i ús, excloent l'etapa de fi de vida.

Per al mercat alemany, l'anàlisi s'ha realitzat per a l'any 2021 emprant un sistema de bateries d'1 MWh de capacitat d'emmagatzematge útil. La potència prequalificada considerada és d'1 MW i la vida útil del sistema s'estableix en 20 anys. A més, s'assumeix que totes les ofertes realitzades són acceptades. El potencial d'escalfament global associat al desplegament del control primari de freqüència a Alemanya en les condicions anteriorment enumerades ascendeix a 288,1 g CO₂/kWh d'energia utilitzada per al control primari de freqüència. Aquest resultat mostra una reducció del 75% en comparació amb l'ús de carbó i del 50% en comparació amb l'ús de gas natural. L'anàlisi de sensibilitat augmenta la capacitat d'emmagatzematge utilitzable a 3 MWh, la qual cosa es tradueix en una reducció addicional del 9% del potencial d'escalfament global en comparació amb la hipòtesi de base. El mercat espanyol s'analitza amb el conjunt de dades de freqüència i la base reguladora alemana, a causa de les importants limitacions de la informació disponible i a la inexistència actual d'un mercat per al control primari de freqüència. El potencial d'escalfament global es calcula per a un sistema de bateries d'1 MWh de capacitat d'emmagatzematge utilitzable, obtenint 115,12 g CO₂/kWh. Suposa una reducció del 90% respecte al carbó i del 80% respecte al gas natural.

Els resultats, en línia amb la recerca acadèmica, destaquen la importància de la fase d'ús en la determinació de l'impacte ambiental dels sistemes d'emmagatzematge d'energia mitjançant bateries. En particular, el mix elèctric de la xarxa resulta ser un factor determinant en les emissions de la fase d'ús del sistema de bateries. Tenint això en compte, la utilització de sistemes de bateries per al subministrament de control de freqüència primària pot exercir un paper cada vegada més valuós amb la reducció contínua de la intensitat de carboni de la xarxa. En línia amb les consideracions anteriors, es recomana la inclusió d'un marc regulador i un mercat per al control primari de freqüència a Espanya.

Paraules clau

Sistemes d'Emmagatzematge Energètic de Bateries, Control de Freqüència Primari, Potencial d'Escalfament Global, Mercats de Balanç.

Table of contents

Acknowledgments.....	3
Keywords.....	4
Abstract.....	5
Abstract - Spanish.....	6
Abstract – Catalan.....	7
List of figures.....	10
List of tables.....	11
List of equations.....	13
1. Introduction.....	14
1.1. Motivation.....	14
1.2. Research question.....	14
1.3. Document structure.....	14
2. Background.....	16
2.1. Electricity context in Europe.....	16
2.1.1. Electricity mix in Europe.....	16
2.1.2. Electricity markets in Europe.....	17
2.2. Electricity context in Germany.....	20
2.3. Electricity context in Spain.....	21
2.4. Ancillary services: Frequency control.....	22
2.4.1. Technical requirements for FCR in Spain and Germany.....	25
2.4.2. Primary control reserve needs and trends in Spain and Germany.....	26
2.5. Battery Energy Storage Systems.....	28
2.5.1. BESS use cases.....	28
2.5.2. BESS for frequency control.....	29
2.5.3. BESS in Germany and Spain.....	30
2.6. Life-cycle assessment.....	32
3. Literature review.....	34
3.1. Life cycle assessment of BESS.....	34
3.1.1. Use case: FCR.....	35
3.2. Modelling of BESS for FCR.....	36
3.3. Production phase GWP for BESS.....	38
4. Methodology.....	40
4.1. Deviation and frequency model.....	41
4.2. Dispatch model.....	42
4.2.1. Dimensioning of BESS: Base case scenario.....	43

4.2.2.	Dimensioning of BESS: Sensitivity analysis scenario	46
4.3.	Environmental analysis model	47
4.3.1.	Grid carbon intensity data.....	48
4.3.2.	Functional unit	48
4.4.	Limitations and assumptions.....	48
5.	Results	50
5.1.	Frequency analysis	50
5.2.	Dispatch model results.....	55
5.2.1.	FCR energy.....	56
5.2.2.	SoC management energy	56
5.3.	Dispatch model results – Sensitivity analysis scenario	56
5.3.1.	FCR energy.....	57
5.3.2.	SoC management energy	58
5.4.	Environmental analysis	58
5.4.1.	Sensitivity analysis.....	59
5.4.2.	The case for Spain	61
6.	Discussion.....	63
6.1.	Limitations.....	64
6.2.	Further research.....	65
7.	Conclusion	66
8.	References.....	68
Annex I.....		73
	Deviation and frequency model script	73
Annex II.....		75
	Dispatch model script.....	75
Annex III.....		81
	Environmental analysis script.....	81

List of figures

Figure 1. European electricity generation by source, 1990-2020 [9].....	16
Figure 2. Market timeframes in Europe [11].....	18
Figure 3. Bidding zone configuration [16].....	19
Figure 4. German electricity generation by source, 1990-2021 [21].	20
Figure 5. Spanish electricity generation by source, 1990-2021 [25].....	21
Figure 6. Grid activation structure [29].....	23
Figure 7. Characteristics of primary control [30].	24
Figure 8. Primary frequency control regulation [32].	24
Figure 9. Global electro-chemical energy storage power capacity shares by main-use case [40].	29
Figure 10. Large-scale BESS energy (left) and power (right) in Germany.	31
Figure 11. Prequalified BESS power for frequency control in Germany from 2017-2023 [51]...	31
Figure 12. Installed capacity of BESS in European countries (in MW) [6].....	32
Figure 13. Project method flowchart.	40
Figure 14. Frequency deviation occurrences in sample time from German grid.....	41
Figure 15. Permissible operating range of FCR units with limited energy storage [47].....	45
Figure 16. Correlation between the maximum deviation and the length of the occurrences. ..	51
Figure 17. Number of deviations per month in 2021.....	51
Figure 18. Average deviation length per month in 2021 [in sec].....	52
Figure 19. Average max deviation per month in 2021 [in Hz].	52
Figure 20. Electricity generation by source in Germany in 2021.	53
Figure 21. Share of solar and number of deviations on the grid side by side for 2021 in Germany.....	53
Figure 22. Frequency profiles on the representative sample of 21st of December 2021 (above) and the 21st of June 2021 (below).....	54
Figure 23. SoC during cold day (21/12/21) from the representative sample.	55
Figure 24. SoC during hot day (21/06/21) from the representative sample.	55
Figure 25. SoC during hot day (21/06/21) from the representative sample in the sensitivity analysis case.	57
Figure 26. SoC during cold day (21/12/21) from the representative sample in the sensitivity analysis case.	57
Figure 27. Emissions on analysed phase.	59
Figure 28. Comparison of GWP between Base Case and Sensitivity Scenario.....	60
Figure 29. Comparison of GWP between Base Case scenario in Germany and Spain.....	61

List of tables

Table 1. Technical requirements of FCR in Spain and Germany.	26
Table 2. Specific requirements for tendering of FCR in Germany [35].	26
Table 3. ENTSOE Members, Electricity Generation in 2020, and FCR Reserve Requirements [37], [38].	27
Table 4. Literature review on climate change LCA analysis on battery systems.	35
Table 5. Main parameters of models in studies related to the modelling of BESS supporting Ancillary Services.	38
Table 6. Parameters of SoC control in studies related to the modelling of BESS supporting Ancillary Services.	38
Table 7. Cradle to gate GWP of selected case studies.	39
Table 8. Parameters of BESS in the base case scenario.	46
Table 9. Parameters of BESS SoC management in the base case scenario.	46
Table 10. Parameters of BESS in the sensitivity analysis scenario.	46
Table 11. Parameters of BESS SoC management in the sensitivity analysis scenario.	47
Table 12. CO2 equivalent operation intensity per technology [76].	48
Table 13. Frequency analysis in 2021.	50
Table 14. UP and DOWN regulation needs in 2021.	50
Table 15. Frequency values on representative sample.	55
Table 16. Total energy dispatched by BESS model.	56
Table 17. Energy dispatched for FCR by the model.	56
Table 18. Energy dispatched for SoC (Deadband utilisation).	56
Table 19. Energy dispatched for SoC (Overfulfilment).	56
Table 20. Energy dispatched for SoC (Scheduled transaction).	56
Table 21. Total energy dispatched by BESS model.	57
Table 22. Energy dispatched for FCR by the model.	57
Table 23. Energy dispatched for SoC (Deadband utilisation).	58
Table 24. Energy dispatched for SoC (Overfulfilment).	58
Table 25. Energy dispatched for SoC (Scheduled transaction).	58
Table 26. Daily emissions from the use-phase.	58
Table 27. Annual and lifespan use phase emissions.	58
Table 28. Annual and lifespan use-phase dispatched energy.	58
Table 29. Emissions in project's scope.	59
Table 30. GWP of BESS in project's scope.	59
Table 31. Daily emissions from the use-phase in the sensitivity scenario.	59
Table 32. Annual and lifespan use phase emissions in the sensitivity scenario.	60
Table 33. Annual and lifespan use-phase dispatched energy in the sensitivity scenario.	60
Table 34. Emissions in project's scope in the sensitivity scenario.	60
Table 35. GWP of BESS in project's scope in the sensitivity scenario.	60
Table 36. Daily emissions from the use phase in Spain.	61

Table 37. Annual and lifespan use phase emissions in Spain.....	61
Table 38. Annual and lifespan use phase dispatched energy in Spain.....	61
Table 39. Emissions in project's scope in Spain.	62
Table 40. GWP of BESS in project's scope in Spain.	62
Table 41. Prequalified capacity for FCR in Germany for 2023 [in GW] [51].....	63

List of equations

Equation 1. Droop equation.....	23
Equation 2. Primary control reserve requirement.....	25
Equation 3. SoC equation.....	42
Equation 4. FCR provision SoC change equations.....	42
Equation 5. Overfulfilment SoC equations.....	43
Equation 6. Deadband utilisation SoC equations.....	43
Equation 7. Scheduled transaction SoC equations.....	43
Equation 8. Energy capacity due to alert state.....	43
Equation 9. Energy capacity due to a previous activation.....	44
Equation 10. Energy capacity due to a delayed effect of the storage management measures.....	44
Equation 11. Energy capacity due to the activation of reserve operation.....	44
Equation 12. Total energy capacity required by German TSOs.....	44
Equation 13. Maximum SoC.....	44
Equation 14. Minimum SoC.....	45
Equation 15. Ratio of usable storage.....	45
Equation 16. Total emissions from Production + Use phases [in kg CO ₂].....	47
Equation 17. Cradle to gate GWP [in kg CO ₂ /kWh].....	47
Equation 18. Production emissions [in kg CO ₂].....	47
Equation 19. Use-phase emissions [in kg CO ₂].....	48
Equation 20. GWP of BESS [in g CO ₂ /kWh].....	48

1. Introduction

1.1. Motivation

This project has been developed within the line of work of *A new standard methodology for assessing the environmental impact of stationary energy storage systems (LCA-SESS)*, one of the projects of the department of Heat and Power at KTH Royal Institute of Technology. The project seeks to create a life cycle assessment (LCA) methodology to evaluate stationary energy storage systems (SESS) using lithium-ion battery (LIB) technology. The method will encompass specific SESS use-stages and end-of-life options, including recycling.

Climate change is one of the most pressing challenges facing humanity in recent decades. Driven by human activities such as the burning of fossil fuels, its impacts have increasingly grown more frequent, severe, and widespread in the last years. Initiatives such as the Kyoto Protocol or the Paris Agreement have been made to address climate change, with the later aiming to limit the temperature rise well below 2 degrees Celsius above pre-industrial levels. Mitigation strategies involve the transition from fossil fuel-based energy to renewable-based energy, increasing energy efficiency and reforestation among others.

As mentioned, one of the key strategies to fight climate change is the transition from fossil fuels to the use of renewable sources to produce energy. The emissions from the energy sector amounted 36.8 Gt in 2022 [1]. From these, electricity and heat accounted for around a 40% with a total of 14.6 Gt, reaching an all-time maximum [1]. The penetration of renewable energy sources to substitute fossil-based ones raises challenges due to their intermittent nature, as well as the lower inertia they provide [2]–[5]. The augment of flexibility in energy systems, therefore, requires grid regulatory mechanisms. One of the possible solutions to it can be found in battery energy storage systems (BESS), which is considered one of the most promising energy storage mechanisms that are available nowadays [6].

Within the project, this work aims to analyse a particular use case and apply it to several markets in Europe. The use case chosen is frequency control – particularly FCR or primary regulation – and it will be analysed for the markets in Germany, with a settled market for FCR, and Spain, without an existing market for such service. It is therefore interesting to assess the impacts that promising technologies such as BESS have and whether their deployment is beneficial or not for the studied markets.

1.2. Research question

The purpose of this project is to investigate the environmental impacts – particularly of global warming potential (GWP) – of the utilisation of lithium-ion BESS in the specific use-case of primary frequency regulation in Spain and Germany.

The research questions to be answered in the project are:

- What is the global warming potential presented by BESS during production and use phases when utilised in primary frequency control in Germany and Spain today?
- To what extent can the inclusion of BESS improve the global warming potential of primary frequency control in Germany and Spain?
- What are the expected impacts of this technology in their use in the coming years?

1.3. Document structure

The document is divided in various Chapters:

- **Abstract.** Contains a summary of the whole projects in English, Spanish and Catalan.
- **Introduction.** Proposes the objectives and research question as well as the motivation to pursue the topic.
- **Background.** Provides an overview of the state of the art regarding electricity markets in Europe – and particularly in Spain and Germany, frequency control, BESS and its use on balancing markets.
- **Literature review.** Sets a summary of the related work done on the topic previously.
- **Methodology.** Describes the gathering of data and the utilised tools.
- **Results.** Communicates the findings supported by tables and figures.
- **Discussion.** Analyses the obtained results further.
- **Conclusion.** Answers the research question and gives final thought and reflection on the topic.

Additionally, the document includes a reference list and an annex with additional information to the main structure previously described.

2. Background

2.1. Electricity context in Europe

2.1.1. Electricity mix in Europe

An electricity mix – also called power generation mix – describes the resources utilised in the production of electricity in a specific area. It refers to the primary energy sources including fossil fuels (oil, natural gas, coal, etc.), renewable energy (hydro, wind, solar, etc.) and nuclear energy (which is considered neither a fossil fuel nor a renewable source [7]). The composition of the electricity mix varies depending on several factors including historical, social, demographic, economic, environmental, or geopolitical. The understanding of the electricity mix, as well as its development and transformation throughout the years can provide relevant insights and help understand future trends in terms of energy security, environmental impacts, energy transition, policy making and others. It is also a helpful way to compare different countries, regions, and states in a meaningful way.

Europe, with reference to the European Union (EU) as a representative entity, receives its energy supply from diverse sources, both domestically generated within Europe and imported from external countries. In the year 2021, the European Union produced 44 percent of its total energy demand while relying on imports for the remaining 56 percent. The EU's energy composition is predominantly derived from five primary sources: crude oil and petroleum products, accounting for 34% of the total; natural gas at 23%; renewable energy, accounting for 17%; nuclear energy comprising 13%; and solid fossil fuels comprising 12% [8].

It is noteworthy that the distribution of these energy sources manifests substantial variation across different member countries. For instance, fossil fuels, particularly in the case of Poland, assume a critical role, contributing to 43% of their energy mix. In contrast, countries like Sweden have the largest share of energy coming from renewable sources, making up a significant 48% of their energy portfolio [8].

The previously mentioned energy sources represent primary energy, obtained directly from natural sources, such as crude oil, wind, or coal. This primary energy can be employed directly or be transformed into secondary energy products for consumption, such as gasoline or electricity.

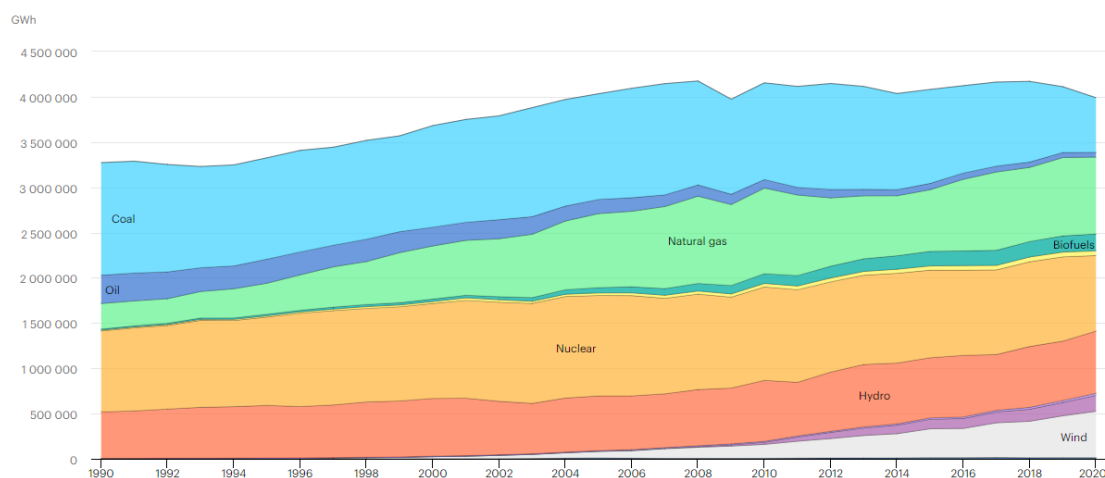


Figure 1. European electricity generation by source, 1990-2020 [9].

With a specific focus on electricity, which represents 24% of the final energy consumed in the EU, it is relevant to recognize the significant proportion derived from renewable sources compared to the total energy mix, accounting for 38% of production in the year 2021 and standing as the predominant source. In contrast, fossil fuels accounted for 36% of production in the same year, while nuclear energy contributed 25% to the overall electricity generation [8].

Once more, it is evident that the electricity mix profile exhibits considerable disparity upon the specific region or country considered. For instance, nations like Poland or Malta rely heavily on fossil fuels, as evidenced by 80% of their electric production originating from such sources. In contrast, France showcases a substantial contribution from nuclear power, accounting for 70% of its electricity generation, while Denmark stands out for deriving 49% of its production from wind energy.

As illustrated in Figure 1, the electricity mix in Europe has undergone substantial transformations since 1990, marked by a great increase in the utilization of renewable resources, notably wind, solar, and biofuels. In tandem, there has been a considerable decline in the utilization of high-emission fossil fuel sources, specifically coal and oil – more notably from the inception of the Paris Agreement into force. However, it is crucial to acknowledge that this shift towards lower-emission sources has also been influenced by an increase in the utilization of natural gas.

Another observation lies in the rise in electricity production across Europe, slightly attenuated by the impact of the Covid-19 pandemic of 2020. Following the pandemic, the electricity production has progressed following the pre-pandemic growth [10].

Concerning the electricity transition in the EU, it is imperative to highlight the repercussions of the gas crisis that following Russia's invasion of Ukraine. The prior trend of renewable sources supplanting the highest-emitting power source, namely coal, has shifted to renewables taking the place of gas. This shift has impeded the pace of emission reduction within the EU and has also slowed down the phase-out of coal and even increased its use, as is the case in Germany [10].

2.1.2. Electricity markets in Europe

As electricity is not a storable good – to a sufficient grade – the production and consumption of electricity is balanced constantly. Trading of electricity occurs both prior and following each time point. Electricity markets in Europe are divided in various trading periods, each possessing specific characteristics. These markets can be categorised into wholesale and balancing markets. The wholesale markets can be further subdivided based on the temporal disparity between the trading and delivery. Figure 2 presents the timeframes of the different existing markets in Europe.

The forward and future markets happen long before the actual dispatch of the electricity, generally between four years and a month before delivery. These markets allow for participants to protect themselves from the uncertainties of shorter-term prices and ensures the selling and buying of a predetermined amount of energy. Forward markets generally lack standardisation and are traded bilaterally over-the-counter (OTC). On the other hand, future markets are standardised and operate on power exchanges.

Day-ahead markets are those in which the participants will sell and buy electricity for the following day in an auction. The electricity is purchased in blocks of an hour and the auction

takes place once a day. The participants log in the orders with the desired quantity (MW per hour/timeunit) as well as the minimum and maximum prices (EUR/MWh) they are willing to pay before the market is cleared at 12:00 p.m. of the day before the delivery. With the willingness of participants to buy and sell in place, the demand and supply curves are established and the electricity price – the market clearing price – will be the intersection of the two curves. Therefore, the market clearing price represents: the cost of producing electricity with the most expensive source needed to fulfil the balance; and the price that the consumers are willing to pay to fulfil their demand. The prices are determined by bidding zones which can be seen in Figure 3. Certain countries feature a single bidding zone – as is the case for Spain, Portugal, or France – whereas others – as in the case of Sweden, Norway, or Italy – feature multiple bidding zones within the national border.

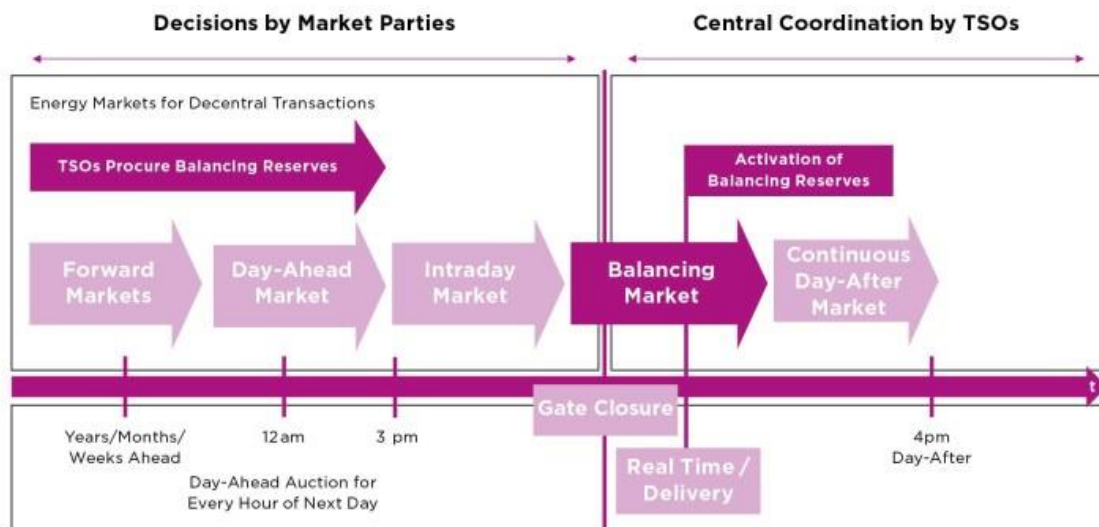


Figure 2. Market timeframes in Europe [11].

The previously mentioned market clearing price, commonly referred to as electricity price as it reflects the hourly value of electricity, is the national electricity price in countries where the bidding zone corresponds to the national border. In countries with multiple bidding zones the prices can be singular for the nation – as it is the “Prezzo Unico Nazionale” in Italy [12] – or multiple – as seen in Norway or Sweden [13], [14].

Intraday markets open after the day-ahead market is closed. This market facilitates buyers and sellers in making volume adjustments based on improved forecasts of demand and renewable electricity production, as well as accounting for unforeseen events, such as power outages. The intraday market allows for continuous trade of electricity of various lengths (quarter-hourly, hourly, etc.) which follows the same procedure of demand and supply match as the day-ahead markets previously explained. From November 2019, 21 countries¹ are part of the Cross-border Intraday (XBID) project. The aim of said project is to “create a single pan European cross zonal intraday market in Europe” [15] Cross zonal intraday markets are a way to address the increasingly fluctuating generation from the higher share of renewable sources in the electricity mix, while allowing for a more secure and optimised electricity market in Europe [2]–[5], [15]. The project partners are the European Nominated Electricity Market

¹ Sweden, Norway, Finland, Estonia, Latvia, Lithuania, Portugal, Spain, France, Netherlands, Belgium, Germany, Austria, Denmark, Bulgaria, Croatia, Czech Republic, Hungary, Poland, Romania, and Slovenia.

Operators (NEMOs), EPEX, SPOT, GME, NordPool and OMIE and the North Western European and Baltic Transmission System Operators.



Figure 3. Bidding zone configuration [16].

Balancing markets are the mechanism through which the TSOs ensure uninterrupted maintenance of the systems' frequency within a defined range, as well as ensuring fulfilment of the required reserves needed to provide a quality service. Nowadays most countries in Europe are members of the European Network of Transmission System Operators (ENTSO-E) with a total of 39 members from 35 countries as well as observer members such as Ukraine – joining in April 2022 – and Turkey – joining in December 2022. These markets and their functioning are further explained in 2.4.

Electricity markets in the European Union are progressing towards a unified market. To reach such objective, energy market rules are being adopted and cross-border infrastructure is being

optimised. The main purpose for a common market design is the incentivisation of clean energy while securing energy at an affordable price [17]. Currently, unified market projects exist for secondary (PICASSO), tertiary (MARI) and replacement reserves (TERRE) [18].

2.2. Electricity context in Germany

The historical electricity generation landscape of Germany predominantly relied on oil and coal until a few decades back. However, the Energiewende, a significant long-term climate and energy strategy, has ushered in a diverse array of electricity production methods within Germany. This strategic initiative is playing a pivotal role in shaping the nation's forthcoming energy portfolio. The Energiewende encompasses a profound transformation of Germany's energy system, involving the gradual discontinuation of coal and nuclear energy, while integrating a substantial share of renewable energy sources instead.

The strategy has been particularly visible in the electricity transition. The increase of renewable electricity is particularly clear in Figure 4, having wind, solar and biofuels increase from a negligible to a considerable share – particularly for wind, becoming the second largest source of electricity production. The Energiewende's plan indicates a renewable share in electricity production of 80% in 2050. The government recently raised this objective to reach the 80% of renewable share in the grid sooner – 2030, which would require of an expansion of grid capacity and renewable integration on the system [19], [20].

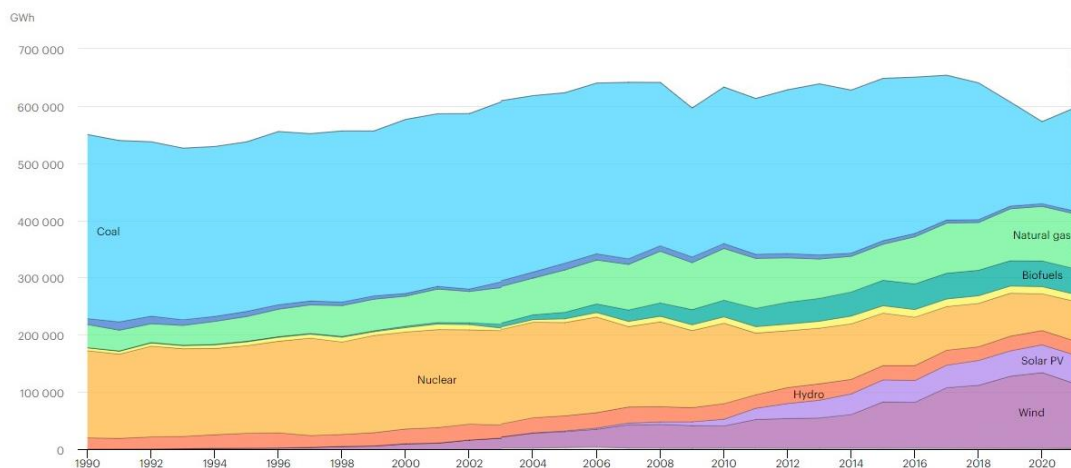


Figure 4. German electricity generation by source, 1990-2021 [21].

The phase-out of coal is planned to happen by 2038 in the Energiewende – and was pushed to 2030 by the German government. However, the energy crisis has affected this objective, and Germany has reactivated coal plants due to the reduced Russian gas supplies [22]. This recent increase in the use of coal can be seen in Figure 4.

One of the challenges confronted by Germany is the mismatch between the demand and production locations within the country. Wind energy predominantly is produced in the northern regions of Germany, whereas demand is largely concentrated in the southern and western parts of the nation. The escalating integration of renewable sources, particularly solar and wind power, has raised complications in electricity transmission. Given Germany's unitary bidding area, this disparity requires the implementation of strategic measures. To address this dissonance, power stations are positioned in the southern areas to compensate for electricity

that cannot be efficiently transported from the north. Concurrently, curtailment measures are applied in the northern regions, shutting down some generation to mitigate congestion risks.

Said grid connectivity challenges carry substantial economic costs, requiring a comprehensive grid expansion plan. This constitutes a focal point of attention of the German government currently.

2.3. Electricity context in Spain

The energy transition is at the centre of the Spain's energy and climate change policies. The 2050 objective within energy and climate is for the electricity mix to be fully renewable. Therefore, the electricity sector is following a massive development in renewables – particularly solar and wind – as well as other measures such as electrification or the deployment of green hydrogen.

The share of renewables in Spain has increased from 24% in 2009 to about 42% in 2022 [23], [24], which is on track with the planned 42% of renewable electricity generation in 2020. As it can be seen in Figure 5, the Spanish electricity generation has experienced a transformation in the last decades. The transformations within the country's electricity mix, notably the increase in the utilization of natural gas and renewable sources, particularly wind energy, coupled with a substantial phasing out of coal (with only a residual share remaining at present), have led to a notable reduction in emissions.

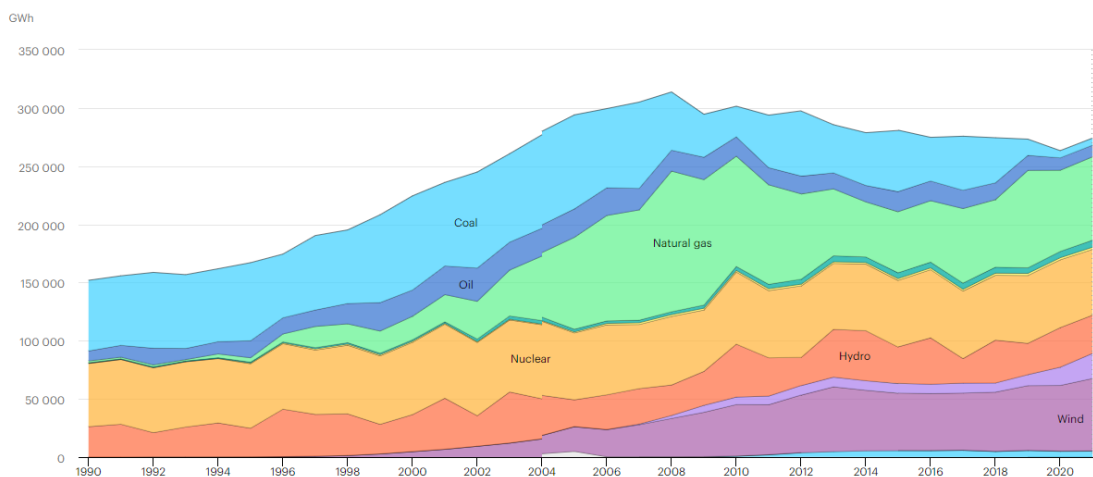


Figure 5. Spanish electricity generation by source, 1990-2021 [25].

As well as coal, Spain is planning to phase out nuclear power, which currently accounts for around 29% of the total national electricity production. With four out of seven reactors closing by the end of 2030, Spain will be left with a system based on variable sources alongside natural gas – currently providing around a third of the electricity production – which will be crucial as a balancing agent of the grid [24].

The electricity mix in Spain will require of a strong integration of renewables in the coming years, which will be tackled by the government with stronger interconnection, storage, demand-side management, and digitalisation. It will be crucial to facilitate the former through swift regulatory proceedings and a well-timed regulatory framework.

2.4. Ancillary services: Frequency control

Ancillary services are a compound of services that regulate the frequency and voltage of power systems while maintaining the balance between supply and demand continuously.

Frequency control is the process that allows an electric system to maintain a stable frequency. It ensures that demand and supply are balanced, providing the system with an electric supply that is secure and of high quality. Changes in frequency can lead numerous grid-related challenges, namely to the malfunction of certain equipment connected to the grid or to electricity provision disruption. Therefore, it is an essential service that needs to be provided to protect the system. The frequency at which the grid operated varies globally, being 50Hz in most parts of the world (including Europe) and 60Hz in other countries such as the United States of America.

The need for this equilibrium is explained by the working basis of synchronous machines. In an electrical system, the steady state is achieved when generation and consumption are balanced. A change in generation or consumption will lead to changes in frequency. For example, if a system that is in balance gets a demand increase, but generation is not affected, the energy will be taken from the kinetic energy of synchronous machines. Therefore, synchronous machines will start to rotate slower which will make the frequency decrease. Similarly, if the generation decreases, the frequency will tend to decrease. The system will detect the frequency and respond to it by increasing generation. The kinetic energy stored in synchronous machines is called inertia. The higher inertia is in a system, the slower the frequency change when an imbalance happens between generation and demand.

Nowadays, systems tend to have lower inertia due to the addition of power sources that do not make use of synchronous machines – as is the case in wind or solar energy – and to the change in the design of certain turbines [2]–[4], [26].

The nomenclature, characteristics, and technical features of ancillary services show variations across the globe, while displaying relatively similar structures. A comprehensive and contemporary literature review on this subject is notably absent, with the last exhaustive survey conducted in 2007 by the Institute of Electrical and Electronics Engineers [27], [28].

As presented in [27], [28] and with general consensus, there are different services of regulation to provide frequency control which are secured by the Transmission System Operator (TSO). These are activated according to frequency deviation ranges and to activation time windows. They are generally divided in three different types:

- **Primary Frequency Control.** Also referred to as Frequency Containment Reserve – FCR. Primary frequency control refers to an automatic control that quickly adjusts the power generation of the providing units to stabilise the frequency.
- **Secondary Frequency Control.** Also referred to as Automatic Frequency Restoration Reserves – aFRR. Secondary frequency control is an automatic response which adjusts the power production to restore nominal frequency. In contrast to primary control, which stabilises frequency deviations, secondary control brings the frequency back to the target value. Secondary control is generally activated 30 seconds after deviation occurrences and lasts until 15 minutes after the deviation commenced.
- **Tertiary Frequency Control.** Also referred to as Manual Frequency Restoration Reserves – mFRR. Tertiary frequency control involves the manual adjustment of participating units. It facilitates the replenishment of primary and secondary reserves

and, in cases where secondary control is insufficient, it restores the frequency to the designated nominal value. Tertiary control is generally activated 15 minutes after the deviation has occurred.

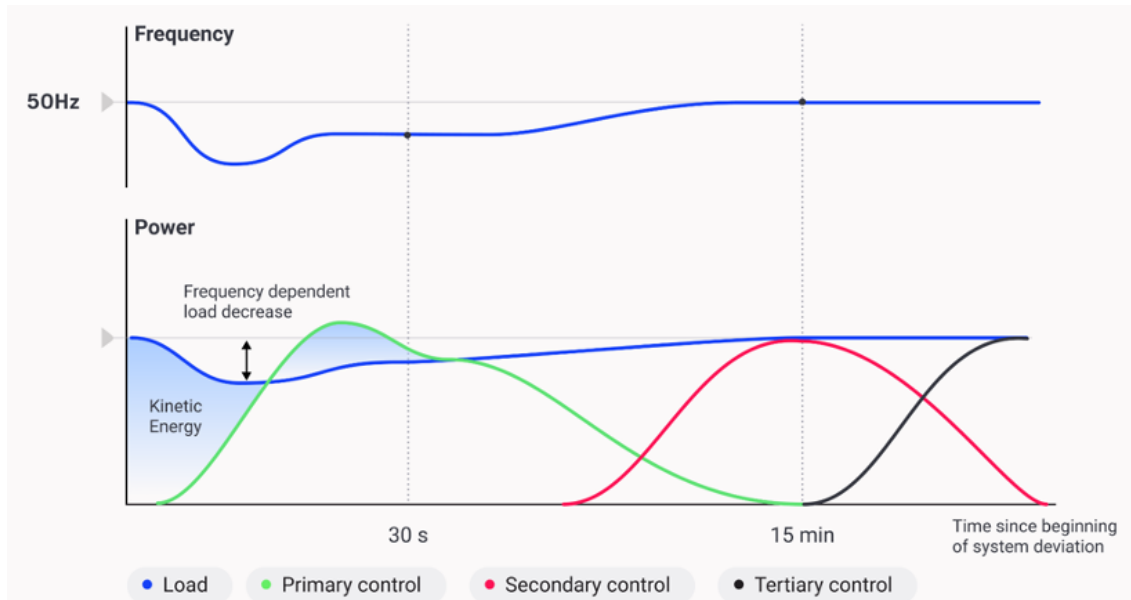


Figure 6. Grid activation structure [29].

As seen in Figure 6, a change in frequency occurs due to a change in load. The change lowers the kinetic energy and triggers the activation of primary control. The activations of primary, secondary and tertiary control occur in a gradual manner. The activation of the different types of frequency control overlap to ensure a smooth transition and recovery of nominal frequency on the grid.

Primary frequency control

As previously mentioned, it refers to an automatic system that enables generator groups to regulate their output power, either increasing or decreasing it, in order to maintain a stable speed and correct any frequency deviation. The primary objective of this control mechanism is to bring the power generation and demand back into equilibrium – not to the nominal frequency, but to a stable frequency value. Notably, primary frequency control is the swiftest of the three response mechanisms, with reserves being activated within a matter of seconds. The generating units providing primary control will generally have to provide full availability within 30 seconds and have a deployment end of around 15 minutes.

Primary control exhibits a direct correlation with frequency deviation. Deviations from the designated nominal frequency ($f_{0,n}$) activate the change of the power output of primary control providers. The ratio of the frequency deviation (Δf) to power output change (ΔP) is called droop value (R), as seen in Equation 1. Droop control is the basis of the functioning of primary frequency control.

$$R = \frac{\Delta f}{\Delta P}$$

Equation 1. Droop equation.

The representation of the droop control in primary frequency control is depicted in Figure 7 where the droop is equivalent to the slope of the line.

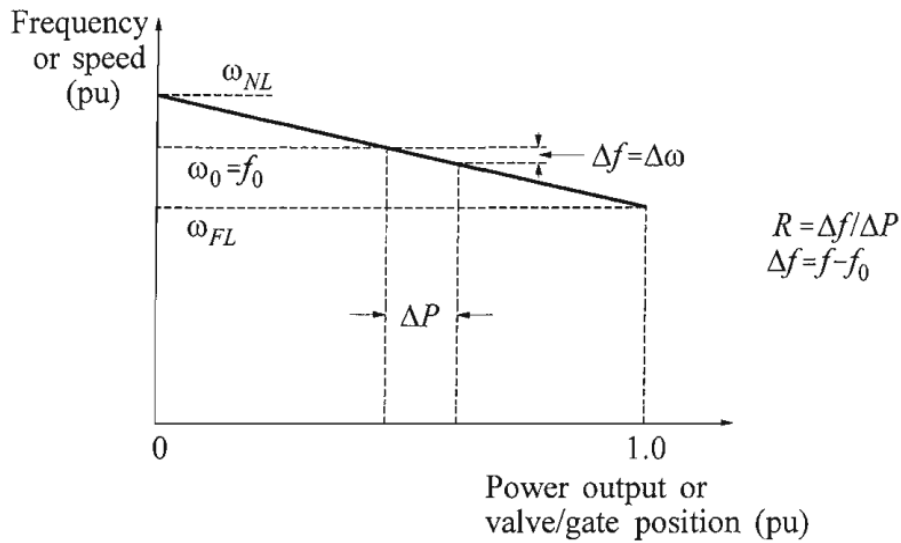


Figure 7. Characteristics of primary control [30].

As previously mentioned, droop control is the basic form of functioning for primary control. Figure 8 depicts the application of droop control in primary frequency regulation, in accordance with the recommendations of ENTSOE [31]. Typically, a deadband is incorporated, representing the frequency range within which deviations from the nominal value do not trigger any alteration in power output. When deviations exceed the deadband's defined range, the frequency providers will be activated either providing a positive or negative power adjustment—positive (also called UP regulation) for frequencies below the nominal threshold and negative (also called DOWN regulation) for frequencies above it. The full deployment of primary control must be reached by providers before the deviation exceeds the maximum of $\pm \Delta f_{max}$.

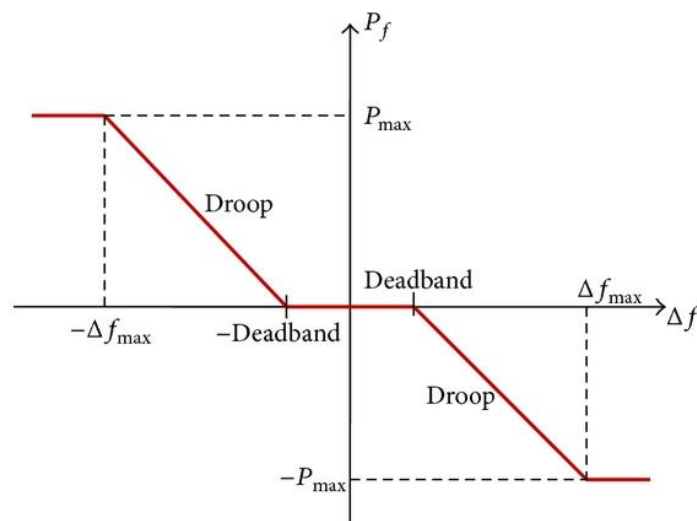


Figure 8. Primary frequency control regulation [32].

2.4.1. Technical requirements for FCR in Spain and Germany

The general requirements for FCR provision in Spain and Germany are coordinated by the ENTSOE – as for every member country. However, the specific requirements are defined by the TSOs of each country. The TSO in Spain is Red Eléctrica Española (REE) and the German transmission system is divided into four regions each of which is controlled by one of the TSOs: Amprion GmbH, TransnetBW GmbH, TenneT TSO GmbH and 50Hertz Transmission GmbH.

The ENTSOE describes the requirement in the Policy Handbook [33]. Certain requirements relevant to this project will be delineated. Firstly, the full activation of primary control reserves is set for a deviation of the system frequency Δf_{max} of 200 mHz from the nominal frequency of 50 Hz. On the physical deployment times, the ENTSOE states that the starting point of action should be seconds after the incident, with a maximum time for 50% of deployment set to 15 seconds and the 100% deployments set to 30 seconds. The deployment must rise at least linearly. The duration of the delivery should be of a minimum of 15 minutes, for the secondary and tertiary control reserves to be set. For each control area established in the European synchronous system, the required primary regulation reserve is calculated with the following expression:

$$RP = \frac{E}{E_T} * RPT (MW)$$

Equation 2. Primary control reserve requirement.

Where:

RP = Required primary regulation reserve.

E = Energy produced the previous year by the national system.

E_T = Total energy produced the previous year by the whole of systems that compound the interconnected European synchronous system.

RPT = Minimum primary regulation reserve established for the interconnected European synchronous system.

The term $\frac{E}{E_T}$ from Equation 2 is also denominated contribution coefficient (c_i) and it is calculated on a yearly basis. All the responsibilities of the process rely on the TSO of each control area, in this case the TSOs of Spain and Germany.

The technical requisites in Spain and Germany display limited differences, with one notable variation being the deadband, representing the optional deviation range with no provision of primary control. This parameter is defined as ± 10 mHz in Germany and is non-existent in Spain. Additionally, another considerable difference exists considering the technical aspects of primary control provision between the two countries, rooted in their distinctive economic frameworks on this service. In Spain, primary control is obligatory but non-remunerable, resulting in a lack of further specifications which remunerated services showcase. The stipulation obliges all generators to reserve 1.5% of their rated output for primary control [34]. The general requisites of FCR have been collected in Table 1.

	Spain	Germany
Paid service	No	Yes
Deployment start	Seconds	Seconds

Full availability	30 seconds	30 seconds
Full activation	± 200 mHz	± 200 mHz
Deployment end (min)	15 minutes	15 minutes
Deadband	0	± 10 mHz

Table 1. Technical requirements of FCR in Spain and Germany.

The specific criteria of the FCR market in Germany displayed in Table 2. The product length is of 4 hours, with automatic activation and continuous provision capability. The offer capacity in Germany must be equal or higher than 1 MW with a resolution of 1 MW. The bids are symmetrical, which means the upward and downward reserves are procured together. Bids can be divisible or indivisible, always with the resolution of 1 MW – if indivisible, offers have a maximum capacity of 25 MW. Furthermore, the German market has specific prerequisites for those providers utilising batteries. These are further explained in Section 4.2 as they are the base for the dispatch model.

Capacity Market	Gate-Opening-Time: 11:00, d-7 Gate-Closing-Time: 8:00, d-1 Product length: 4 hours
Minimum offer capacity	1 MW
Resolution	1 MW
Maximum offer capacity (indivisible)	25 MW
Activation	Automatic
Activation period	Full activation within 30 seconds
Compensation	Capacity price
Symmetrical	Yes
Divisible	Optional

Table 2. Specific requirements for tendering of FCR in Germany [35].

2.4.2. Primary control reserve needs and trends in Spain and Germany

The total primary control reserve for the UCTE synchronous area is 3000 MW, as established by the ENTSOE [36]. The ENTSOE requires each member country to reserve a minimum capacity for FCR. The share corresponding to each one of the ENTSOE members is calculated yearly as previously mentioned in Section 2.4.1.

As it can be seen in Table 3 the requirements of Spain and Germany in 2021 would be 258.35 MW and 555.74 MW respectively. These values have been obtained proceeding as explained in Section 2.4.1, utilising the electricity generation from the previous year, 2020. As it can be seen Germany accounts for the largest electricity production from the members of the ENTSOE, while Spain is the third largest electricity producer.

Country	Company	Electricity generation 2020 [GWh]	%	MW
Austria	Austrian Power Grid AG Vorarlberger Übertragungsnetz GmbH	69591,40	2,35	70,62
Albania	OST sh.a – Albanian Transmission System Operator	5313,00	0,18	5,39
Bosnia and Herzegovina	Nezavisni operator sustava u Bosni i Hercegovini	16818,00	0,57	17,07
Belgium	Elia System Operator SA	86123,90	2,91	87,39
Bulgaria	Electroenergien Sistemen Operator	37234,90	1,26	37,78

EAD (Електроенергиен системен оператор)				
Switzerland	Swissgrid ag	70020,00	2,37	71,05
Cyprus	Cyprus Transmission System Operator	4650,30	0,16	4,72
Czech Republic	ČEPS a.s.	75118,00	2,54	76,23
Germany	TransnetBW GmbH TenneT TSO GmbH Amprion GmbH 50Hertz Transmission GmbH	547662,00	18,52	555,74
Denmark	Energinet	27875,70	0,94	28,29
Estonia	Elering AS	5316,80	0,18	5,40
Spain	Red Eléctrica de España S.A.	254591,00	8,61	258,35
Finland	Fingrid Oyj	66598,40	2,25	67,58
France	Réseau de Transport d'Electricité	509870,70	17,25	517,39
Greece	Independent Power Transmission Operator S.A.	45334,70	1,53	46,00
Croatia	HOPS d.d.	12875,10	0,44	13,07
Hungary	MAVIR Magyar Villamosenergia-ipari Átviteli Rendszerirányító Zártkörűen Működő Részvénytársaság	5327,60	0,18	5,41
Ireland	EirGrid plc	31518,80	1,07	31,98
Iceland	Landsnet hf	18778,70	0,64	19,06
Italy	Terna - Rete Elettrica Nazionale SpA	271648,00	9,19	275,65
Lithuania	Litgrid AB	5261,30	0,18	5,34
Luxembourg	Creos Luxembourg S.A.	2205,50	0,07	2,24
Latvia	AS Augstsprieguma tīkls	5441,70	0,18	5,52
Montenegro	Crnogorski elektroprenosni sistem AD	3378,00	0,11	3,43
Northern Ireland	System Operator for Northern Ireland Ltd	9671,00	0,33	9,81
Netherlands	TenneT TSO B.V.	119879,80	4,05	121,65
Norway	Statnett SF	154302,70	5,22	156,58
Republic of North Macedonia	Transmission System Operator of the Republic of North Macedonia	5032,80	0,17	5,11
Poland	Polskie Sieci Elektroenergetyczne S.A. PSE S.A.	145903,50	4,94	148,06
Portugal	Rede Eléctrica Nacional, S.A.	52278,30	1,77	53,05
Romania	C.N. Transelectrica S.A.	51923,70	1,76	52,69
Serbia	Akcionarsko društvo Elektromreža Srbije	35273,90	1,19	35,79
Sweden	Svenska Kraftnät	160914,00	5,44	163,29
Slovenia	ELES, d.o.o.	16289,70	0,55	16,53
Slovak Republic	Slovenská elektrizačná prenosová sústava, a.s.	26369,00	0,89	26,76

Table 3. ENTSOE Members, Electricity Generation in 2020, and FCR Reserve Requirements [37], [38].

The need for FCR is consequentially directly related to the electricity generation of a country. Therefore, the future requirements will be tied to the increase or decrease of production in each country. However, it could be expected to foresee a more nuanced requirement coming

from the ENTSOE as renewables increasingly take a larger share of the electricity mix, leading to growing frequency control needs – as it could be wind and solar share in the grid.

2.5. Battery Energy Storage Systems

The electricity production is changing rapidly on a global scale. The centralised electricity generation has turned into a distributed generation with low power based on renewable sources [39]. The many advantages of renewables follow uncertainties related to availability. One of the solutions utilised currently is that of energy storage systems (ESS). Various technologies facilitate energy storage, among which are battery energy storage systems (BESS). BESS have popular due to their high efficiency and the quick response. Some of the drawbacks from BESS are the high price and the need for a long-lasting lifespan [39].

Numerous battery types exist, each possessing distinct characteristics, as well as their own set of advantages and disadvantages. Lead batteries are the most mature currently, with a low cost but lower efficiency and lifespan compared to other technologies; sodium-ion batteries are efficient and possess high specific energy, but they require very high temperatures to be used – it is also considerably more dangerous as sodium is explosive on contact with water; lithium-ion batteries have become the preferred battery technology.

Electro-chemical storage is one of the fastest growing markets although the total installed capacity is around 1.9 GW. From the various technologies, lithium-ion is the preferred with a share of 59% of the total installed capacity [40]. Lithium-ion batteries have become the predominant technology of choice in recent times. Although it was utilised in mobile devices at first, it diversified its uses to electrical vehicles and stationary energy storage systems. The design of cells and improvements in the technology facilitated the production of packs which provide higher power [39].

2.5.1. BESS use cases

BESS can be set linked to consumption centres (“behind the meter” storage) and in the generation centre (“utility-scale”) for various use cases. Some of the more common uses for BESS are:

Integration of renewable energy in the electric grid. The use of batteries is key to integrate renewable energy in the electric grid. It is predominantly accomplished through two different supporting use cases:

- Time-shifting. It consists of the storage of energy during periods of demand lower than generation and the provision of energy during periods of high demand. It is a method to deal with the variability of renewable energy production.
- Capacity firming. It assists renewable-based electricity production to be delivered in a uniform manner, reducing the intermittent generation.

Grid support services. BESS are also utilised to support the electric grid through various use cases:

- Frequency regulation. BESS are particularly suited for primary frequency control, which requires a short response time. It is a demanding use as it requires of continuous charging and discharging of the batteries.
- Voltage regulation. It consists of the dispatch or absorption of reactive power to keep the voltage level requirements.

- Electric supply reserve capacity - Spinning. It corresponds to the extra unused power capacity which can be dispatched within minutes of receiving a signal from the grid. It is used to compensate for any unexpected loss of an operating generator [41].

Service stacking. BESS can also provide several of the previously mentioned services simultaneously, which is called service stacking. Service stacking is an approach used to guarantee a favourable return on the investment made in the BESS, as it optimizes the utilization of battery capacities [42].

As seen in Figure 9, the most common use for batteries is that of frequency regulation, taking around 50% of the total share by use cases [40]. According to the International Renewable Energy Agency, the capacity of BESS for stationary applications by 2030 has to increase by around least 17 times compared to the levels of 2017 to fulfil the requirements of renewable energy in the mix, leading to a total capacity of around up to 181 GWh by 2030 [40], [43].

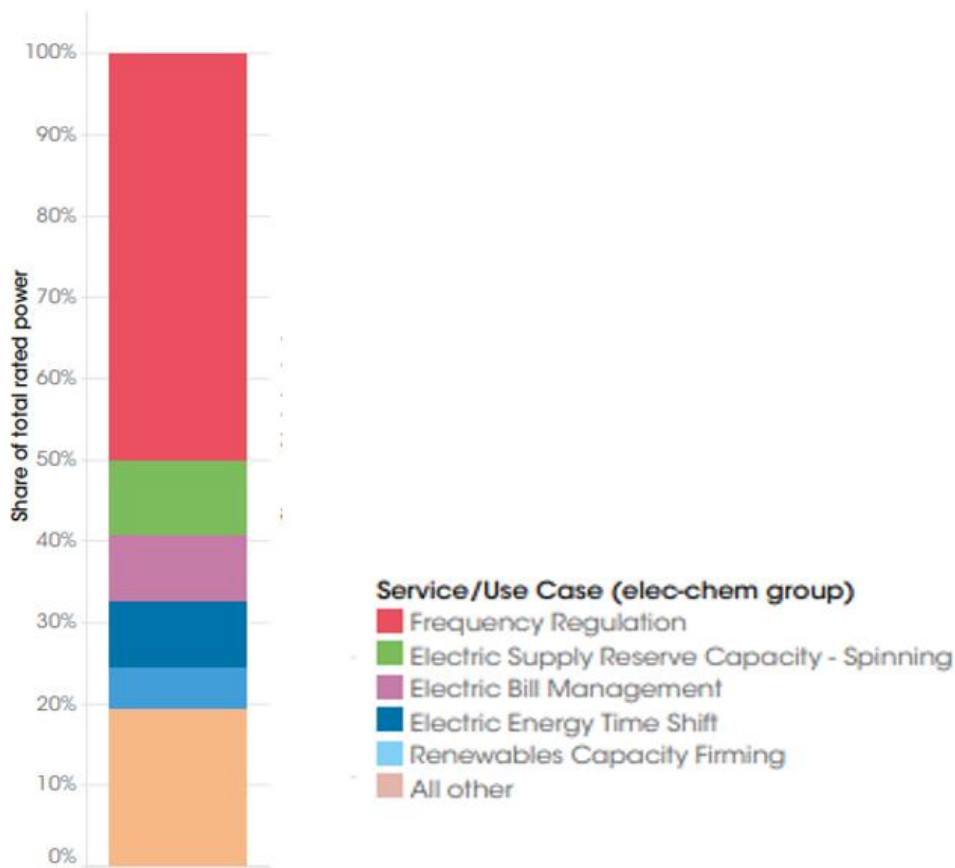


Figure 9. Global electro-chemical energy storage power capacity shares by main-use case [40].

Some examples of use cases of BESS include the battery system supporting renewable energies in Minamisoma, Japan. The 40MW/40MWh system built by Toshiba is utilised to integrate a solar panel field [39]. Another example is the 40MW system supporting frequency regulation in Glassenbury, United Kingdom. Produced by LG, it is part of the grid frequency control system since 2016 [39].

2.5.2. BESS for frequency control

One of the uses that BESS can provide, relevant to the current analysis as delineated in previous sections, is the support of the electric grid – particularly frequency control. This service has been identified as the most profitable and most valuable of the use cases available

with BESS [6], [39], [41], [44], [45]. The main reason for BESS being particularly well suited for frequency control lies in the high power capacity, extended cycle life when utilised in partial cycles, a low cost for battery cycles, and a fast response [46]. As it has been described previously frequency control is divided into various types of regulation, with primary frequency control being exceptionally well suited to be provided by BESS. This is due to the fast response required from providers of primary control.

BESS have been identified as a viable way of providing frequency control for several decades. However, their current deployment is mainly concentrated in a limited number of markets across the globe. Notably, in Europe, BESS finds predominant utilization in Germany and the UK, while on other continents, prominent deployment locations include Australia and the United States. The low rate of implementation can be linked to several reasons, with proper legislation supporting the inclusion of BESS in the balancing markets being one of the main ones. The two countries with a higher integration of BESS for provision of frequency control in Europe, Germany and the UK, have specific regulation for the provision of this services with BESS [47]–[49].

A regulatory system that supports the inclusion of alternative sources for frequency regulation is key to allow BESS to participate in the regulation on the electricity grid. In Germany, the TSOs set regulation related to battery storage systems in 2015, defining the state of charge (SoC) of the batteries in different conditions and other requirements of battery systems looking to provide ancillary services [50]. As countries identify the need to include new grid supporting technologies such as BESS, legislation will transform balancing markets, opening new opportunities for these technologies [40].

2.5.3. BESS in Germany and Spain

Germany is one of the leading storage markets on a global scale. By the end of 2021 around 430,000 stationary battery storage systems were operating in this country [43]. The total power of the BESS was 2.64 GW and the battery energy capacity was 4.46 GWh. Considering the cumulative energy of EVs, charging stations and stationary batteries, the total battery energy would be 44 GWh – which is larger than the total hydro storage energy in the country.

The large-scale BESS have been constructed almost solely for the provision of FCR in Germany. However, the prices for FCR provision dropped as a consequence of a saturation of the market. This led to a decrease in BESS installation as can be seen in Figure 10. 2021 ended with a total of 620 MW and 750 MWh of large-scale BESS installed. Considering that the FCR market size was of 555 MW in 2021, as seen in Table 3, it can be asserted that the market achieved a state of saturation that year.

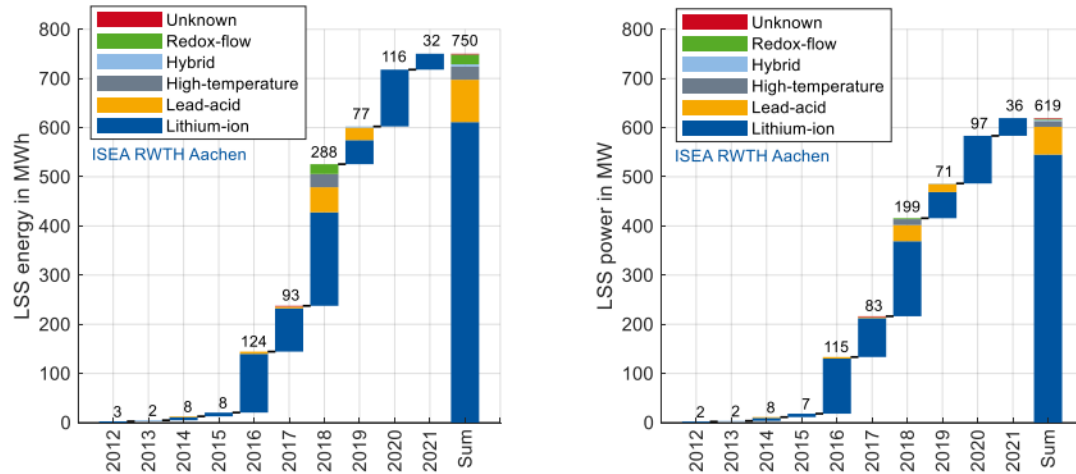


Figure 10. Large-scale BESS energy (left) and power (right) in Germany.

The prequalified power capacity of BESS in 2022 indicated a plateau in the expansion of BESS prequalification [43]. Nonetheless, the prequalified capacity for FCR increased from 480MW in 2022 to 630MW in 2023 as depicted in Figure 11, indicating the continued growth of BESS despite the market's saturation.

As it can be seen in Figure 10, the largest share of large-scale BESS uses the lithium-ion technology, being the only type installed from 2021. Batteries installed in 2021 had an energy capacity ranging from 1 MWh to 10 MWh [43]. The largest project of that year would be expected to be used for service stacking – a tendency that could grow in Germany as the FCR market became increasingly saturated.

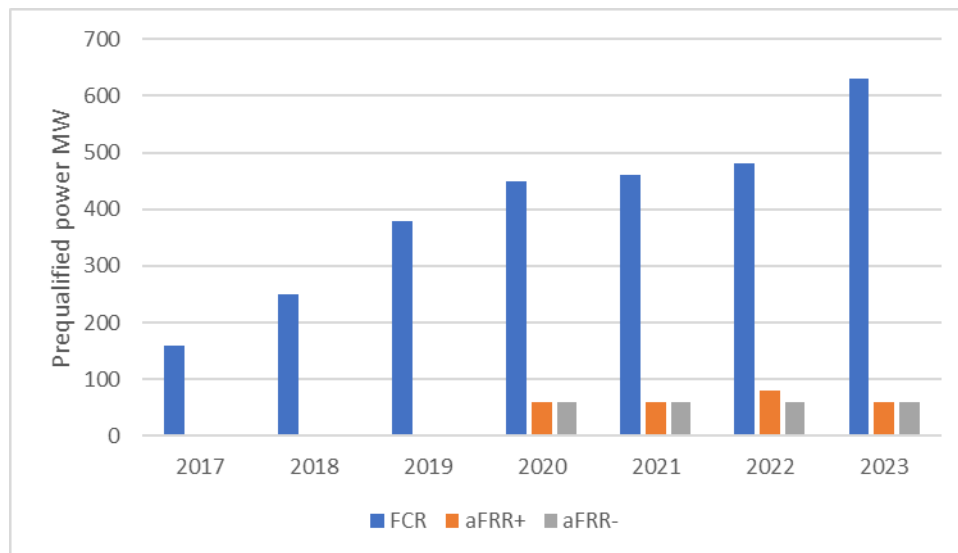


Figure 11. Prequalified BESS power for frequency control in Germany from 2017-2023 [51].

In contrast, Spain's progress in the field of BESS is less advanced. As depicted in Figure 12, Spain currently does not have a substantial magnitude of installed battery capacity. Currently the biggest BESS is located in the Gran Canaria and used for energy shifting as part of an Endesa Store project [39].

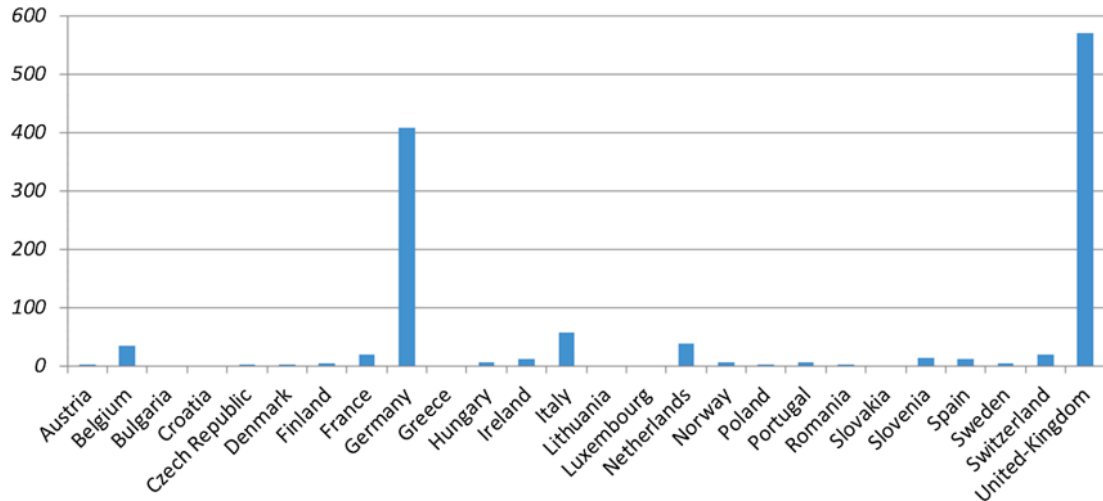


Figure 12. Installed capacity of BESS in European countries (in MW) [6].

The Spanish Government released their Energy Storage Strategy in 2021, which provides a number of lines of action to put energy storage to the service of the energy transition in the short and long term. Among them is the regulatory alteration for the integration of energy storage systems into the provision of balancing services.

As for the National Integrated Energy and Climate Plan (PNIEC) 2021-2030, the planned increase in installed battery capacity is of 0.5 GW by 2025 and 2.5 GW by 2030 to maximise the production capacity of renewable technologies [52]. Considering the current values of installed capacity, as from Figure 12, the objective appears to be challenging.

2.6. Life-cycle assessment

Life cycle assessment (LCA) is a methodology to evaluate and measure the impacts of a product or service throughout its life cycle. The scope of these impacts is diverse, encompassing toxic releases, particulate matter, greenhouse gas emission, land use changes or water consumption.

Life-cycle assessment comprehensively incorporates all phases integral to the production and disposal of a product or service. This includes an exhaustive examination of inputs, such as raw material extraction, energy utilization during production, water consumption, and others, as well as outputs in the form of emissions or waste. Generally, the life of a product or service is categorized into several distinct phases, namely raw material acquisition, manufacturing, use/reuse, and end-of-life/disposal.

The LCA methodology, following the standardisation from the International Organisation for Standardisation's (ISO) 14000 series [53] comprises four distinct stages:

Goal and scope definition.

The first stage defines the purpose and the scope of the system analysed. This methodology can be used for two types of purposes: the single system approach and the comparative LCA. The single system approach serves to evaluate the impacts of a singular product or service, whereas the comparative LCA entails the comparison with a second similar service or product.

In terms of scope, it is imperative to establish a functional unit, particularly in the context of comparative LCA. Alongside defining the functional unit, the determination of system

boundaries is equally essential, as it describes the extent of analysis and specifies the life-cycle phases to be examined – cradle to grave, cradle to gate, gate to gate, etc.

Life-cycle inventory.

In this phase, the various flows occurring within the pre-defined system are defined and modelled. These flows encompass inputs such as raw materials utilized, energy consumption, or fuel usage for transportation, as well as outputs, including emissions or water utilization. This phase is also characterised by the gathering of all data needed to approach the analysis which requires an iterative approach to account for newly found challenges throughout the LCA process.

Life-cycle impact assessment.

During this phase, the previously collected data is processed to yield results gathering all relevant impact categories under consideration. Current software tools like Simapro, OpenLCA, or GaBi are commonly employed to execute this phase. The life-cycle impact assessment discerns the most influential stages within the life of the product or service. The impacts can be categorised according to the area affected – related to human wellbeing, ecosystems, etc.

Interpretation.

The ultimate stage is designed to elucidate the data, assess its sensitivity, and derive the conclusive outcomes. It is pertinent to furnish an evaluation of identified uncertainties. This phase also serves the purpose of scrutinizing preceding stages and corroborating the attained accuracy.

3. Literature review

In this chapter the compilation of the literature and data gathered to fulfil the analysis is presented. Firstly, on the modelling of BESS – particularly for the use of this study, FCR. Secondly, those utilised for the environmental analysis, coming from literature data. And lastly, the ones utilised for the economic analysis.

3.1. Life cycle assessment of BESS

LCA analysis of batteries has been performed for years now considering various battery technologies, use cases and scopes. A comprehensive literature review, including works such as the ones from Porzio and Scown [54], [55], and Pellow et al. [56], offers a fundamental synthesis of the latest advancements in the field of life cycle assessment (LCA) of batteries as well as recommendations for future research on the topic. Previous work on the LCA analysis of batteries include various types of batteries as vanadium redox flow (VRFB) or lithium-ion (Li-ion) [54], [56]–[58]. However, most of the latest work regarding LCA of batteries focuses on Li-ion batteries. Table 4 shows a brief collection of the analysed literature on LCA of batteries.

Jones, Gilbert and Stamford [57] reviewed the use of batteries in substitution for equivalent diesel electric and natural gas generation, and it was always found as beneficial in terms of climate change mitigation potential with life cycle global warming potentials of 185-440 kg CO₂ eq/MWh for Li-ion and 121-443 kg CO₂ eq/MWh for VRFB. The use of renewable sources in its life use, the use of easily recyclable parts, and a reduced use of part replacement was found to help lower the global warming potential (GWP) of the batteries. The energy mix of the use stage was also found to be one of the key drivers of the battery storage system environmental performance alongside other factors, namely the systems efficiency by Oliveira et al. [58]. In the comparative study of Liang et al. [59] the carbon footprints of Li-ion and nickel metal hydride were analysed with Li-ion found to be the most environmentally friendly of the two, especially for raw materials, production, and use phase.

Ryan et al. [60] found that use phase impacts were more significant than upstream or end-of-life impacts when batteries were used for frequency regulation. The most influential parameter being the electricity mix and the fuel price. The round-trip efficiency was determined to be the battery-specific most relevant parameter to the impacts of the batteries. Again, Jenu et al. [61] identified the electricity mix to be one of the key drivers when it came to assess climate change impacts. The study also revealed that a decrease in the battery's cycle depth increased its service life significantly. Moreover, the uncertainty of the production and recycling phases was found to be of marginal significance throughout the complete life cycle of the battery. The use of batteries in place of combined cycle gas turbine plants in the UK was found to have the potential to lower up to 87% of greenhouse gas emissions in 2035 in the study conducted by Chowdhury et al. [62].

Porzio and Scown [55] present four main recommendations. Firstly, they encourage researchers to focus on long-term trends in resource depletion rather than fixed reserves. Secondly, they recommend the consideration of non-standard extraction practices which can cause significant impacts. The third recommendation describes to the definition of the functional unit. The authors emphasise the need to prioritise the use of kWh (either in terms of capacity or energy delivered) while disregarding alternative functional units such as kg of battery mass. Lastly, the authors recommend the analysis of various battery manufacturing facility scales to acknowledge size-related effects.

Source	Jones et al. [57]	Oliveira et al. [58]	Liang et al. [59]	Jenu et al. [61]	Chowdhury et al. [62]
Functional Unit	1 MWh ²	1 kWh ³	1000 kWh	25.3MWh ⁴	1kWh ⁵
Scope	Cradle to grave	Cradle to grave	Raw material extraction to use phase ⁶	Cradle to grave	Cradle to grave
Type	Li-ion (LFP), VRFB	Li-ion	Li-ion	Li-ion (NMC)	Li-ion
Use	Electricity system services ⁷	-	-	Electricity generation coupled with PV	Grid energy services
Emission reduction	Yes	-	Yes	Yes	Yes

Table 4. Literature review on climate change LCA analysis on battery systems.

On their review study Pellow et al. [56] provide recommendations specific to the grid-scale stationary LIB BESS. Firstly, the authors recommend the integration of use phase impacts into the life cycle assessment analysis of BESS, given its substantial, if not predominant, role in their life-cycle impacts. The authors also emphasise that the use case modelling aligns with the diverse scenarios of BESS operation, encompassing the simultaneous possible use cases, often referred to as "value stacking." In forthcoming research, they recommend the establishment of specific material inventories for stationary applications, as the lack of consideration of such components undermines the accuracy of the LCA analysis. Future research should incorporate, the authors indicate, the meticulous examination of alternative end-of-life scenarios beyond recycling, as recommended by the review findings – considering that it is not always a possible option. Lastly, the authors recommend compiling reliable primary data – directly obtained from manufacturers – of stationary battery systems as such data is currently not widely available and leads to higher levels of uncertainty.

3.1.1. Use case: FCR

It's noteworthy that specific research concerning the life-cycle analysis of BESS employed for FCR is still limited and relatively recent, with studies emerging from 2015 onwards. In this Section, a brief overview of each analysed study is provided, followed by a summary of their conclusions.

Oliveira et al. [63] conducted an analysis exploring the utilization of different storage technologies, including Li-Ion, for FCR in Belgium. The study provides an assessment of environmental impacts, encompassing factors such as climate change, human toxicity, particulate matter formation, and fossil resource depletion. The scope for the project

² Of electricity output.

³ Of energy previously stored in Lithium battery.

⁴ As in the reference case used in the study.

⁵ Of electricity generated.

⁶ Not including recycling.

⁷ Such as renewables support, balancing, reserve, and black-start.

examined the production, use, and end-of-life phases. The lifespan of the battery was considered to be of five to ten years.

Koj et al. [64] provided a comparative analysis, focusing on the utilization of BESS in comparison to coal power plants to fulfil the entire FCR requirements in Germany for the year 2013. The battery technology utilised in this analysis was Li-ion, and the chosen lifespan for the battery was set at 20 years. Notably, the research scope did not encompass the end-of-life phase. Various environmental impacts were assessed, including GWP.

Hiremath [65] Hiremath conducted a comparative analysis, encompassing various battery technologies, among which Li-ion was included. This study explored different stationary applications for BESS, such as area and frequency analysis in Germany. The analysis incorporated the assessment of GWP and other environmental impacts, including resource availability into account. However, the study did not factor in the end-of-life phase. The analysed temporal horizon was 20 years of service, involving the deployment of multiple batteries.

Ryan et al. [60] examined the integration of BESS for FCR provision in the United States. The analysis included the production and end-of-life phases, assessed using LCA data. Additionally, the use phase was examined through a dispatch model. The study involved a comparative assessment between the utilization of coal and natural gas power plants and BESS. The environmental impacts explored in the analysis included GWP, cumulative energy demand, and acidification.

Jones et al. [57] provided a comparative analysis focusing on three BESS technologies: lithium-ion phosphate (LFP), vanadium redox flow battery (VRFB), and liquid air energy storage (LAES) for FCR in Great Britain. This study solely assessed the environmental impact of GWP. GWP reductions were quantified by comparing these BESS technologies to the use of diesel-electric and natural gas generation. The lifespan of the BESS in this analysis was estimated to be between 7.5 and 10 years. The research encompassed the production and use phase stages as well as the end-of-life phase.

The analyses conducted in various locations – albeit diverse in their contexts –, and substantially diverse lifetime periods, consistently demonstrate an overall reduction in environmental impacts when deploying BESS instead of fossil fuel-powered technologies. These studies underscore the potential for these emerging technologies to play a substantial role in providing ancillary services, especially as renewable energy integration increases within the grid. Additionally, these investigations emphasise the pivotal role of the use phase in driving environmental impacts, notably GWP.

Moreover, these studies highlight that the inclusion of renewable energy sources in the grid further amplifies the positive environmental impacts associated with BESS. Consequently, BESS emerges as a technology well-suited for facilitating the transition of the electric grid towards a renewable-based system.

3.2. Modelling of BESS for FCR

Previous research regarding the utilisation of BESS for FCR include a variety of modelling approaches and specific characteristics, with some tailored to the specific requisites of the designated location, while others established according to the scope and objectives of the researchers. The characteristics with their given values, utilised to model the use of BESS in FCR in previous work have been outlined in Table 5.

Thien et al. and Fleer et al. [66], [67] approach the modelling of the FCR in Germany, with similar values for the nominal state of charge and efficiency consideration. However, Fleer et al. [67] provide a more nuanced model – with a consideration of the SoC limits for the activation of the SoC management strategies of overfulfillment and scheduled transactions. Battery sizes diverge within the selected cases with Fleer et al. [67] selecting a 1 MW and a 2 MW nominal power battery battery to provide a comparative analysis of the economic implications of different sizing of the BESS, while Thien et al. [66] and Groza et al. [68] selected a larger battery size, of 4 and 11 MW respectively. Iurilli et al. [5] provided a comparative analysis selecting 6 different power-electrical capacity sizes ranging from 0.5 MW/0.5 MWh to 10 MW/10 MWh, maintaining the regulating power to 1 MW. Marchgraber et al. [69] established various energy to power ratios to provide their comparative analysis, but the specific selected values for the energy and power are not disclosed.

The nominal SoC value is set at 50% for Marchgraber et al., Iurilli et al. and Fleer et al. [5], [67], [69] and 60% for Groza et al. and Thien et al. [66], [68]. As for the selected permissible SoC, the values vary throughout the selected cases. Iurilli et al. [5] designates 0% as the lower threshold and 100% as the upper. Fleer et al. and Groza et al. [67], [68] select different maximum and minimum values, related to the ratio of usable capacity and the requisites for FCR provision.

Source	Marchgraber et al. [69]	Groza et al. [68]	Thien et al. [66]	Iurilli et al. [5]	Fleer et al. [67]
Market	Austria	Latvia	Germany	Italy	Germany
Application	FCR	FCR	FCR	FCR	FCR
Nominal Power [MW]	Variable	11	4 ⁸	Various	1/ 2 ⁹
BESS Nominal Electrical Capacity [MWh]	Variable	7	-	Various	1.8/3.6 ¹⁰
Available BESS Electricity [MWh]	-	5.6	-	-	2
State of charge (min)	-	10%	-	0%	30%
State of charge (norm)	50%	60%	60%	50%	50%
State of charge (max)	-	90%	-	100%	70%
Efficiency	-	92%	80-97%	-	95%
Deadband [Hz]	± 0.01	± 0.01	± 0.01	± 0.02	± 0.01

⁸ Reference value. The study analysed a set of several batteries.

⁹ Two different prequalified power values were utilised in the study.

¹⁰ Respectively according to the Nominal Power.

Time-step [s]	1	60	1	1	1
Self-discharge	-	No	No	-	Yes

Table 5. Main parameters of models in studies related to the modelling of BESS supporting Ancillary Services.

Additionally, some authors provide specifications for the SoC management strategies which are illustrated in Table 6. These include the upper and lower SoC limits for the activation of the overfulfillment and the scheduled transactions as well as the power and duration of the scheduled transactions.

Source	Groza et al. [68]	Thien et al. [66]	Fleer et al. [67]
Upper limit for overfulfillment	65%	No limitation	50%
Lower limit for overfulfillment	55%	No limitation	50%
Upper limit for scheduled transactions	70%	-	70%
Lower limit for scheduled transactions	30%	-	30%
Scheduled transaction power rating/energy exchange	1MW	0.1-1.4 MW	0.8 MW/0.2 MWh 1.6 MW/ 0.4MWh ¹¹
Contract duration for scheduled transactions	1 hour	15 minutes	15 minutes

Table 6. Parameters of SoC control in studies related to the modelling of BESS supporting Ancillary Services.

3.3. Production phase GWP for BESS

Several studies related to LCA on batteries have been presented previously in 3.1. To complement the analysis for the current project use case, various case studies were selected to calculate the production – also termed cradle to gate – emissions. As seen in Table 7, the values for GWP are predominantly computed in terms of kg of carbon dioxide (CO₂) emissions per kilowatt-hour (kWh). By contrast Stenzel et al. [70] establish the emissions for the total provision of FCR in a year in Germany. Ryan et al. [60] additionally provide the GWP in terms of kg CO₂ per MW as well as kWh.

The values utilised to calculate the emissions in the project range from 33.1 kg CO₂/kWh to 145 kg CO₂/kWh. The type of battery studied is in all cases Li-ion, which is the selected technology for the project.

Source	Ellingsen et al. [71]	Kim et al. [72]	Stenzel et al. [70]	Ryan et al. [60]	Notter et al. [73]
FU	1 kWh ¹²	1 kWh ¹³	551MW ¹⁴	1 MW ¹⁵	1 km ¹⁶
GWP production	38-356 kg CO ₂ /kWh	39-63 kg CO ₂ /kWh	1250000 kg CO ₂ /FU	2172 kg CO ₂ /MW-	50 kg CO ₂ /kWh

¹¹ Respectively for the 1MW/2MWh and 2MW/2MWh systems.

¹² Of battery capacity.

¹³ Of battery capacity.

¹⁴ Total primary control power demand in Germany in 2015.

¹⁵ Of symmetrical reserve capacity for a year

¹⁶ Driven by a vehicle with electric drivetrain on the European road network.

phase				year	
				33.1 kg	
				CO2/kWh	
Type	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion

Table 7. Cradle to gate GWP of selected case studies.

4. Methodology

The method followed is outlined in the present chapter. Figure 13 presents a flowchart of the reasoning followed in the study. There are four main stages in which the project can be divided. Firstly, the literature review which has been described in Chapter 3. The second stage to the process resides on the data collection. A portion of the data is acquired during the literature review stage. The characterization of the BESS is established through the collection of research findings, followed by the pertinent adjustments to align with the project's specific scope and requirements. This research is assessed in Section 3.2. Data related to the production phase of BESS, particularly the GWP, is also obtained from the literature review stage in Section 3.3. Additionally, the grid carbon intensity in Germany and Spain is obtained from this previous stage. The data collection process encompasses the acquisition of the FCR requirement and the grid frequency data, both sourced from respective national entities. The third phase involves the construction of models to fulfil the project's objectives. To facilitate the project, three models have been developed in the Python programming language: a deviation and frequency model –which is fed to the environmental analysis, a dispatch model, and an environmental analysis model. The final stage centres around the analysis of the outcomes derived from the modelling phase. A statistical analysis is conducted using the results generated by the deviation and frequency model. Moreover, the results produced by the environmental analysis model undergo scrutiny and subsequent comparison with existing literature, alongside an examination in a sensitivity case scenario.

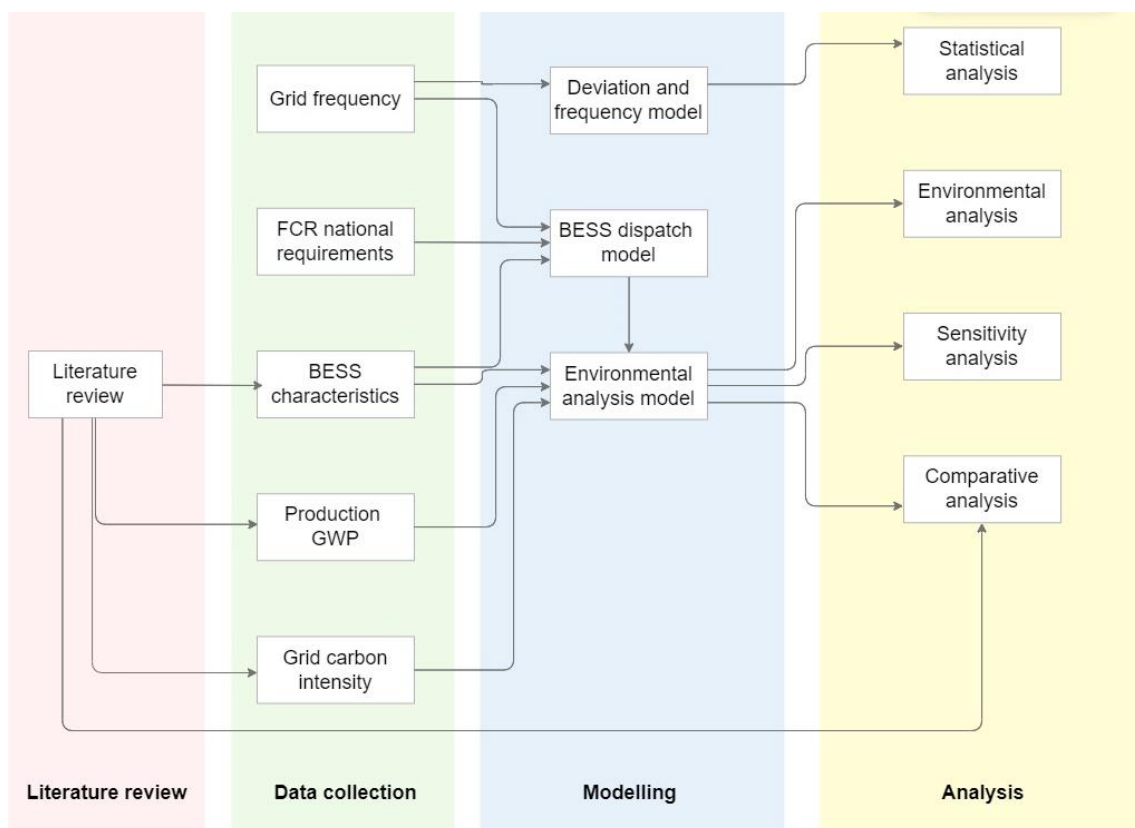


Figure 13. Project method flowchart.

4.1. Deviation and frequency model

The deviation and frequency model facilitates a statistical analysis of the frequency's attributes on a daily, monthly, and yearly basis. This in-depth comprehension of the grid's frequency dynamics serves as a fundamental basis for comprehending the operational behaviour of the dispatch model and, subsequently, the environmental analysis.

The input data can be accessed through the German TSO Transnet BW website [74]. The data files available on the website provide monthly information on the frequency of the grid with a resolution of once second. Such files are stored as CSV files containing the following parameters:

- DATE: Full date of the measurement in YYYY-MM-DD format.
- TIME: The time of the day where the measurement was recorded.
- TYPE OF DATA: The type of data which is frequency for the extent of this project.
- VALUE: The frequency value with an accuracy of 0.001 Hz.

In accordance with the technical specifications set by the German TSOs (Section 2.4.1), an occurrence, as defined for the purposes of the model, will encompass any deviation from the nominal frequency exceeding 10 mHz in either the positive or negative direction. Figure 14 shows five occurrences on a sample from the German grid frequency.

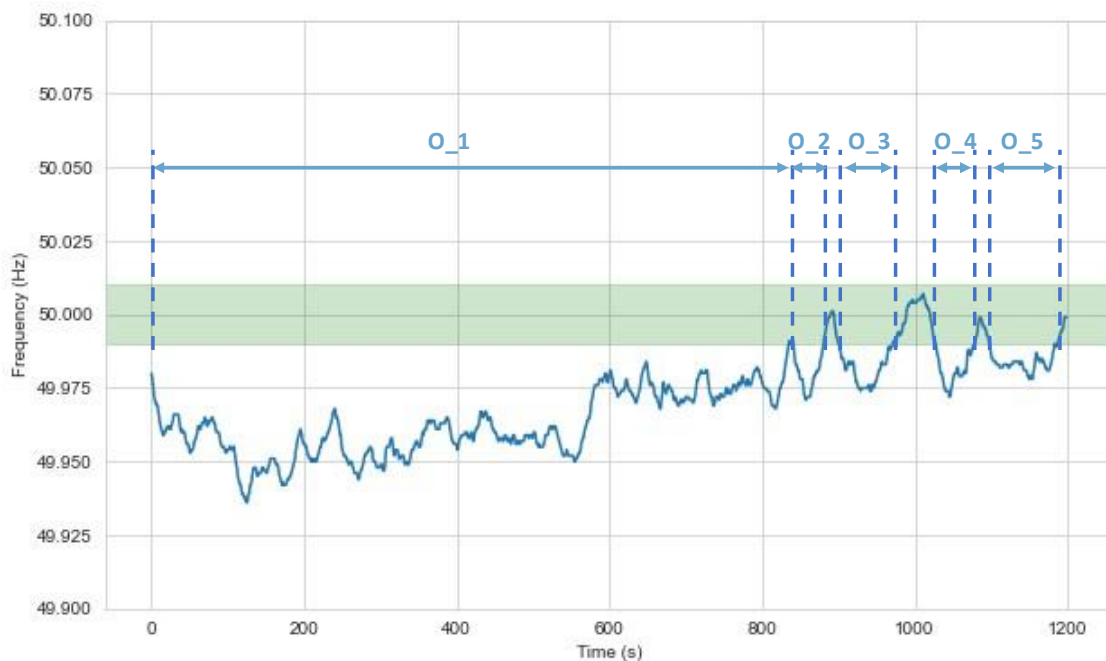


Figure 14. Frequency deviation occurrences in sample time from German grid.

The model generates a database to compile information on the characteristics of each occurrence within the selected year. The parameters encompass:

- Length: Obtains the length of the deviation in sec.
- Max_dev: Obtains the maximum deviation value within a single occurrence.
- Av_dev: Obtains the average deviation value within a single occurrence.
- Start_time: Obtains the starting time for the occurrence.
- Finish_time: Obtains the finishing time for the occurrence.

4.2. Dispatch model

The assessment of the utilisation of BESS for FCR is conducted through the development of a simulation model in Python. The functioning of the model is based on the frequency data from the German grid. The frequency data has a resolution on one second, which is the time step selected for the model. The model obtains the SoC of the BESS in each time step, following the requirement of the German TSOs [47].

The SoC in each time step ($SoC(t)$) is calculated considering the energy requirements from the frequency deviations, as well as accounting for energy deployed for the SoC management to fulfil with the requirements from the German TSO, as seen in Equation 3. The SoC is managed in three different manners:

- Overfullfilment (ΔSoC_{OF}). This involves the provision of FCR up to 120% of the requisite power, consistently providing no less than the TSOs stipulated requirements.
- Deadband utilisation (ΔSoC_{DB}). It involves the process of either charging or discharging the battery whenever the battery is within the deadband frequency range. The battery charging or discharging is determined by the grid's frequency; specifically, a positive frequency deviation necessitates battery charging, while a negative frequency deviation mandates discharging.
- Scheduled transaction (ΔSoC_{ST}). This process consists of the procurement or sale of electricity to or from the grid in order to maintain the stipulated SoC levels within the BESS.

All the previously mentioned energy deployment variants – whether they may be charging or discharging from/to the grid – are impacted by efficiency of the BESS (η_{BESS}).

$$SoC(t) = SoC(t - 1) + \eta_{BESS} * (\Delta SoC_{FCR}(t) + \Delta SoC_{OF}(t) + \Delta SoC_{DB}(t) + \Delta SoC_{ST}(t))$$

Equation 3. SoC equation.

The ΔSoC_{FCR} is calculated as indicated in Equation 4. Firstly, the frequency deviation ($\Delta f(t)$) from the nominal frequency (f_0) is calculated. The frequency deviation is then utilised to calculate the energy dispatched on each time step ($\Delta E_{FCR}(t)$), which accounts for the prequalified power (P_{FCR}). Lastly, the SoC change is calculated as the quotient of the dispatched energy and the total battery energy (E_{batt}).

$$\begin{aligned} \Delta f(t) &= f_0 - f(t) \\ \Delta E_{FCR}(t) &= P_{FCR} * \frac{\Delta f(t)}{0.2 \text{ Hz}} * 1s \\ \Delta SoC_{FCR}(t) &= \frac{\Delta E_{FCR}(t)}{E_{batt}} * 100 \end{aligned}$$

Equation 4. FCR provision SoC change equations.

The ΔSoC_{OF} is calculated as indicated in Equation 5. The energy dispatched for overfullfilment (ΔE_{OF}) is equivalent to 20% of the energy dispatched for FCR provision in each time step. The SoC change is calculated in the same manner as in Equation 4.

$$\Delta E_{OF} = \Delta E_{FCR}(t) * 0.2$$

$$\Delta SoC_{OF}(t) = \frac{\Delta E_{OF}(t)}{E_{batt}} * 100$$

Equation 5. Overfullfilment SoC equations.

The ΔSoC_{DB} is calculated as depicted in Equation 6. The procedure to calculate said SoC follows the same logic as the FCR provision SoC calculated of Equation 4, but only operated when the frequency is within the deadband range.

$$\begin{aligned} \Delta f(t) &= f_0 - f(t) \\ \Delta E_{DB}(t) &= P_{FCR} * \frac{\Delta f(t)}{0.2 \text{ Hz}} * 1s \\ \Delta SoC_{DB}(t) &= \frac{\Delta E_{DB}(t)}{E_{batt}} * 100 \end{aligned}$$

Equation 6. Deadband utilisation SoC equations.

The ΔSoC_{ST} is calculated as shown in Equation 7. The energy dispatched on each time step is equivalent to the quotient between the total energy transaction scheduled ($Energy_{ST}$) and the duration of the said transaction ($Duration_{ST}$). The SoC change is calculated following the same logic as Equation 4.

$$\begin{aligned} \Delta E_{ST} &= \frac{Energy_{ST}}{Duration_{ST}} \\ \Delta SoC_{ST}(t) &= \frac{\Delta E_{ST}(t)}{E_{batt}} * 100 \end{aligned}$$

Equation 7. Scheduled transaction SoC equations.

4.2.1. Dimensioning of BESS: Base case scenario

The variables utilised for the characterisation of the BESS have been selected following the analysis of related literature and legislation, and considering the scope of a master thesis project.

The base case model consists of the analysis of two representative days selected from the year 2021 in the German market. The dimensioning of the BESS has been selected to be able to participate in the FCR market with the minimum prequalified power of 1 MW. The minimum energy available that the BESS needs to have is calculated according to the requirements from the German TSOs [47]. The dimensioning must fulfil four criteria:

- Dimensioning of the energy capacity for the alert state.

The minimum activation period is of 15 minutes, therefore for a 1 MW prequalified power in the symmetrical case the energy capacity needed would be of 0.5 MWh as seen in Equation 8.

$$Energy_1 = 2 * P_{pq} MW * \frac{1}{4} h = 0.5 \text{ MWh}$$

Equation 8. Energy capacity due to alert state.

- Consideration of the energy capacity due to a previous activation.

Assumed a first activation that falls within the alert state, the consideration of a subsequent activation is made for a ± 100 mHz for 15 minutes. Therefore, for the symmetrical case the energy capacity required would be of 0.25 MWh as calculated in Equation 9.

$$Energy_2 = 2 * P_{pq} MW * \frac{1}{2} * \frac{1}{4} h = 0.25 \text{ MWh}$$

Equation 9. Energy capacity due to a previous activation.

- Consideration of a delayed effect of the storage management measures.

Another consideration from the German TSOs comes from the lags caused by operating point shifts in storage management. The lags require additional energy capacity that can be covered by FCR, assuming a ± 50 mHz deviation. The time assumed for the lag is 30 minutes which would require 0.25 MWh in the symmetrical case as shown below in Equation 10.

$$Energy_3 = 2 * P_{pq} MW * \frac{1}{4} * \frac{1}{2} h = 0.25 \text{ MWh}$$

Equation 10. Energy capacity due to a delayed effect of the storage management measures.

- Consideration of energy capacity for activating reserve operation.

The German TSOs require FCR units with limited capacity to be able to switch to reserve operation before their energy storage is exhausted for 5 minutes (the time required for full aFRR activation). Hence, for the base case scenario of this project, the energy capacity required would be of 0.08 MWh. This value is calculated for the symmetrical case as seen in Equation 11.

$$Energy_4 = 2 * P_{pq} MW * \frac{1}{2} * \frac{1}{12} h = 0.08 \text{ MWh}$$

Equation 11. Energy capacity due to the activation of reserve operation.

The total required energy capacity is calculated as follows:

$$Energy_t = Energy_1 + \max\{Energy_2; Energy_3\} + Energy_4$$

Equation 12. Total energy capacity required by German TSOs.

In the present scenario that is equal to:

$$Energy_t = 0.5 \text{ MWh} + \max\{0.25 \text{ MWh}; 0.25 \text{ MWh}\} + 0.08 \text{ MWh} = 0.83 \text{ MWh}$$

Hence, the BESS must possess a minimum available energy capacity of 0.83 MWh.

The selection of the SoC and the usable storage capacity is equally dependent on criteria established by the TSOs. The operating range of FCR units is delimited by the prequalified power and the usable storage capacity. Therefore, the selection of either the SoC limits or the usable storage capacity will determine the value of the other. The SoC limits are calculated as follows:

$$SoC_{max} = \frac{E_{usable} - 0.25h \times P_{pq}}{E_{usable}}$$

Equation 13. Maximum SoC.

$$SoC_{min} = \frac{0.25h \times P_{pq}}{E_{usable}}$$

Equation 14. Minimum SoC.

Where:

E_{usable} : Usable energy storage

P_{pq} : Prequalified power

The limit values of SoC can be seen in relation to the ratio of usable storage capacity in Figure 15. The ratio of usable storage capacity is determined as:

$$ratio = E_{usable}/P_{pq}$$

Equation 15. Ratio of usable storage.

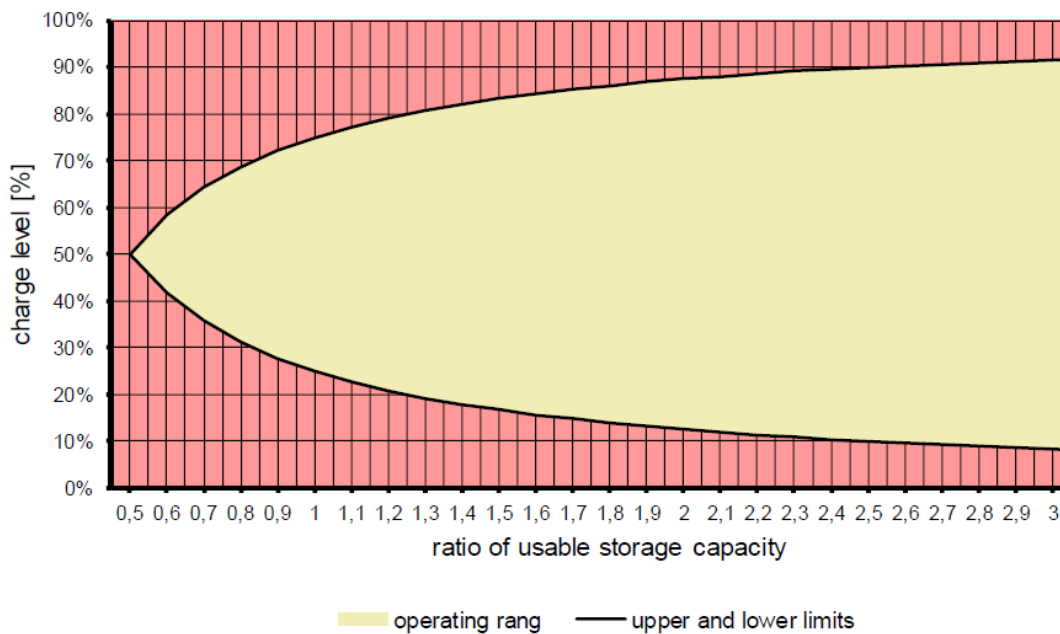


Figure 15. Permissible operating range of FCR units with limited energy storage [47].

For the base case scenario, the usable storage capacity selected is 1.2MWh – fulfilling the minimum energy available requirement, making the upper and lower SoC limits 80 and 20 percent. The limit SoC values define the maximum depth of discharge (DOD) value. For the base case scenario, the nominal SoC is equal to 60 percent. The parameters of the battery system deployed for the exploration of this scenario are seen in Table 8.

Parameter	Units	Value
Rated power	MW	1.25
Prequalified power	MW	1
Usable storage capacity	MWh	1.2
Lifespan	Years	20
Provision time (min)	Min	15
Efficiency	%	95
Max SoC	%	80
Nominal SoC	%	60

Min SoC	%	20
Product time	Hour	4
Activation	Times/day	6
Deadband	Hz	± 0.01

Table 8. Parameters of BESS in the base case scenario.

Battery management is executed through the three methodologies as delineated in Section 4.2. The SoC thresholds triggering each respective battery management technique are detailed in Table 9. The scheduled transactions of procured energy are set with an energy exchange of 0.2 MWh, and a duration of 15 minutes. Activation of these transactions occurs when the SoC falls below the 30 percent threshold.

Parameter	Value
Upper limit for overfulfillment	65%
Lower limit for overfulfillment	55%
Upper limit for scheduled transactions	70%
Lower limit for scheduled transactions	30%
Schedule transaction energy exchange	0.2 MWh
Contract duration for scheduled transactions	15 minutes

Table 9. Parameters of BESS SoC management in the base case scenario.

4.2.2. Dimensioning of BESS: Sensitivity analysis scenario

The sensitivity analysis is conducted through the analysis of a different ratio of usable storage capacity, while maintaining the bid size selected as for the base case scenario. The selected rated power for this scenario is 2 MW and the usable storage capacity 3 MWh. That corresponds to a ratio of 3, following the same calculations as presented in the base case scenario in Section 4.2.1. The SoC maximum and minimum vary accordingly proceeding equally to the previous scenario. The maximum SoC is equal to 91.6% and the minimum to 8.3% in the sensitivity analysis scenario. The rest of the variables remain equal to the base case scenario.

Parameter	Units	Value
Rated power	MW	2
Prequalified power	MW	1
Usable storage capacity	MWh	3
Lifespan	Years	20
Provision time	Min	15
Efficiency	%	95
Max SoC	%	91.6
Min SoC	%	8.3
Product time	Hour	4
Activation	Times/day	6

Table 10. Parameters of BESS in the sensitivity analysis scenario.

The parameters selected for the SoC management in the sensitivity analysis scenario are displayed in Table 11. The parameters for overfulfillment remain unchanged from those in the base case scenario, while adjustments are made to the values of the upper and lower limits for scheduled transactions, setting them at 81.6% and 18.3%, respectively.

Parameter	Value
Upper limit for overfulfillment	65%
Lower limit for overfulfillment	55%
Upper limit for scheduled transactions	81.6%
Lower limit for scheduled transactions	18.3%
Schedule transaction energy exchange	0.2 MWh
Contract duration for scheduled transactions	15 minutes

Table 11. Parameters of BESS SoC management in the sensitivity analysis scenario.

4.3. Environmental analysis model

The environmental analysis model is delineated in this Section. Firstly, the total emissions from the lifetime use of the BESS are calculated as shown in Equation 16. The *Production* term accounts for the emissions related to the extraction of raw materials and the manufacturing of the battery systems. The *Use* term accounts for the use phase of the battery system. The analysis was conducted utilising two main sources of information. The emission values associated with the *Production* of the BESS were obtained from existing literature, particularly from [60], [71]–[73]; and the *Use* term emissions were calculated with a combination of the dispatch model output data and an external data source [75].

$$Emissions_{Total} = Emissions_{Production} + Emissions_{Use}$$

Equation 16. Total emissions from Production + Use phases [in kg CO₂].

The emissions originating from the *Production* phase are sourced from the existing literature, as described in Section 3.3. The GWP values presented in Table 7 range from 33.1 kg CO₂/kWh¹⁷ to a maximum of 356 kg CO₂/kWh. The value utilised for the present project was calculated as the average of the selected literature following Equation 17. The emissions are calculated as depicted in Equation 18.

$$GWP_{av} = \frac{\sum GWP_n}{n}$$

Equation 17. Cradle to gate GWP [in kg CO₂/kWh].

$$Emission_{Production} = E_{usable} * GWP_{av}$$

Equation 18. Production emissions [in kg CO₂].

The emissions associated to the *Use* phase of the BESS encompass two terms:

- **Internal.** Emissions related to the dispatch of FCR. These include both the obligatory energy dispatch and the energy expended in two out of the three SoC management strategies: overfulfillment and deadband utilisation. The considered emissions come solely from the DOWN FCR provision, namely the charging of the battery.
- **External.** Emissions related to the scheduled transactions, purchased from the electricity spot market.

¹⁷ In kg CO₂ by kWh of energy capacity.

To assess the impacts of the energy dispatched a comprehensive database from Electricity Maps [75] was employed, including diverse emission values from the electricity grid. Equation 19 shows the manner in which the use-phase emissions are calculated.

$$Emissions_{Use} = Emissions_{Internal} + Emissions_{External}$$

Equation 19. Use-phase emissions [in kg CO₂].

The GWP of the BESS utilised for the provision of FCR, seen in Equation 20, is calculated as the quotient of the total emissions from the lifetime use of the BESS and the total dispatched energy calculated with the dispatch model.

$$GWP_{BESS} = \frac{Emissions_{total}}{Energy_{total}}$$

Equation 20. GWP of BESS [in g CO₂/kWh].

4.3.1. Grid carbon intensity data

The emissions from the grid were obtained through the use of a carbon emission data following a request from Electricity Maps [75]. Their primary interest lies in real-time carbon accounting, with their methodology comprehensively described in [76]. Their database has an hourly resolution and utilises the operation intensity values listed in Table 12.

Technology	Intensity [kg CO ₂ eq/MWh]
Coal	1167
Oil	1033
Gas	583
Biomass	50.9
Hydro	16.2
Nuclear	10.3
Wind	0.141
Geothermal	0.00664
Solar	0.00410

Table 12. CO₂ equivalent operation intensity per technology [76].

The database has several variables, of which two were used in the project. The parameters used encompass:

- datetime: Full date and time of the data in the row in ISO format (YYYY-DD-MM 0:00:00).
- Carbon_intensity_avg: Carbon intensity of electricity consumed using life cycle emission factors in g CO₂ eq/kWh.

4.3.2. Functional unit

The functional unit for the project is selected considering existing literature on BESS LCA as well as the data utilised for the use-phase emissions. For the extent of this project the analysed impact analysed is GWP measured through g CO₂/kWh of energy dispatched.

4.4. Limitations and assumptions

A significant limitation within the scope of this project arises from the severely restricted access to information pertaining to the provision of FCR in Spain. The dimensions of the reserves, the mix of service providers, and additional particulars concerning the operation of the balancing service are not publicly disclosed. The general functioning of FCR, as defined by

the ENSTOE as well as review paper on ancillary services has been defined in Section 2.4. However, none of the review papers on ancillary services were able to provide any supplementary information on the procurement of FCR in Spain [27], [28], [34], [77], [78]. Edmunds et al. [79] explore the participation of wind energy in response and reserve markets in Great Britain and Spain, noting the limited information that is available publicly available on FCR procurement in Spain. As every plant connected to the grid needs to provide the service, they point out that some technologies – namely, wind and solar – rely on renting conventional sources of electricity to provide the required service. The same analysis from Edmunds et al. [79] provides recommendations in terms of policy. They strongly suggest that Spain establishes a FCR market that allows renewables sources to participate in the future. On their analysis of household photovoltaic (PV) self-consumption, Hernández et al. [80] analyse the potential use of PV in the provision of FCR. For the financial analysis, they deploy historical tendering data from the European market, as the FCR market is not regulated in Spain. The inclusion of Spain in the Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO), the Manually Activated Reserves Initiative (MARI) and the Trans-European Replacement Reserves Exchange (TERRE) is indicative of Spain’s intention of supporting the unification of the balancing markets within Europe. Spain could potentially explore the option of participating in the equivalent European FCR market, which currently comprises 11 member countries¹⁸, including Germany. Moreover, the unavailability of frequency data further expands these limitations on the analysis of the Spanish FCR deployment. While requests were made to REE for access to this data for research purposes, they declined to share it.

Given the previously delineated limitations and the project's defined scope, the following assumptions have been formulated:

- The bids are placed for every product slot in a day (6) and is assumed to be accepted.
- The BESS is only used to provide FCR and does not provide other services.
- The use-phase emissions only account for the energy exchanged from the BESS – other use-phase related emissions as could be maintenance are considered negligible.
- The lifespan of the BESS is considered to be 20 years and maintain the initial usable energy capacity throughout its lifespan – no aging is considered.
- The case of Spain is analysed with the German frequency dataset and regulatory base.

The previous assumptions have been made to fit the modelling needs as well as adjusting to the scope of a master thesis, with the pertinent simplifications.

¹⁸ Austria, Belgium, Denmark, France, Slovenia and Switzerland

5. Results

This Chapter is devoted to the explanation of the results obtained from the three models previously described in Chapter 4. This will be achieved through the examination of the deviation and frequency outcomes, followed by the results derived from the dispatch model, encompassing both the base case scenario and the sensitivity analysis scenario. Lastly, the environmental analysis results will be presented, accounting for the base case scenario, the sensitivity case scenario, and the specific case of Spain.

5.1. Frequency analysis

The input data consisted of the frequency of the German electric grid as described previously in Section 4.1 which was analysed to provide a better understanding of the requirements of the market. The frequency of the grid is the main input utilised in the model. Therefore, a deeper analysis of this data is explored to obtain relevant input related to the modelling and posterior economic and environmental analysis.

The data from the year 2021 for the German grid presented various relevant results. Firstly, the main characteristics that were explored were the percentage of time where the frequency values were within range (49.99-50.01) and out of it.

Time within range [%]	Time out of range [%]
39.51	60.49

Table 13. Frequency analysis in 2021.

The values obtained are presented in Table 13, revealing that the frequency remains within acceptable limits approximately 40% of the time. This underscores the critical necessity of employing balancing services for the majority of the year.

	UP regulation [%]	DOWN regulation [%]
From total	29.66	30.81
From out of range	49.05	50.95

Table 14. UP and DOWN regulation needs in 2021.

The duration during which the frequency falls outside the acceptable range can be categorized into two segments: one where it is below the boundary, necessitating UP regulation, and another where it exceeds the boundary, necessitating DOWN regulation. As depicted in Table 14, the requirement for DOWN regulation was marginally superior to that for UP regulation.

The frequency deviations obtained with the deviation and frequency model were subjected to further analysis using Python programming language. Firstly, one of the objectives of this analysis was to examine the relationship between the maximum deviation and the duration of the occurrences. As demonstrated in Figure 16, a distinct positive correlation is found between the duration and the maximum deviation. Furthermore, Figure 16 illustrates the occurrence of certain events that surpass a predetermined threshold – depicted with three colourful areas, indicating different conditions that trigger an alert state. However, the vast majority of occurrences fall within the acceptable boundaries.

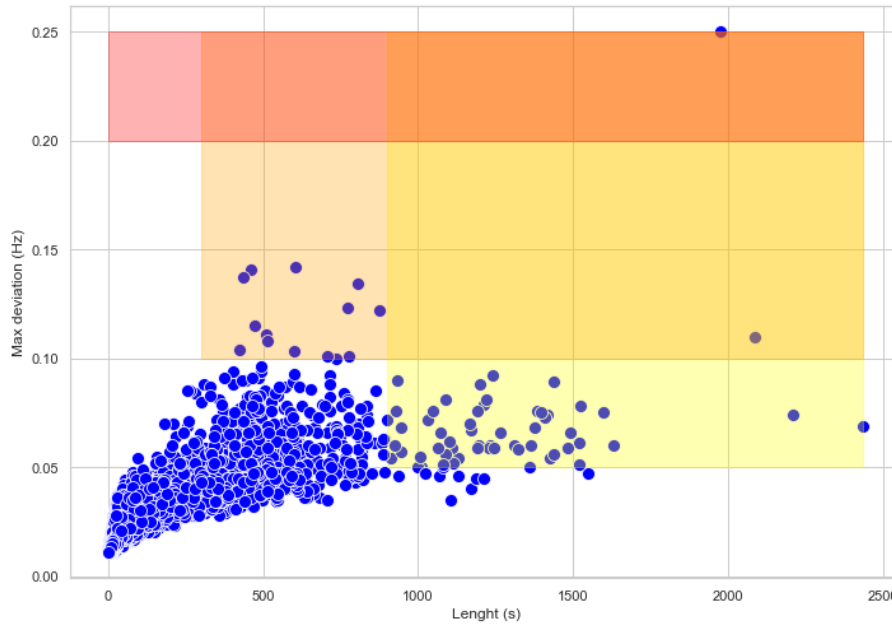


Figure 16. Correlation between the maximum deviation and the length of the occurrences.

Figure 17 reveals a clear variation in the number of deviations based on the month. Notably, the warmer months exhibit a higher frequency of deviations compared to the colder months. Specifically, January exhibits the fewest deviations, while August demonstrates the highest number of deviations, consistently aligning with the previously established trend.

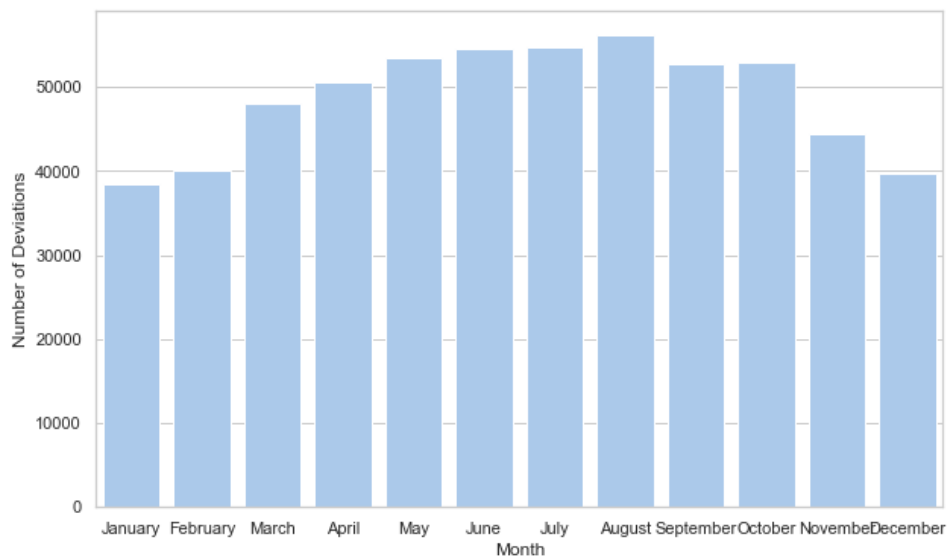


Figure 17. Number of deviations per month in 2021.

This can be explained by different factors, with the share of renewables in the electricity mix – particularly that of solar – being the main one. As it was explained previously, inertia is lower in renewables sources compared to traditional sources as gas or coal power plants. Therefore, the times of the year with a higher inclusion of these low-inertia sources are those with a higher need when it comes to balancing services. As it can be seen Figure 20, the share of solar increases notably in the warmer months of the year – being the ones with higher average sunshine hours – which makes the frequency more variable as it has been shown in other studies [2]–[4] and increases the number of deviations which can be seen in Figure 17.

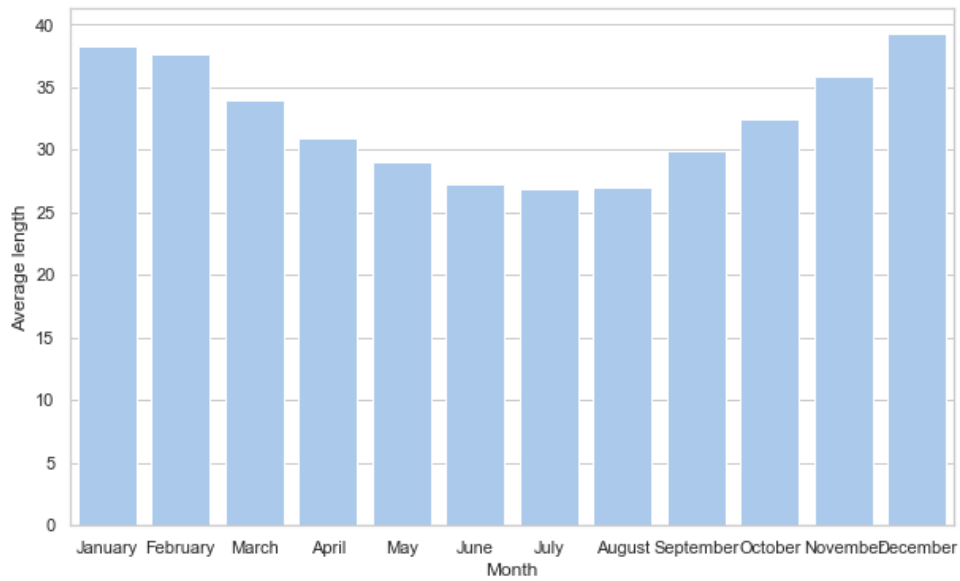


Figure 18. Average deviation length per month in 2021 [in sec].

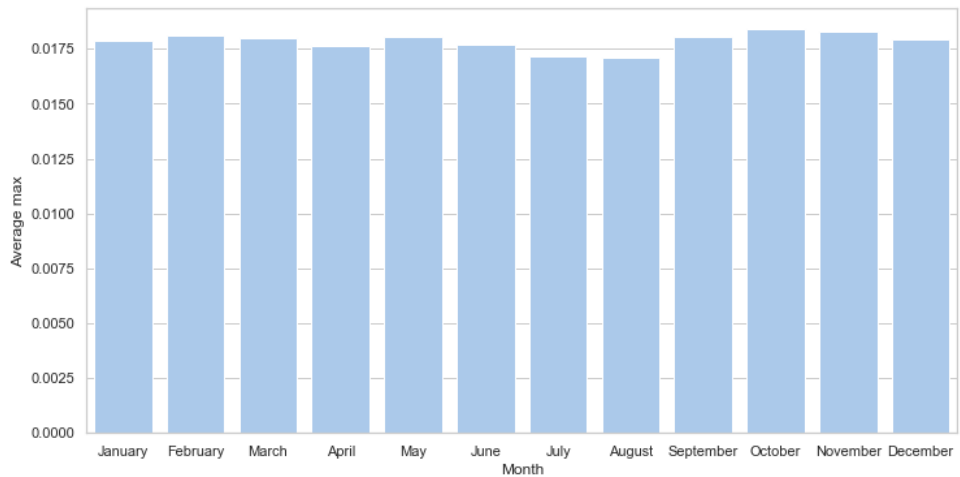


Figure 19. Average max deviation per month in 2021 [in Hz].

Figure 21 illustrates the relation between the share of solar energy and the number of deviations. This side-by-side comparison provides a clearer visualization of the correlation between these two variables. However, as seen in Figure 18, these occurrences have a shorter average length in the warmer months compared to the colder ones. The maximum deviation for the occurrences is relatively constant throughout the year as seen in Figure 19.

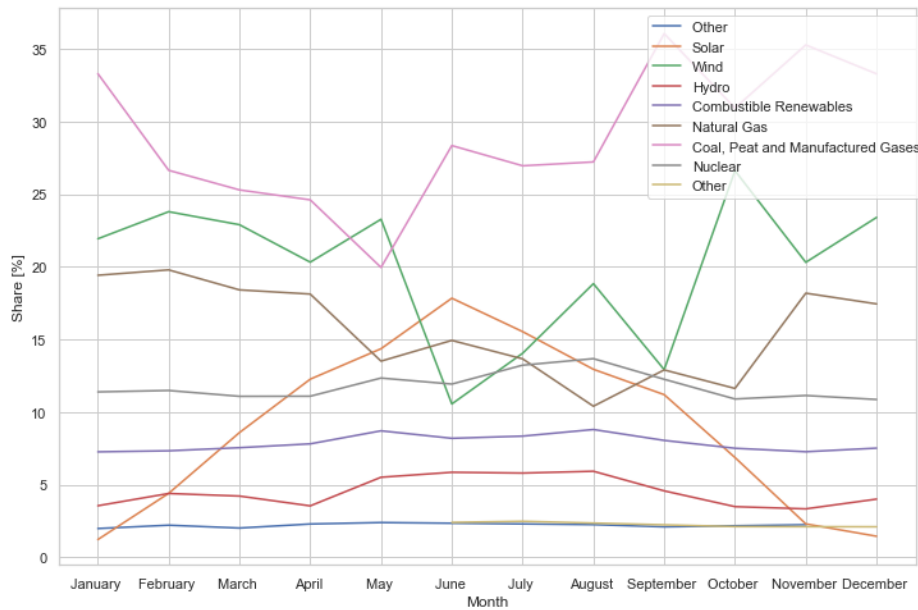


Figure 20. Electricity generation by source in Germany in 2021.

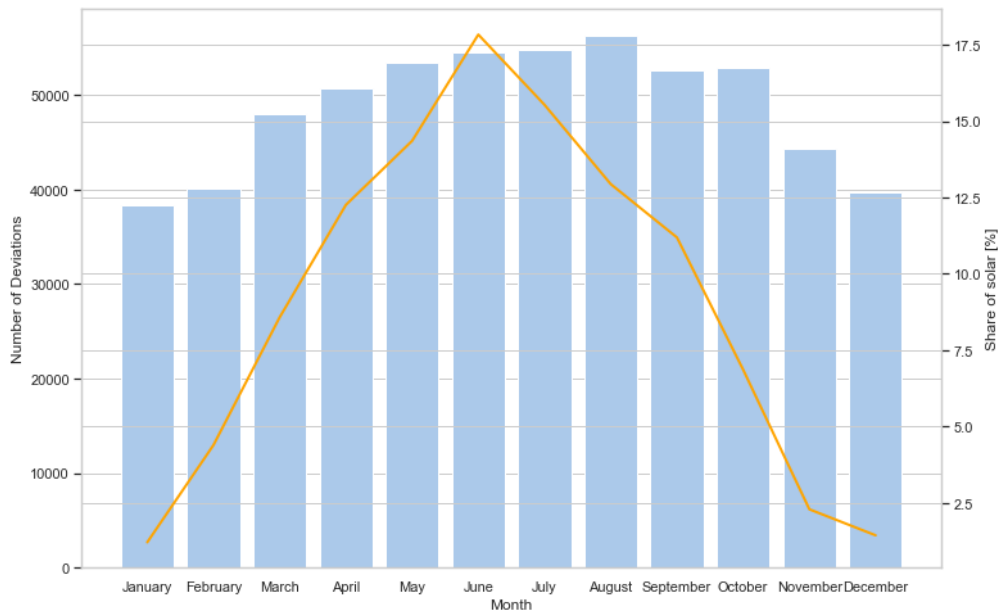


Figure 21. Share of solar and number of deviations on the grid side by month for 2021 in Germany.

The previous analysis served as a foundational framework for substantiating the selection of a two-day period as an illustrative example to examine the market dynamics and the utilization of battery systems over the one-year timeframe previously mentioned.

The 21st of June was selected as a representative sample of the warmer months, while the 21st of December was chosen to exemplify the colder months. These days were selected as they are the Summer and the Winter Solstices respectively.

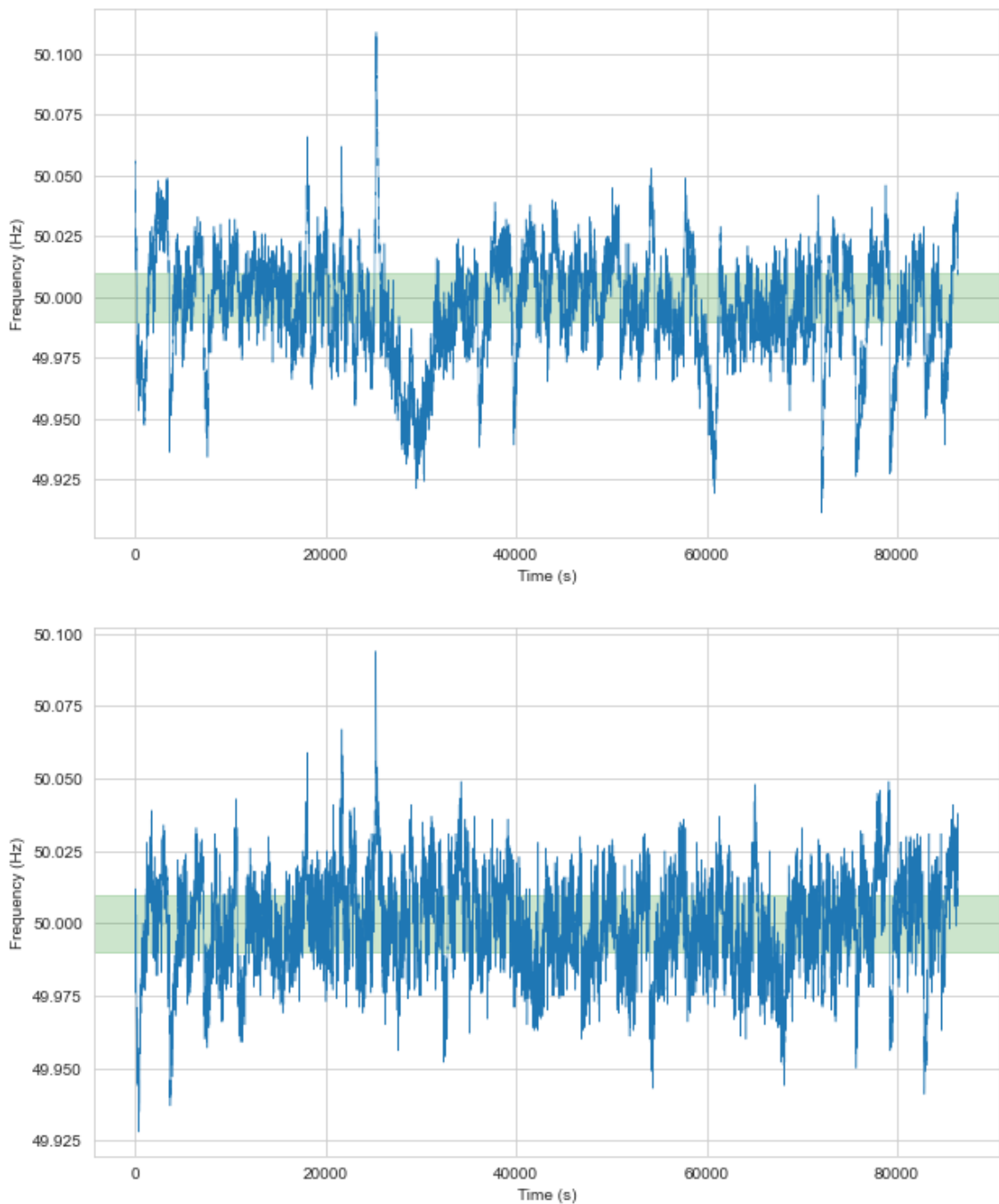


Figure 22. Frequency profiles on the representative sample of 21st of December 2021 (above) and the 21st of June 2021 (below).

The representation of the frequency on both days can be observed in Figure 22, and the basic frequency statistics are shown in Table 15. The tendency analysed previously is to be observed on the frequency behaviour of the representative sample in terms of quantity and length of occurrences. The cold day presents fewer occurrences which have generally larger deviations from the nominal frequency while the hot day presents the opposite behaviour.

	Time within range [%]	Time above boundaries [%]	Time below boundaries [%]
Cold day	36.21	26.37	37.42

Warm day	44.95	26.51	28.54
-----------------	-------	-------	-------

Table 15. Frequency values on representative sample.

5.2. Dispatch model results

The dispatcher model obtains the energy deployed in UP regulation, DOWN regulation, and the energy dispatched for the management of the SoC.

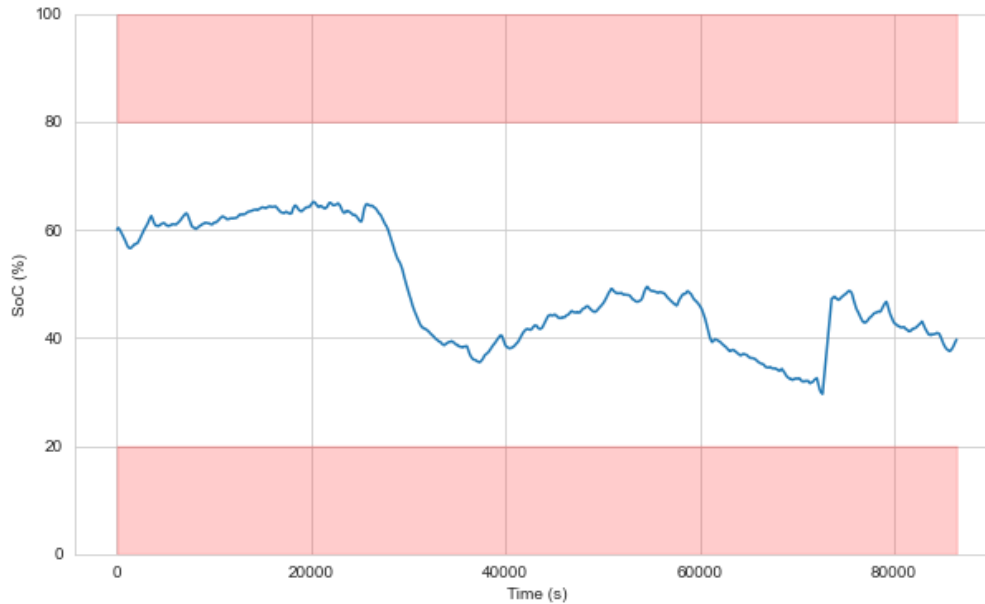


Figure 23. SoC during cold day (21/12/21) from the representative sample.

As it can be seen in Figure 23 and Figure 24, the SoC is maintained within both the upper and lower limits which are represented in red in the graphs. Considering the two representative days, the cold day shows a more substantial decline in charge. This phenomenon can be attributed to the longer deviations in frequency, as evidenced by the findings presented previously in Figure 18.

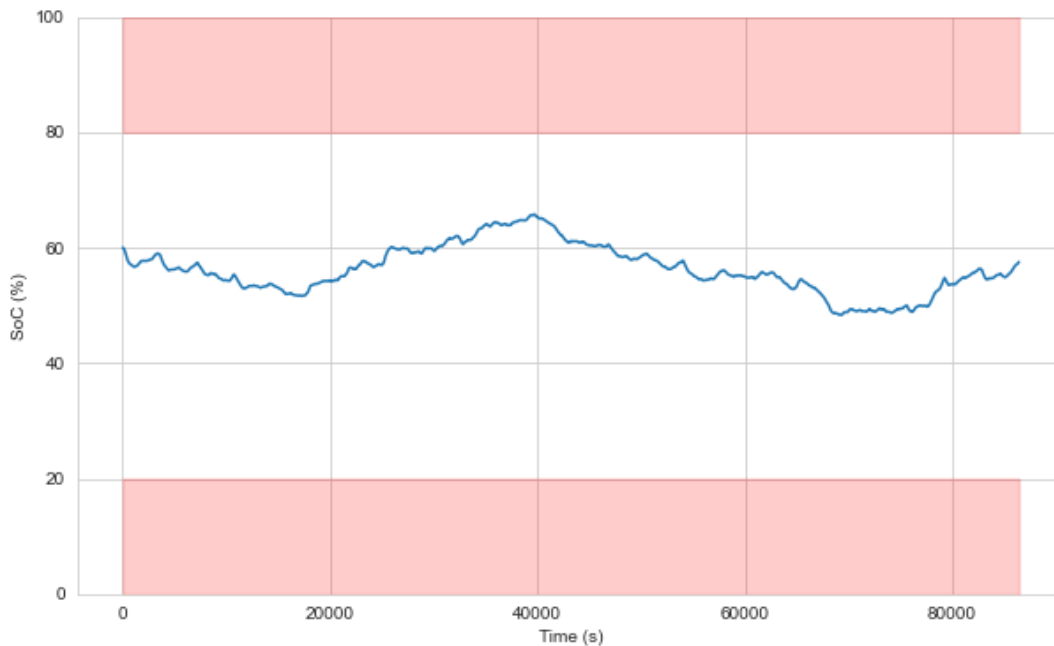


Figure 24. SoC during hot day (21/06/21) from the representative sample.

The total energy dispatched by the model on each of the representative days is depicted in Table 16.

	Total Energy UP [MWh]	Total Energy DOWN [MWh]
Cold day	1.53693	0.87295
Hot day	0.84998	0.81909

Table 16. Total energy dispatched by BESS model.

5.2.1. FCR energy

The energy dispatched for FCR – without considering the SoC management energy is listed in Table 17.

	FCR UP [MWh]	FCR DOWN [MWh]
Cold day	1.33432	0.77956
Hot day	0.84765	0.76314

Table 17. Energy dispatched for FCR by the model.

5.2.2. SoC management energy

The energy dispatched for all three SoC management strategies is presented in Table 18, Table 19 and Table 20.

	DB UP [MWh]	DB DOWN [MWh]
Cold day	0.00212	0.00150
Hot day	0.00018	0.00163

Table 18. Energy dispatched for SoC (Deadband utilisation).

	OF UP [MWh]	OF DOWN [MWh]
Cold day	0.00049	0.09189
Hot day	0.00215	0.05432

Table 19. Energy dispatched for SoC (Overfulfilment).

	ST BUY [MWh]	ST SELL [MWh]
Cold day	0.2	0
Hot day	0	0

Table 20. Energy dispatched for SoC (Scheduled transaction).

5.3. Dispatch model results – Sensitivity analysis scenario

Similarly, the results obtained from the model for the sensitivity analysis scenario are presented. The SoC on both selected days is presented in Figure 25 and Figure 26. The SoC remains comfortably within established limits in both cases, attributable to the larger available energy of 3 MWh.

In comparison to the base case scenario, the most notable difference observed is the absence of scheduled transaction energy either being purchased or sold. This stems from the increased energy capacity, which results in each time step's SoC change constituting a smaller proportion of the total BESS capacity. The remaining dispatched energy values remain consistent when compared to the base case scenario.

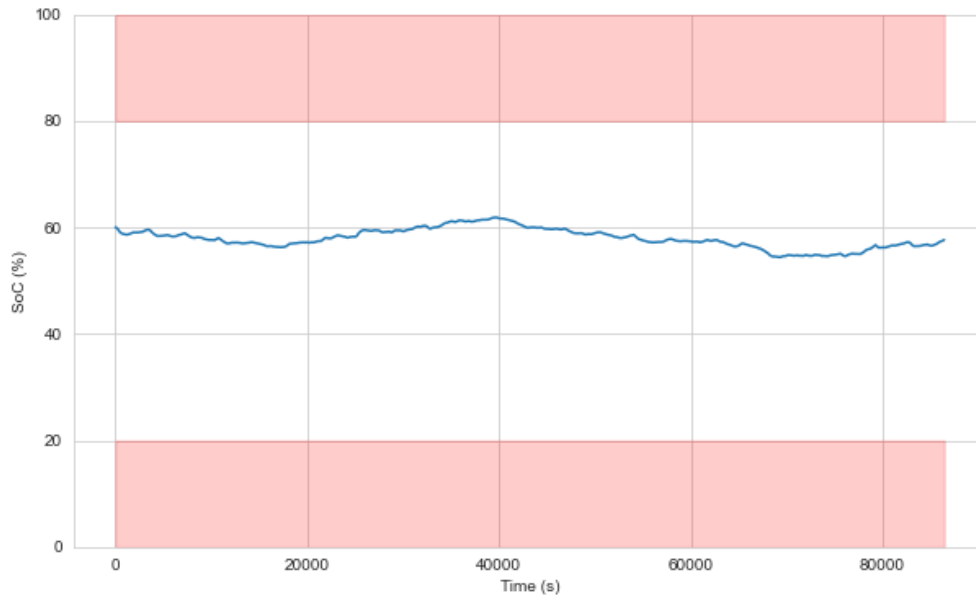


Figure 25. SoC during hot day (21/06/21) from the representative sample in the sensitivity analysis case.

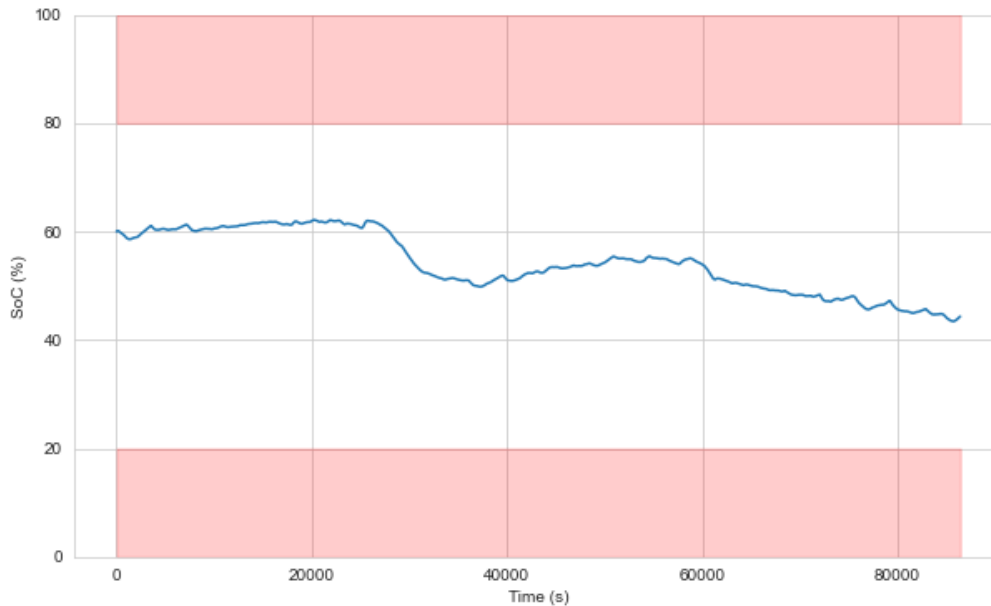


Figure 26. SoC during cold day (21/12/21) from the representative sample in the sensitivity analysis case.

The total energy dispatched by the BESS is presented in Table 21.

	Total Energy UP [MWh]	Total Energy DOWN [MWh]
Cold day	1.33693	0.87295
Hot day	0.84998	0.81909

Table 21. Total energy dispatched by BESS model.

5.3.1. FCR energy

	FCR UP [MWh]	FCR DOWN [MWh]
Cold day	1.33432	0.77956
Hot day	0.84765	0.76314

Table 22. Energy dispatched for FCR by the model.

5.3.2. SoC management energy

	DB UP [MWh]	DB DOWN [MWh]
Cold day	0.00212	0.00150
Hot day	0.00018	0.00163

Table 23. Energy dispatched for SoC (Deadband utilisation).

	OF UP [MWh]	OF DOWN [MWh]
Cold day	0.00049	0.09189
Hot day	0.00215	0.05432

Table 24. Energy dispatched for SoC (Overfulfilment).

	ST BUY [MWh]	ST SELL [MWh]
Cold day	0	0
Hot day	0	0

Table 25. Energy dispatched for SoC (Scheduled transaction).

5.4. Environmental analysis

The environmental analysis was conducted as described in Section 4.3. For the determination of use emissions, the hourly carbon intensity of electricity consumed from the Electricity Maps database is correlated with the scheduled transactions during the charging of the battery – when procured energy is in use.

Selected day	Battery [kg CO₂]	Market [kg CO₂]
Cold day	576.6	136.1
Warm day	331.6	0

Table 26. Daily emissions from the use-phase.

As seen in Table 26, the use-phase emissions from the battery happen in both representative days, whereas the emissions coming from the market only occur on the cold day. By extrapolating the findings from the chosen sample days to calculate the entire annual and operational lifespan, it is deduced that the cumulative emissions originating from the use phase amount to 190584.75 and 3811695 kg of CO₂ as seen in Table 27.

Time	Value [kg CO₂]
Year	190584.75
Lifespan (20 years)	3811695

Table 27. Annual and lifespan use phase emissions.

The total energy dispatched by the BESS and for FCR is presented in Table 16 and Table 17 respectively. The extrapolated annual and lifespan values are listed in Table 28.

Time	Total energy [MWh]	FCR energy [MWh]
Year	744.40	678.75
Lifespan (20 years)	14888.16	13575

Table 28. Annual and lifespan use-phase dispatched energy.

The total emissions from the production and use phases are shown in Table 29. The emissions for the production phase calculated as shown in Equation 18 make 99330 kg CO₂. The total emissions from the production and use phases amount to 3911025 kg of CO₂.

Phase	Emissions [kg CO₂]
Production	99330
Use	3811695

TOTAL

3911025

Table 29. Emissions in project's scope.

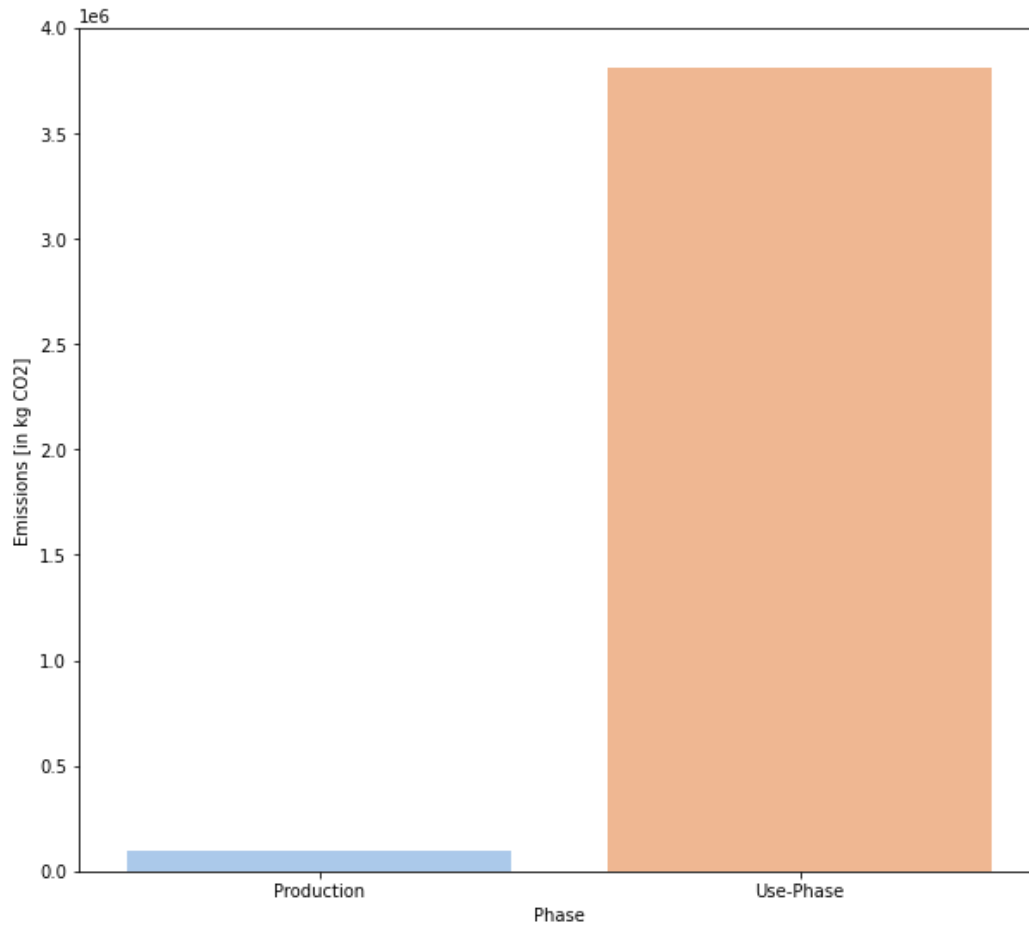


Figure 27. Emissions on analysed phase.

Therefore, the GWP of the BESS would be equal to 262.69 g CO₂/kWh if the total energy dispatched is considered and 288.10 g CO₂/kWh is only the energy dispatched for FCR is considered.

GWP (total energy) [g CO ₂ /kWh]	GWP (FCR energy) [g CO ₂ /kWh]
262.69	288.10

Table 30. GWP of BESS in project's scope.

5.4.1. Sensitivity analysis

The sensitivity analysis adheres to the same fundamental principles as the base case scenario, incorporating the attributes described in Section 4.2.2. The results obtained from the environmental model, shown in Table 31, remain consistent with those in the previous case, with the market emissions being the sole parameter that has undergone alteration. In the sensitivity scenario the market emissions are zero for both warm and cold days. The annual and lifespan emissions are affected by this reduction of emissions compared to the base case scenario, as depicted in Table 32.

Selected day	Battery [kg CO ₂]	Market [kg CO ₂]
Cold day	576.6	0
Warm day	331.6	0

Table 31. Daily emissions from the use-phase in the sensitivity scenario.

Time	Value [kg CO ₂]
Year	165746.5
Lifespan (20 years)	3314930

Table 32. Annual and lifespan use phase emissions in the sensitivity scenario.

The energy dispatched by the battery is the same as the base case scenario when considering the energy devoted to FCR provision only. However, this value differs when the total energy is considered due to the scheduled transaction not occurring. These results are listed in Table 33.

Time	Total energy [MWh]	FCR energy [MWh]
Year	707.90	678.75
Lifespan (20 years)	14158	13575

Table 33. Annual and lifespan use-phase dispatched energy in the sensitivity scenario.

The production phase emissions in this scenario are higher as the energy capacity is increased. The emission amount to 248325 kg of CO₂, making the total 3563255 kg CO₂, as seen in Table 34.

Phase	Emissions [kg CO ₂]
Production	248325
Use	3314930
TOTAL	3563255

Table 34. Emissions in project's scope in the sensitivity scenario.

The GWP is marginally lower than in the base case scenario as listed in Table 35. A comparative graph showcases this difference in Figure 28.

GWP (total energy) [g CO ₂ /kWh]	GWP (FCR energy) [g CO ₂ /kWh]
251.68	262.49

Table 35. GWP of BESS in project's scope in the sensitivity scenario.

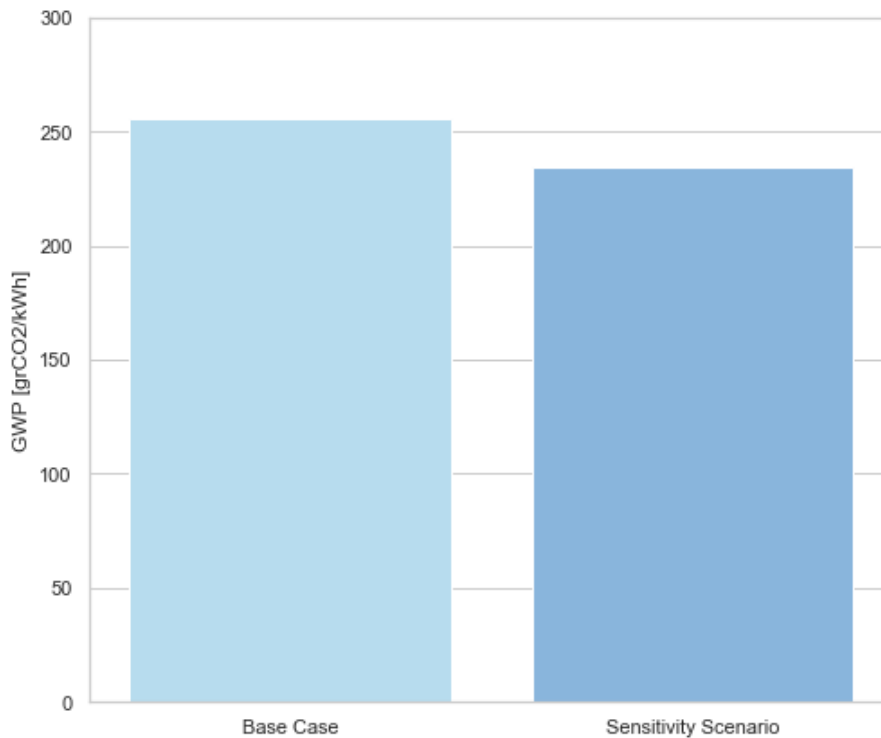


Figure 28. Comparison of GWP between Base Case and Sensitivity Scenario.

5.4.2. The case for Spain

As mentioned in Section 4.4, the case for Spain is analysed through the German frequency, considering the requisites from this country. The carbon intensity of the Spanish grid is sourced from Electricity Maps data, following the same methodology employed for the case of Germany. This data is then incorporated to the environmental model to calculate the estimated emissions during the use phase within the Spanish market.

The daily emissions for Spain are listed in Table 36 and the annual and lifespan values are displayed in Table 37. There is an evident difference with the German case, with the Spanish emissions being significantly lower.

Selected day	Battery [kg CO ₂]	Market [kg CO ₂]
Cold day	236.62	58.84
Warm day	146.17	0

Table 36. Daily emissions from the use phase in Spain.

Time	Value [kg CO ₂]
Year	73288.97
Lifespan (20 years)	1465779.5

Table 37. Annual and lifespan use phase emissions in Spain.

The dispatched energy considered is the same as the base case from the German case. The values are listed in Table 38.

Time	Total energy [MWh]	FCR energy [MWh]
Year	707.90	679.75
Lifespan (20 years)	14158	13595

Table 38. Annual and lifespan use phase dispatched energy in Spain.

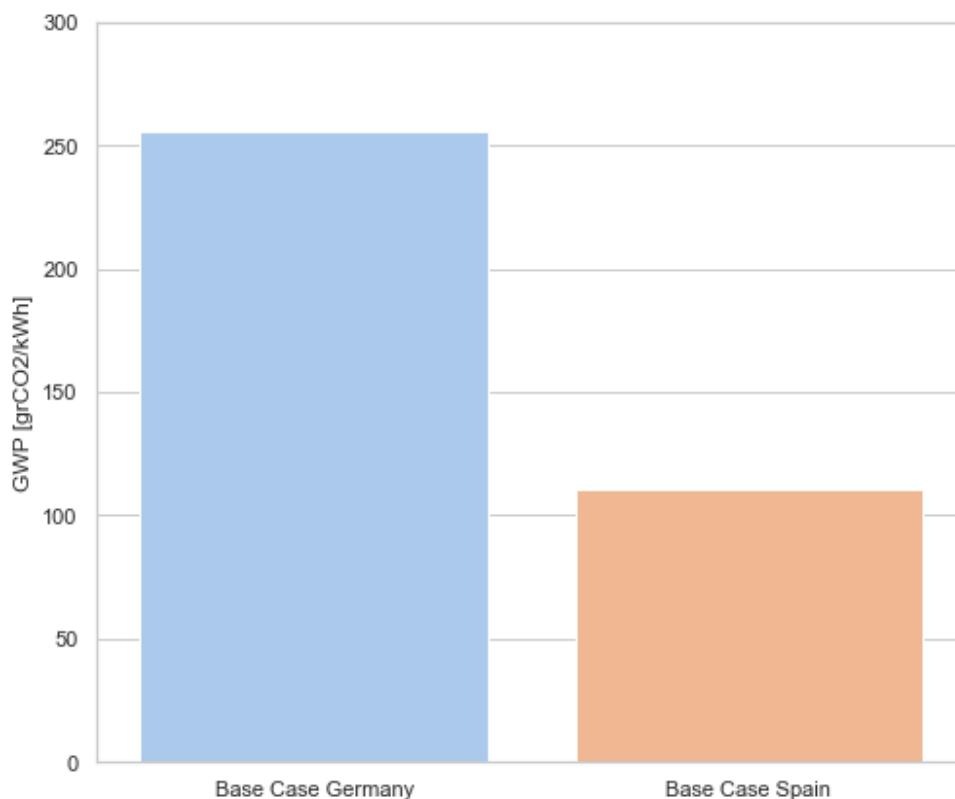


Figure 29. Comparison of GWP between Base Case scenario in Germany and Spain.

The values presented in Table 39 represent the aggregate emissions from both the production and use phases. Production phase emissions are quantified at 99330, considering that the battery characteristics are equal to those from the German base case scenario. Leveraging the total emissions and dispatched energy data, the GWP is computed, with results listed in Table 40. Figure 29 illustrates a comparative graph of the GWP between the base case scenario in Germany and Spain, with the latter exhibiting a value less than half of the observed in the former.

Phase	Emissions [kg CO2]
Production	99330
Use	1465779.5
TOTAL	1565109.5

Table 39. Emissions in project's scope in Spain.

GWP (total energy) [g CO2/kWh]	GWP (FCR energy) [g CO2/kWh]
110.54	115.12

Table 40. GWP of BESS in project's scope in Spain.

6. Discussion

Based on the results derived from the models presented in Chapter 5, the integration of BESS for FCR in Germany appears to yield a noteworthy reduction in GWP when compared to conventional fossil fuel sources such as coal, oil, and natural gas. In the base case scenario, the GWP is calculated at 262.69 g CO₂/kWh when considering the total energy dispatched by the BESS, and 288.10 g CO₂/kWh when only the energy deployed for FCR is considered. These values are significantly lower than the carbon intensity associated with fossil fuel sources, with coal emitting approximately 1167 g CO₂/kWh (resulting in a 75% reduction), oil emitting around 1033 g CO₂/kWh (equating to a 72% reduction), and natural gas emitting roughly 583 g CO₂/kWh (leading to a 50% reduction) [76]. In contrast, when compared to the carbon intensity of hydro – the main prequalified capacity source of FCR in Germany – the battery has a significantly higher GWP. Considering that fossil fuel sources accounted for more than double the prequalified capacity of battery storage in Germany in 2023 as seen in Table 41, there is still room for improvement with new technologies such as BESS. Furthermore, if Germany continues to follow the Energiewende strategy, the share of renewables in the grid will continue to increase in the next years, helping lower the use-phase emissions of BESS in FCR.

Technologie	FCR
Nuclear	0,14
Lignite	0,48
Hard coal	0,48
Gas	0,37
Oil	-
Biogas/-mass	0,04
Water	4,79
Battery storage	0,63
Demand/DSM	0,02
Wind	-
Others	-
Summe	6,95

Table 41. Prequalified capacity for FCR in Germany for 2023 [in GW] [51].

In the case of Spain, the results indicate an even more substantial reduction in GWP when compared to conventional fossil fuel sources. The GWP in Spain stands at 110.54 g CO₂/kWh when considering the total energy dispatched, and 115.12 g CO₂/kWh when considering only the energy deployed for FCR. These values represent a 60% reduction compared to the GWP values obtained in Germany. In comparison to traditional sources, the utilization of BESS in Spain would lead to a reduction of 90% for coal, 89% for oil, and 80% for natural gas emissions. In line with Edmunds et al.'s [79] perspective, the incorporation of new technologies into a regulated FCR market could indeed yield environmental benefits compared to the current state of frequency control practices in Spain. Considering Spain's Energy Storage Strategy, the PNIEC, and its participation in other European balancing markets, it is reasonable to anticipate that BESS will play a role in FCR provision in the future, potentially leading to positive environmental impacts.

The GWP results obtained in this study are consistent with those reported in the literature, as reviewed in Section 3.1.1. For instance, Oliveira et al. [63] reported GWP values of approximately 800 g CO₂/kWh when considering the UCTE 2004 electricity mix and around 200 g CO₂/kWh when using the electricity mix from Belgium in 2011. Similarly, Koj et al. [64] obtained emission values of approximately $800 \cdot 10^6$ kg CO₂ per functional unit¹⁹ in their analysis, while Hiremath et al. [65] reported GWP values of around 780 g CO₂/kWh, presumptively based on the German electricity mix from approximately 2014/2015. Jones et al. obtain a GWP of around 250 g CO₂/kWh and 400 g CO₂/kWh depending on the specific combination of the battery's lifespan and total utilised time scenario, considering Great Britain's electricity mix from presumably 2019. These findings suggest consistency and reliability in the assessment of GWP across various studies and scenarios.

Furthermore, the analysis revealed that the impacts of the use phase were predominant, accounting for the majority of emissions from the project's scope. In the case of Germany, production emissions contributed to approximately 2.5% of the total, whereas in Spain, they accounted for approximately 6.4% of the total emissions. This underscores the significance of the use phase in determining the overall environmental performance of BESS deployed for ancillary services, with emissions during production being a relatively smaller contributor in comparison. These results are in complete alignment with findings in academic research, where it has been consistently identified that use-phase emissions, particularly those associated with the electricity mix, dominate the environmental impact of BESS [57], [60], [63]–[65].

The sensitivity case scenario revealed that increasing the battery's capacity from 1.2 MWh to 3 MWh led to a 9% reduction in GWP. This outcome underscores the significance of use-phase emissions, which can potentially offset the increase in emissions from the production phase associated with a larger battery size. Hence, for BESS used exclusively for a single service, it is advisable to tailor the size of the battery to match the projected maximum depth of discharge. This approach would mitigate the need for scheduled transactions, which contribute to increased use-phase emissions, and also result in a reduced investment.

6.1. Limitations

Some of the limitations encountered in the project come from the assumptions made, which are specified in Section 4.4. Taking an average for the production phase of Li-ion batteries does not capture the specific characteristics and impacts associated with individual battery manufacturers. Factors such as the location of the manufacturing site can significantly influence the emissions generated during the production phase. For instance, a battery produced in China may have higher emissions compared to one produced in Sweden due to differences in the energy profiles of these regions. Therefore, when conducting a LCA of Li-ion batteries, a consideration of the location-specific variations would allow for a more accurate representation of the environmental impacts. Agreeing with Pellow et al.'s [56] perspective, utilising primary data for the production phase emissions would contribute to a more precise representation of the environmental impacts associated with BESS production.

The analysis of the Spanish FCR use case proved to be challenging due to the unavailability of public information. This lack of data not only delays the progress of research but also makes it difficult to create accurate representations of how the adoption of new technologies might

¹⁹ Provision of 551 MW of FCR in Germany for 20 years.

impact the future of ancillary services in countries such as Spain. As observed, in countries like Germany, where BESS has been deployed for FCR and there is a robust regulatory framework, research in this area has gained momentum in recent years. The high level of transparency in Germany, including the provision of data upon request, played a pivotal role in facilitating a comprehensive analysis of the use of BESS for FCR in this country.

6.2. Further research

The research conducted in this project offers valuable insights, but there are opportunities for further exploration that should be considered, taking into account the uncertainties and limitations of the current scope. Firstly, for a more precise assessment of the production phase emissions, collaborating with the industry to obtain location-specific primary data could be beneficial. Additionally, to comprehensively analyse the full life-cycle impacts of BESS, it would be advisable to include end-of-life emissions, as this area of research expands in the following years.

Secondly, the analysis of use-phase emissions could be expanded to encompass various scenarios. For instance, exploring different future energy mix scenarios, scenarios considering potential lifespan extensions, scenarios that vary the percentage of placed/accepted BESS bids, and scenarios comparing single vs. stacked services could provide a more nuanced understanding of BESS's environmental impacts in the provision FCR. These extensions would contribute to a more comprehensive and robust assessment of the technology's sustainability. Furthermore, it would be valuable to incorporate additional impact categories beyond GWP. Assessing social impacts, acidification potential, and the availability of critical resources, such as lithium, which are essential components of batteries, should be considered. The dispatch model could be further improved by expanding the considerations selected, as could be the degradation of the battery. Expanding the analysis to include these factors would provide a more holistic view of the environmental and societal consequences associated with BESS deployment.

Finally, conducting an economic analysis would further enhance the comprehensive assessment of BESS deployment in FCR. This would enable an exploration of the potential interplay between environmental, social, and economic factors, offering a more holistic perspective on the implications of BESS utilization in frequency control.

7. Conclusion

This thesis project explores the environmental implications of Battery Energy Storage Systems (BESS) when deployed for Frequency Control Reserve (FCR) in Germany and Spain. The primary focus of this research centres on the assessment of Global Warming Potential (GWP) associated with BESS technology. Although batteries have been a long-standing technology, their recent application in stationary energy storage, particularly in conjunction with renewable energy sources, has gained significant interest. This interest is underpinned by the global commitment to reduce emissions, as reflected in countries' Nationally Determined Contributions (NDCs) and energy transition strategies. As power systems increasingly incorporate renewable energy sources, characterized by low inertia, the demand for grid balancing services escalates. The provision of these essential ancillary services can be realised through a variety of technologies. However, achieving such services with low-emission sources is crucial for aligning with global energy transition objectives. Therefore, this project has been defined to investigate the GWP implications of BESS deployment in grid frequency regulation, offering valuable insights into the intersection of energy storage, environmental sustainability, and the transition to a low-carbon energy landscape.

To conduct this research, three Python-based models were meticulously developed:

- **Deviation and Frequency Model:** This model was crafted to provide a comprehensive statistical analysis of the frequency characteristics within the German grid. It serves as the foundation for understanding the grid's behaviour and its implications.
- **Dispatch Model:** The dispatch model is an integral component of the research, responsible for calculating the total energy dispatched by the BESS in two distinct representative days. The insights gathered from this model are extrapolated to provide estimates for annual and lifespan energy dispatch, offering valuable data for further analysis.
- **Environmental Model:** Designed to assess the environmental footprint, the environmental model calculates emissions generated during both the use and production phases of the BESS. The model calculates the GWP in grams of CO₂ per kilowatt-hour (g CO₂/kWh) in terms of FCR-deployed energy and of total dispatched energy.

These models, form the basis for comprehensive evaluation and analysis of the environmental impact of BESS in the context of grid frequency regulation in the selected countries.

In Germany, the GWP obtained amounts to 262.69 g CO₂/kWh for total energy dispatched and 288.10 g CO₂/kWh for FCR-deployed energy. Meanwhile, in Spain, the GWP amounts to 110.54 g CO₂/kWh for total energy dispatched and 115.12 g CO₂/kWh for FCR-deployed energy. These findings highlight the significant reduction in carbon emissions associated with BESS when utilized for FCR, compared to traditional carbon-based sources. The potential to contribute to a more sustainable energy ecosystem is found in both selected countries, particularly in Spain, where emissions reductions are notably substantial.

These results are consistent with academic research emphasizing the significance of the use-phase, particularly in relation to the electricity mix of the grid, in determining the environmental impacts of BESS. Considering this, the prospect of BESS utilization in FCR in Spain becomes particularly interesting for the future. It highlights the potential benefits of creating a market that accommodates new technologies within this specific ancillary service,

ultimately contributing to more environmentally sustainable energy systems in Spain and beyond.

To conclude, the rising demand for FCR, driven by the growing share of RES in the grid, can be provided by BESS with a positive impact compared with other traditional sources. Importantly, as the carbon intensity of the electricity input continues to improve, BESS can play an increasingly valuable role in achieving more environmentally sustainable and resilient energy systems.

8. References

- [1] IEA, 'CO2 Emissions in 2022', 2022.
- [2] P. Tielens and D. Van Hertem, 'The relevance of inertia in power systems', *Renew. Sustain. Energy Rev.*, vol. 55, pp. 999–1009, Mar. 2016, doi: 10.1016/j.rser.2015.11.016.
- [3] S. Saha, M. I. Saleem, and T. K. Roy, 'Impact of high penetration of renewable energy sources on grid frequency behaviour', *Int. J. Electr. Power Energy Syst.*, vol. 145, p. 108701, Feb. 2023, doi: 10.1016/j.ijepes.2022.108701.
- [4] B. Hartmann, I. Vokony, and I. Táczai, 'Effects of decreasing synchronous inertia on power system dynamics—Overview of recent experiences and marketisation of services', *Int. Trans. Electr. Energy Syst.*, vol. 29, no. 12, 2019, doi: 10.1002/2050-7038.12128.
- [5] P. Iurilli, C. Brivio, and M. Merlo, 'SoC management strategies in Battery Energy Storage System providing Primary Control Reserve', *Sustain. Energy Grids Netw.*, vol. 19, p. 100230, Sep. 2019, doi: 10.1016/j.segan.2019.100230.
- [6] Y. Hu, M. Armada, and M. Jesus Sanchez, 'Potential utilization of battery energy storage systems (BESS) in the major European electricity markets', *Appl. Energy*, vol. 322, p. 119512, Sep. 2022, doi: 10.1016/j.apenergy.2022.119512.
- [7] European Commission, 'Renewable energy directive'. https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en (accessed Aug. 04, 2023).
- [8] eurostat, 'Shedding light on energy - 2023 edition'. https://ec.europa.eu/eurostat/cache/interactive-publications/energy/2023/04_01_01 (accessed Aug. 04, 2023).
- [9] IEA, 'Europe data explorer', *IEA*. <https://www.iea.org/regions/europe> (accessed Jul. 26, 2023).
- [10] Ember, 'European Electricity Review 2022', 2022.
- [11] 'Overview Electricity Markets in Europe'. <https://www.amprion.net/Market/Market-Report/Overview-Electricity-Markets-in-Europe/> (accessed Jul. 26, 2023).
- [12] Mercato Elettrico, 'GME's Markets - Electricity Market - MGP, MI, MPEG, MSD'. <https://www.mercatoelettrico.org/en/mercati/mercatoelettrico/mpe.aspx> (accessed Aug. 01, 2023).
- [13] Nordpool, 'Bidding areas'. <https://www.nordpoolgroup.com/en/the-power-market/Bidding-areas/> (accessed Aug. 01, 2023).
- [14] Nordpool, 'Day-ahead prices'. <https://www.nordpoolgroup.com/en/Market-data1/Dayahead/Area-Prices/ALL1/Hourly/> (accessed Aug. 01, 2023).
- [15] 'Cross-Border Intraday (XBID) Project'. [https://www.amprion.net/Energy-Market/Congestion-Management/Multi-Regional-Coupling-\(MRC\)-and-Cross-Border-Intraday-\(XBID\)/Content-Page.html](https://www.amprion.net/Energy-Market/Congestion-Management/Multi-Regional-Coupling-(MRC)-and-Cross-Border-Intraday-(XBID)/Content-Page.html) (accessed Aug. 01, 2023).
- [16] ENTSOE, 'Bidding Zone Configuration Technical Report 2021', 2021.
- [17] 'Electricity market design'. https://energy.ec.europa.eu/topics/markets-and-consumers/market-legislation/electricity-market-design_en (accessed Jul. 28, 2023).
- [18] ENTSOE, 'Electricity Balancing'. https://www.entsoe.eu/network_codes/eb/ (accessed Sep. 24, 2023).
- [19] IEA, 'Germany 2020 - Energy Policy Review', 2020.
- [20] 'Q2 What role does renewable energy play in Germany's power mix?' <https://www.agora-energiawende.de/en/the-energiawende/the-german-energiawende/q2-what-role-does-renewable-energy-play-in-germanys-power-mix/> (accessed Aug. 17, 2023).
- [21] IEA, 'Germany data explorer', *IEA*. <https://www.iea.org/countries/germany> (accessed Jul. 26, 2023).

- [22] J. Coleman, 'Germany Reopens Coal Plants Because Of Reduced Russian Energy', *Forbes*. <https://www.forbes.com/sites/juliecoleman/2022/07/08/germany-reopens-coal-plants-because-of-reduced-russian-energy/> (accessed Aug. 16, 2023).
- [23] 'Renewable energy could account for 50% of Spain's electricity generation mix in 2023 | Red Eléctrica'. <https://www.ree.es/en/press-office/news/press-release/2023/03/renewable-energy-could-account-for-50percent-of-spains-electricity-generation-mix-in-2023> (accessed Aug. 17, 2023).
- [24] IEA, 'Spain 2021 - Energy Policy Review.', 2021.
- [25] IEA, 'Spain data explorer', *IEA*. <https://www.iea.org/countries/spain> (accessed Jul. 26, 2023).
- [26] F. Milano, F. Dörfler, G. Hug, D. J. Hill, and G. Verbič, 'Foundations and Challenges of Low-Inertia Systems (Invited Paper)', in *2018 Power Systems Computation Conference (PSCC)*, Jun. 2018, pp. 1–25. doi: 10.23919/PSCC.2018.8450880.
- [27] Y. G. Rebours, D. S. Kirschen, M. Trotignon, and S. Rossignol, 'A survey of frequency and voltage control ancillary services - Part I: Technical features', *Ieee Trans. Power Syst.*, vol. 22, no. 1, pp. 350–357, Feb. 2007, doi: 10.1109/TPWRS.2006.888963.
- [28] Y. G. Rebours, D. S. Kirschen, M. Trotignon, and S. Rossignol, 'A survey of frequency and voltage control ancillary services - Part II: Economic features', *Ieee Trans. Power Syst.*, vol. 22, no. 1, pp. 358–366, Feb. 2007, doi: 10.1109/TPWRS.2006.888965.
- [29] Karel De Brabandere, 'Voltage and frequency droop control in low voltage grids by distributed generators with inverter front-end', Katholieke Universiteit Leuven | Catholic University of Leuven | KU Leuven, 2006.
- [30] P. Kundur and O. P. Malik, *Power system stability and control*, Second edition. New York: McGraw Hill Education, 2022.
- [31] ENTSOE, 'Network Code for Requirements for Grid Connection applicable to all Generators,' 2012', 2012.
- [32] M. Delfanti, D. Falabretti, M. Merlo, and G. Monfredini, 'Distributed Generation Integration in the Electric Grid: Energy Storage System for Frequency Control', *J. Appl. Math.*, vol. 2014, p. e198427, Jun. 2014, doi: 10.1155/2014/198427.
- [33] UCTE, 'Operation Handbook P1 – Policy 1: Load-Frequency Control and Performance [C]', 2009. https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/publications/entsoe/Operation_Handbook/Policy_1_final.pdf
- [34] E. L. Miguez, I. E. Cortes, L. R. Rodriguez, and G. L. Camino, 'An overview of ancillary services in Spain', *Electr. Power Syst. Res.*, vol. 78, no. 3, pp. 515–523, Mar. 2008, doi: 10.1016/j.epsr.2007.03.009.
- [35] Regelleistung, 'Frequency Containment Reserve'. <https://www.regelleistung.net/en-us/General-info/Types-of-control-reserve/Frequency-Containment-Reserve>
- [36] ENTSOE, 'Operation Handbook'. [Online]. Available: <https://www.entsoe.eu/publications/system-operations-reports/>
- [37] 'Monthly Electricity Statistics – Data Tools', *IEA*. <https://www.iea.org/data-and-statistics/data-tools/monthly-electricity-statistics> (accessed Jun. 22, 2023).
- [38] A. Deane, 'Electricity generation and supply in Scotland, Wales, Northern Ireland and England, 2016 to 2020'.
- [39] J. Alonso del Valle, J. C. Viera Pérez, M. González Vega, D. Anseán González, V. M. García Fernández, and C. J. Blanco Viejo, 'Sistemas de almacenamiento masivo de energía con baterías (BESS): Estado actual y tendencias de futuro', *XXVI Annu. Semin. Autom. Ind. Electron. Instrum. SAAEI-2019*, 2019, Accessed: Mar. 09, 2023. [Online]. Available: <https://digibuo.uniovi.es/dspace/handle/10651/56930>
- [40] IRENA, 'Electricity Storage and Renewables: Costs and Markets to 2030', International Renewable Energy Agency, Abu Dhabi, 2017. [Online]. Available: /media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf?rev=a264707cb8034a52b6f6123d5f1b1148

- [41] C. D. Parker, 'APPLICATIONS – STATIONARY | Energy Storage Systems: Batteries', in *Encyclopedia of Electrochemical Power Sources*, J. Garche, Ed., Amsterdam: Elsevier, 2009, pp. 53–64. doi: 10.1016/B978-044452745-5.00382-8.
- [42] 'Service stacking using energy storage systems for grid applications – A review', *J. Energy Storage*, vol. 60, p. 106639, Apr. 2023, doi: 10.1016/j.est.2023.106639.
- [43] J. Figgenger *et al.*, *The development of battery storage systems in Germany: A market review (status 2022)*. 2022.
- [44] A. Filippa, S. Hashemi, and C. Traholt, 'Economic Evaluation of Frequency Reserve Provision using Battery Energy Storage', in *2019 IEEE 2nd International Conference on Renewable Energy and Power Engineering (REPE)*, Toronto, ON, Canada: IEEE, Nov. 2019, pp. 160–165. doi: 10.1109/REPE48501.2019.9025133.
- [45] Ministerio para la transición ecológica y el reto demográfico, 'Estrategia de almacenamiento energético', Ministerio para la transición ecológica y el reto demográfico, Spain, 2021. [Online]. Available: https://www.miteco.gob.es/es/prensa/estrategiaalmacenamiento_tcm30-522655.pdf
- [46] Y.-K. Wu and K.-T. Tang, 'Frequency Support by BESS – Review and Analysis', *Energy Procedia*, vol. 156, pp. 187–191, Jan. 2019, doi: 10.1016/j.egypro.2018.11.126.
- [47] Regelleistung, 'Prequalification Conditions'. 2022. Accessed: Jun. 26, 2023. [Online]. Available: <https://pq-portal.energy/Download>
- [48] National Grid ESO, 'Firm frequency response balancing service'. 2019. [Online]. Available: <https://www.nationalgrideso.com/document/148811/download>
- [49] National Grid, 'Testing guidance for providers of enhanced frequency response balancing service'. 2017. [Online]. Available: <https://www.nationalgrid.com/sites/default/files/documents/EFR%20Testing%20Guidance%20VD3%20%28Final%29.pdf>
- [50] A. Zeh, M. Mueller, M. Naumann, H. C. Hesse, A. Jossen, and R. Witzmann, 'Fundamentals of Using Battery Energy Storage Systems to Provide Primary Control Reserves in Germany', *Batter.-Basel*, vol. 2, no. 3, p. 29, Sep. 2016, doi: 10.3390/batteries2030029.
- [51] Amprion GmbH, 'Prequalified power 2017-2023 - Data request', 2023.
- [52] Ministerio para la Transición Ecológica y el Reto Demográfico, 'Plan Nacional Integrado de Energía y Clima (PNIEC) 2021-2030', 2021.
- [53] ISO, 'ISO 14040:2006(en), Environmental management — Life cycle assessment — Principles and framework'. <https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en> (accessed Aug. 08, 2023).
- [54] 'Life-Cycle Assessment Considerations for Batteries and Battery Materials - Porzio - 2021 - Advanced Energy Materials - Wiley Online Library'. <https://onlinelibrary.wiley.com/doi/full/10.1002/aenm.202100771> (accessed Aug. 09, 2023).
- [55] J. Porzio and C. Scown, 'Life-Cycle Assessment Considerations for Batteries and Battery Materials', *Adv. Energy Mater.*, vol. 11, p. 2100771, Jul. 2021, doi: 10.1002/aenm.202100771.
- [56] M. A. Pellow, H. Ambrose, D. Mulvaney, R. Betita, and S. Shaw, 'Research gaps in environmental life cycle assessments of lithium ion batteries for grid-scale stationary energy storage systems: End-of-life options and other issues', *Sustain. Mater. Technol.*, vol. 23, p. e00120, Apr. 2020, doi: 10.1016/j.susmat.2019.e00120.
- [57] C. Jones, P. Gilbert, and L. Stamford, 'Assessing the Climate Change Mitigation Potential of Stationary Energy Storage for Electricity Grid Services', *Environ. Sci. Technol.*, vol. 54, no. 1, pp. 67–75, Jan. 2020, doi: 10.1021/acs.est.9b06231.
- [58] L. Oliveira, M. Messagie, S. Rangaraju, J. Sanfelix, M. Hernandez, and J. Van Mierlo, 'Key Issues of Lithium-Ion Batteries – From Resource Depletion to Environmental Performance Indicators', *J. Clean. Prod.*, vol. 108, Jun. 2015, doi: 10.1016/j.jclepro.2015.06.021.

- [59] Y. Liang *et al.*, 'Life cycle assessment of lithium-ion batteries for greenhouse gas emissions', *Resour. Conserv. Recycl.*, vol. 117, pp. 285–293, Feb. 2017, doi: 10.1016/j.resconrec.2016.08.028.
- [60] N. A. Ryan, Y. Lin, N. Mitchell-Ward, J. L. Mathieu, and J. X. Johnson, 'Use-phase drives lithium-ion battery life cycle environmental impacts when used for frequency regulation', *Environ. Sci. Technol.*, vol. 52, no. 17, pp. 10163–10174, 2018.
- [61] S. Jenu, I. Deviatkin, A. Hentunen, M. Myllysilta, S. Viik, and M. Pihlatie, 'Reducing the climate change impacts of lithium-ion batteries by their cautious management through integration of stress factors and life cycle assessment', *J. Energy Storage*, vol. 27, Nov. 2019, doi: 10.1016/j.est.2019.101023.
- [62] J. Chowdhury, N. Balta-Ozkan, P. Goglio, Y. Hu, L. Varga, and L. McCabe, 'Techno-environmental analysis of battery storage for grid level energy services', *Renew. Sustain. Energy Rev.*, vol. 131, p. 110018, Jul. 2020, doi: 10.1016/j.rser.2020.110018.
- [63] L. Oliveira, M. Messagie, J. Mertens, H. Laget, T. Coosemans, and J. Van Mierlo, 'Environmental performance of electricity storage systems for grid applications, a life cycle approach', *Energy Convers. Manag.*, vol. 101, pp. 326–335, Sep. 2015, doi: 10.1016/j.enconman.2015.05.063.
- [64] J. C. Koj *et al.*, 'Life cycle assessment of primary control provision by battery storage systems and fossil power plants', *Energy Procedia*, vol. 73, pp. 69–78, 2015.
- [65] M. Hiremath, K. Derendorf, and T. Vogt, 'Comparative Life Cycle Assessment of Battery Storage Systems for Stationary Applications', *Environ. Sci. Technol.*, vol. 49, no. 8, pp. 4825–4833, Apr. 2015, doi: 10.1021/es504572q.
- [66] T. Thien, D. Schweer, D. vom Stein, A. Moser, and D. U. Sauer, 'Real-world operating strategy and sensitivity analysis of frequency containment reserve provision with battery energy storage systems in the german market', *J. Energy Storage*, vol. 13, pp. 143–163, Oct. 2017, doi: 10.1016/j.est.2017.06.012.
- [67] J. Fleeer, S. Zurmühlen, J. Badeda, P. Stenzel, J.-F. Hake, and D. U. Sauer, 'Model-based Economic Assessment of Stationary Battery Systems Providing Primary Control Reserve', *Energy Procedia*, vol. 99, pp. 11–24, Nov. 2016, doi: 10.1016/j.egypro.2016.10.093.
- [68] E. Groza, S. Kiene, O. Linkevics, and K. Gicevskis, 'Modelling of Battery Energy Storage System Providing FCR in Baltic Power System after Synchronization with the Continental Synchronous Area', *Energies*, vol. 15, no. 11, p. 3977, May 2022, doi: 10.3390/en15113977.
- [69] J. Marchgraber, W. Gawlik, and C. Alács, 'Modellierung und Simulation von Batteriespeichern bei der Erbringung von Primärregelleistung', *E Elektrotechnik Informationstechnik*, vol. 136, no. 1, pp. 3–11, Feb. 2019, doi: 10.1007/s00502-019-0704-1.
- [70] P. Stenzel, J. C. Koj, P. Zapp, W. Hennings, and A. Schreiber, 'Primary control provided by large-scale battery energy storage systems or fossil power plants in Germany and related environmental impacts', *J. Energy Storage*, vol. 8, no. FZJ-2016-04788, pp. 300–310, 2016.
- [71] L. A.-W. Ellingsen, C. R. Hung, and A. H. Strømman, 'Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions', *Transp. Res. Part Transp. Environ.*, vol. 55, pp. 82–90, Aug. 2017, doi: 10.1016/j.trd.2017.06.028.
- [72] H. C. Kim, T. J. Wallington, R. Arsenault, C. Bae, S. Ahn, and J. Lee, 'Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis', *Environ. Sci. Technol.*, vol. 50, no. 14, pp. 7715–7722, Jul. 2016, doi: 10.1021/acs.est.6b00830.
- [73] D. A. Notter *et al.*, 'Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles', *Environ. Sci. Technol.*, vol. 44, no. 17, pp. 6550–6556, Sep. 2010, doi: 10.1021/es903729a.

- [74] 'Control Reserve Demand + Activation', *Homepage*. <https://www.transnetbw.de/en/energy-market/ancillary-services/control-reserve-demand-activation> (accessed May 30, 2023).
- [75] Electricity Maps, 'Electricity maps database - Data request', 2023.
- [76] B. Tranberg, O. Corradi, B. Lajoie, T. Gibon, I. Staffell, and G. B. Andresen, 'Real-Time Carbon Accounting Method for the European Electricity Markets', *Energy Strategy Rev.*, vol. 26, p. 100367, Nov. 2019, doi: 10.1016/j.esr.2019.100367.
- [77] J. T. Saraiva, H. Heitor, N. Correia, and R. Araujo, 'Ancillary services — The current situation in the iberian electricity market and future possible developments', in *2011 IEEE Trondheim PowerTech*, Trondheim: IEEE, Jun. 2011, pp. 1–8. doi: 10.1109/PTC.2011.6019452.
- [78] J. T. Saraiva, H. Heitor, N. Correia, and R. Araujo, 'Ancillary services in the Iberian Electricity market — Current situation and harmonization approaches', in *2011 8th International Conference on the European Energy Market (EEM)*, Zagreb, Croatia: IEEE, May 2011, pp. 556–561. doi: 10.1109/EEM.2011.5953074.
- [79] C. Edmunds, S. Martín-Martínez, J. Browell, E. Gómez-Lázaro, and S. Galloway, 'On the participation of wind energy in response and reserve markets in Great Britain and Spain', *Renew. Sustain. Energy Rev.*, vol. 115, p. 109360, Nov. 2019, doi: 10.1016/j.rser.2019.109360.
- [80] J. C. Hernández, F. Sanchez-Sutil, F. J. Muñoz-Rodríguez, and C. R. Baier, 'Optimal sizing and management strategy for PV household-prosumers with self-consumption/sufficiency enhancement and provision of frequency containment reserve', *Appl. Energy*, vol. 277, p. 115529, Nov. 2020, doi: 10.1016/j.apenergy.2020.115529.

Annex I

Deviation and frequency model script

```
import os
import pandas as pd
import seaborn as sns
import pandas as pd
import numpy as np
import matplotlib
from numpy import mean

#Check if the frequency is out of range
def check_frequency(time_count):
    global deviation
    global dev_initial
    global dev_final
    global df
    if abs(df['FREQUENCY'][time_count] - nominal_freq) >= 0.01:
        dev_initial = time_count
        return True

    return False

#Check if the frequency has gone back to the acceptable range
def check_deactivate(time_count):
    global deviation
    global dev_initial
    global dev_final
    global df
    if abs(df['FREQUENCY'][time_count] - nominal_freq) < 0.01:
        dev_final = time_count
        dev_db = df.iloc[dev_initial:dev_final]
        max_dev = max(abs(dev_db['FREQUENCY'] - nominal_freq))
        av_dev = mean(abs(dev_db['FREQUENCY'] - nominal_freq))
        length = dev_final - dev_initial

        # New list to append Row to DataFrame
        row = [length, max_dev, av_dev, dev_initial, dev_final]
        deviation.loc[len(deviation)] = row

    return False

    return True

def run_model():
    global df
    global deviation
    deviation =
pd.DataFrame(columns=['length', 'max_dev', 'av_dev', 'start_time', 'finish
_time'])
    deviation
    #Run the model for the whole product time
    activate = False
    time_count = 0
    dev_initial = 0
    dev_final = 0
    product_time = len(df)
```

```

#The model runs as long as the product time goes
while time_count < (product_time-1):
    time_count = time_count + 1
    #Check the frequency deviation if provision in off
    if not activate:
        activate = check_frequency(time_count)
    #Check if BESS is activated and providing service
    else:
        activate = check_deactivate(time_count)

    return deviation

# Define the function to extract the information you need from each
CSV file
def extract_info(file_path):
    global df

    # Load the CSV file into a Pandas DataFrame
    df = pd.read_csv(file_path, sep=',', names=['DATE', 'TIME',
'DATA', 'FREQUENCY'])
    result = run_model()

    # Return the extracted information
    return result

# Initialize a list to store the extracted information from each CSV
file
all_info = []
nominal_freq = 50

# Loop through each file in the folder and extract the information
using the defined function
for file_name in os.listdir(folder_path):
    if file_name.endswith('.csv'):
        file_path = os.path.join(folder_path, file_name)
        info = extract_info(file_path)
        all_info.append(info)

# Concatenate all the extracted information into a single DataFrame
df_all_info = pd.concat(all_info)

# Save the concatenated DataFrame to a new CSV file
df_all_info.to_csv('C:\\Users\\...\\deviation_v1.csv', index=False)

```

Annex II

Dispatch model script

```

import seaborn as sns
import pandas as pd
import numpy as np
import matplotlib
import os
from numpy import mean
from matplotlib import pyplot as plt

#Import 21st of June
BC = pd.read_csv('202106_Frequenz.csv', sep=',', names=['DATE',
'TIME', 'DATA', 'FREQUENCY'])
BC = BC[BC['DATE'] == '2021-06-21']
first_index = BC.index[0]
last_index = BC.index[-1]

##MODEL PARAMETERS
#Nominal frequency and boundaries
nominal_freq = 50
db_limit_down = 49.99
db_limit_up = 50.01

#Provision time = 15 minutes
provision_time = 15*60

#Product time = 4 hours
product_time = BC.index[-1]

#Power of the BESS (Rated power) = 1.25 MW
P_BESS = 1.25

#Power of the bid (Prequalified power) = 1 MW
P_bid = 1

#Available energy content = 1.25MWh
E_total = 1.25

#Energy saved for each activation (Constraint on a vailable energy
content) = 0.83 MWh
energy_activation = 0.83

#Efficiency of the battery system
efficiency = 0.95

#Activation time = 2 seconds
activation_t = 2

#Scheduled transaction values (duration = 15 min and energy exchange =
0.2MWh)
st_duration = 15*60
st_value = 0.2*3600

#State of charge limit values

```

```

soc_min = 20.0
soc_max = 80.0
soc_av = 60.0
soc_min_of = 55.0
soc_max_of = 65.0
soc_min_st = 30.0
soc_max_st = 70.0

#Check if the frequency is out of range
def check_frequency():
    global soc
    'I could add the activation check here as well'
    if abs(BC['FREQUENCY'][t_bc] - nominal_freq) >= 0.01:
        return True
    else:
        if soc < 60 and (BC['FREQUENCY'][t_bc] - nominal_freq) > 0:
            dev = BC['FREQUENCY'][t_bc] - nominal_freq
            power = (dev)/0.2
            power_db_down.loc[len(power_db_down)] = [abs(power),
BC['TIME'][t_bc]]
            soc_change = abs(power)/4500*100
            soc = soc + soc_change
        elif soc > 60 and (BC['FREQUENCY'][t_bc] - nominal_freq) < 0:
            dev = BC['FREQUENCY'][t_bc] - nominal_freq
            power = (dev)/0.2
            power_db_up.loc[len(power_db_up)] = [abs(power),
BC['TIME'][t_bc]]
            soc_change = abs(power)/4500*100
            soc = soc - soc_change
        return False

#Change in time step
def provision_on():
    global t_prov
    global activate
    if t_prov <= provision_time:
        t_prov = t_prov + 1
    else:
        activate = False
        t_prov = 0
    return

def check_st_duration():
    global st_flag
    global st_timer
    global st_duration
    if st_timer <= st_duration:
        st_timer = st_timer + 1
    else:
        st_flag = False
        st_timer = 0
    return

```

```
#Defines the SoC for scheduled transactions
def st_provision():
    if not st_buy:
        soc_st = 0.0177

#Changes the SoC levels
def state_change():
    global soc
    global st_flag
    global st_buy
    dev = BC['FREQUENCY'][t_bc] - nominal_freq
    power = (dev)/0.2
    soc_change = abs(power)/4500*100
    if dev < 0:
        if soc > soc_max_st:
            if not st_flag:
                st_flag = True
                st_buy = False
                check_st_duration()
                power = power*1.2
                soc_change = abs(power)/4500*100
                soc_st = (st_value/st_duration)/4500*100
                soc = soc - soc_change - soc_st
                power_of_up.loc[len(power_of_up)] = [(abs(power)/6),
BC['TIME'][t_bc]]
                power_list_up.loc[len(power_list_up)] =
[(abs(power)/1.2), BC['TIME'][t_bc]]
                power_st_sell.loc[len(power_st_sell)] = [(soc_st),
BC['TIME'][t_bc]]
            else:
                check_st_duration()
                power = power*1.2
                soc_change = abs(power)/4500*100
                soc_st = (st_value/st_duration)/4500*100
                if st_buy:
                    soc = soc + soc_change + soc_st
                    power_st_buy.loc[len(power_st_buy)] = [(soc_st),
BC['TIME'][t_bc]]
                else:
                    soc = soc + soc_change - soc_st
                    power_st_sell.loc[len(power_st_sell)] = [(soc_st),
BC['TIME'][t_bc]]
                power_of_up.loc[len(power_of_up)] =
[(abs(power)/6), BC['TIME'][t_bc]]
                power_list_up.loc[len(power_list_up)] =
[(abs(power)/1.2), BC['TIME'][t_bc]]
                elif soc > soc_max_of:
                    if not st_flag:
                        power = power*1.2
                        soc_change = abs(power)/4500*100
                        soc = soc - soc_change
                        power_of_up.loc[len(power_of_up)] = [(abs(power)/6),
BC['TIME'][t_bc]]
                        power_list_up.loc[len(power_list_up)] =
[(abs(power)/1.2), BC['TIME'][t_bc]]
                    else:
```

```

        check_st_duration()
        power = power*1.2
        soc_st = (st_value/st_duration)/4500*100
        soc_change = abs(power)/4500*100
        if st_buy:
            soc = soc + soc_change + soc_st
            power_st_buy.loc[len(power_st_buy)] = [(soc_st),
BC['TIME'][t_bc]]
        else:
            soc = soc + soc_change - soc_st
            power_st_sell.loc[len(power_st_sell)] = [(soc_st),
BC['TIME'][t_bc]]
            power_of_up.loc[len(power_of_up)] = [(abs(power)/6),
BC['TIME'][t_bc]]
            power_list_up.loc[len(power_list_up)] =
[(abs(power)/1.2), BC['TIME'][t_bc]]
        else:
            if not st_flag:
                soc = soc - soc_change
                power_list_up.loc[len(power_list_up)] = [(abs(power)),
BC['TIME'][t_bc]]
            else:
                check_st_duration()
                soc_st = (st_value/st_duration)/4500*100
                if st_buy:
                    soc = soc + soc_change + soc_st
                    power_st_buy.loc[len(power_st_buy)] = [(soc_st),
BC['TIME'][t_bc]]
                else:
                    soc = soc + soc_change - soc_st
                    power_st_sell.loc[len(power_st_sell)] = [(soc_st),
BC['TIME'][t_bc]]
                    power_list_up.loc[len(power_list_up)] = [(abs(power)),
BC['TIME'][t_bc]]
            else:
                if soc < soc_min_st:
                    if not st_flag:
                        st_flag = True
                        st_buy = True
                        check_st_duration()
                        power = power*1.2
                        soc_change = abs(power)/4500*100
                        soc_st = (st_value/st_duration)/4500*100
                        soc = soc + soc_change + soc_st
                        power_of_down.loc[len(power_of_down)] =
[(abs(power)/6), BC['TIME'][t_bc]]
                        power_list_down.loc[len(power_list_down)] =
[(abs(power)/1.2), BC['TIME'][t_bc]]
                        power_st_buy.loc[len(power_st_buy)] = [(soc_st),
BC['TIME'][t_bc]]
                    else:
                        check_st_duration()
                        power = power*1.2
                        soc_change = abs(power)/4500*100
                        soc_st = (st_value/st_duration)/4500*100
                        if st_buy:
                            soc = soc + soc_change + soc_st

```

```

        power_st_buy.loc[len(power_st_buy)] = [(soc_st),
BC['TIME'][t_bc]]
        else:
            soc = soc + soc_change - soc_st
            power_st_sell.loc[len(power_st_sell)] = [(soc_st),
BC['TIME'][t_bc]]
            power_of_down.loc[len(power_of_down)] =
[(abs(power)/6), BC['TIME'][t_bc]]
            power_list_down.loc[len(power_list_down)] =
[(abs(power)/1.2), BC['TIME'][t_bc]]
            elif soc < soc_min_of:
                if not st_flag:
                    power = power*1.2
                    soc_change = abs(power)/4500*100
                    soc = soc + soc_change
                    power_of_down.loc[len(power_of_down)] =
[(abs(power)/6), BC['TIME'][t_bc]]
                    power_list_down.loc[len(power_list_down)] =
[(abs(power)/1.2), BC['TIME'][t_bc]]
                else:
                    check_st_duration()
                    soc_st = (st_value/st_duration)/4500*100
                    power = power*1.2
                    soc_change = abs(power)/4500*100
                    if st_buy:
                        soc = soc + soc_change + soc_st
                        power_st_buy.loc[len(power_st_buy)] = [(soc_st),
BC['TIME'][t_bc]]
                    else:
                        soc = soc + soc_change - soc_st
                        power_st_sell.loc[len(power_st_sell)] = [(soc_st),
BC['TIME'][t_bc]]
                    power_of_down.loc[len(power_of_down)] =
[(abs(power)/6), BC['TIME'][t_bc]]
                    power_list_down.loc[len(power_list_down)] =
[(abs(power)/1.2), BC['TIME'][t_bc]]
                else:
                    if not st_flag:
                        soc = soc + soc_change
                        power_list_down.loc[len(power_list_down)] =
[(abs(power)), BC['TIME'][t_bc]]
                    else:
                        check_st_duration()
                        soc_st = (st_value/st_duration)/4500*100
                        if st_buy:
                            soc = soc + soc_change + soc_st
                            power_st_buy.loc[len(power_st_buy)] = [(soc_st),
BC['TIME'][t_bc]]
                        else:
                            soc = soc + soc_change - soc_st
                            power_st_sell.loc[len(power_st_sell)] = [(soc_st),
BC['TIME'][t_bc]]
                        power_list_down.loc[len(power_list_down)] =
[(abs(power)), BC['TIME'][t_bc]]

#Run the model for the whole modelling time
activate = False

```

```
t_bc = BC.index[0]
t_prov = 0
st_timer = 0
st_flag = False
st_buy = False
soc = soc_av
soc_db = 0
soc_of = 0
soc_st = 0
soc_list = []
power_db_up = pd.DataFrame(columns=['value', 'time'])
power_db_down = pd.DataFrame(columns=['value', 'time'])
power_of_up = pd.DataFrame(columns=['value', 'time'])
power_of_down = pd.DataFrame(columns=['value', 'time'])
power_st_sell = pd.DataFrame(columns=['value', 'time'])
power_st_buy = pd.DataFrame(columns=['value', 'time'])
power_list_up = pd.DataFrame(columns=['value', 'time'])
power_list_down = pd.DataFrame(columns=['value', 'time'])

while t_bc < product_time:
    soc_list.append(soc)
    t_bc = t_bc + 1
    #Check the frequency deviation if provision in off
    if not activate:
        activate = check_frequency()
    #Check if BESS is activated and providing service
    else:
        provision_on()
        state_change()
```

Annex III

Environmental analysis script

```

import seaborn as sns
import pandas as pd
import numpy as np
import matplotlib
import os
from numpy import mean
from matplotlib import pyplot as plt

BC = pd.read_csv('DE.csv', sep=',')
BC_DE = BC[BC['datetime'].str.startswith('2021-06-21')]

import pandas as pd

# Load the databases into pandas DataFrames
df_de = BC_DE
df_fcr = BC_FCR
df_of = BC_OF
df_db = BC_DB
df_st = BC_ST
external_emission = []
internal_emission = []

# Iterate through each row in 'df_st'
for i in range(len(df_st)):
    time_st = df_st.iloc[i,1][0:2]

    for i in range(len(df_de)):
        time_de = df_de.iloc[i,0][11:13]
        if time_st == time_de:
            external_emission.append(df_de.iloc[i,5])

# Iterate through each row in 'df_fcr'
for i in range(len(df_fcr)):
    time_fcr = df_fcr.iloc[i,1][0:2]
    power_fcr = df_fcr.iloc[i,0]

    for i in range(len(df_de)):
        time_de = df_de.iloc[i,0][11:13]
        if time_fcr == time_de:
            internal_emission.append(df_de.iloc[i,5]*power_fcr/3.6)

# Iterate through each row in 'df_of'
for i in range(len(df_of)):
    time_of = df_of.iloc[i,1][0:2]
    power_of = df_of.iloc[i,0]

    for i in range(len(df_de)):
        time_de = df_de.iloc[i,0][11:13]
        if time_of == time_de:
            internal_emission.append(df_de.iloc[i,5]*power_of/3.6)

# Iterate through each row in 'df_db'
for i in range(len(df_db)):
    time_db = df_db.iloc[i,1][0:2]
  
```

```
power_db = df_db.iloc[i,0]

# Iterate through each row in 'df_de'
for i in range(len(df_de)):
    time_de = df_de.iloc[i,0][11:13]
    if time_db == time_de:
        internal_emission.append(df_de.iloc[i,5]*power_db/3.6)

#External and internal emission calculation
external_emissions =
sum(external_emission)/len(external_emission)*200/1000

internal_emissions = sum(internal_emission)/1000
```