SCHOOL OF ENGINEERING

ELECTRICAL POWER RESEARCH GROUP

INVESTIGATING TECHNO-ECONOMIC FACTORS INFLUENCING THE FUTURE VALUE OF ENERGY STORAGE TECHNOLOGIES

A THESIS SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

STALIN ELOY MUÑOZ VACA

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Abstract

The decarbonization of electricity networks, all over the world, has led to an increasing amount of renewable generation in the energy mix. Although renewable generators produce clean and eco-friendly energy, high-penetration levels of renewables could also impose techno-economic challenges to the grid caused by their intermittent and stochastic character, compromising not only the security of electricity networks but also their energy equity.

Renewable Energy Generation (REG) Providers can support electricity networks to address these challenges by providing grid-services and applications using different solutions. Energy Storage (ES) Devices are a flexible, yet expensive, smart grid solution able to store amounts of energy at one instant for their later utilization. The main barrier for their widespread proliferation has been, however, the high investment costs required to acquire and install these devices. This research investigates the factors influencing the future value of Energy Storage Technologies. The strategy to tackle this aim is based on designing, developing and implementing a techno-economic framework that allows the assessment of ES devices at planning stage. The framework is comprised of various models to examine diverse factors contributing with the value of ES devices. The simulation results of these framework models determine the maximum revenue that REG Providers can obtain from using ES devices alongside with the ES sizing design to achieve these outcomes.

The outcomes of this work show the value for REG providers of using ES devices to address multiple applications and to profit from different energy market, the benefits and drawbacks of applying ES technologies in mandatory and non-mandatory service schemes, the value of using ES devices in mutual operation with renewable generators, the advantages of selecting ES technologies, and the contributions that enhancing the technical and economic features of ES technologies have on the value. The findings from this research can facilitate the widespread deployment of ES devices by providing valuable information to REG providers and investors when considering investments in ES technologies, technology developers to prioritize areas of enhancement in ES device, policy makers and regulators to understand the end to end effects that current regulations might produce on the interested parties and selling companies to expand the range of ES devices and hybrid combinations to offer for customers.

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I, Stalin Eloy Muñoz Vaca, confirm that this thesis and the work presented in it are my own achievement.

I have read and understand the penalties associated with plagiarism.

Signed:  ____________

Date: 21-09-2020

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List of Publications

CONFERENCE PROCEEDINGS

- **S. Munoz Vaca**, C. Patsios, and P. Taylor, "Enhancing frequency response of wind farms using hybrid energy storage systems," in 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), 2016, pp. 325–329. DOI: 10.1109/ICRERA.2016.7884560
- **S. Munoz Vaca**, C. Patsios, and P. Taylor, "Sizing of hybrid energy storage systems for frequency response of solar farms in Ecuador," in 2017 IEEE PES Innovative Smart Grid Technologies Conference – ISGT Latin America, vol. 2017–January, pp. 1–7. DOI: 10.1109/ISGT-LA.2017.8126749

BOOK CHAPTER

- P. Taylor, C. Patsios, **S. Munoz Vaca**, D. Greenwood, and N. Wade, "Energy Storage Integration," in Storing Energy, Elsevier, 2016, pp. 433–476. DOI: 10.1016/B978-0-12-803440-8.00021-X

Abbreviations

Acronym	Definition
BM	Balancing Mechanism
CAES	Compressed Air Energy Storage
CRF	Capital Recovery Factor
CUSC	Connection and Use of System Code
DFR	Dynamic Frequency Response
DFT	Discrete Fourier Transform
DoD	Depth of Discharge
DSR	Demand Side Response
DWT	Discrete Wavelet Transform
EFR	Enhanced Frequency Response
ENTSO-E	European Network of Transmission System Operators for Electricity
ERPS	Enhanced Reactive Power Service
ESO	Electricity System Operator
ES	Energy Storage
ES1	Energy-dense Storage Technology
ES2	Power-dense Storage Technology
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
FES	Flywheel Energy Storage
FFR	Firm Frequency Response
FFRA	Firm Frequency Response and Wholesale Market Interaction
GB	Great Britain

HESS	Hybrid Energy Storage System
LAES	Liquid air energy storage
LP	Linear programming
MFR	Mandatory Frequency Response
MFRA	Mandatory Frequency Response and Wholesale Market Interaction
MID	Market Index Data
MILP	Mixed-Integer Linear Programming
OF	Objective Function
OFGEM	Office of Gas and Electricity Markets
ORPS	Obligatory Reactive Power Service
PVS	Photovoltaic Stations
REG	Renewable Energy Generation
RG	Renewable Generator
REP	Response Energy Payment
SC	Supercapacitors
SOC	State of Charge
SOH	State of Health
STOR	Short Term Operating Reserves
T&D	Transmission and Distribution Networks
TES	Thermal Energy Storage
TSR	Total System Revenue
UK	United Kingdom
UPS	Uninterruptible Power Systems
VRFB	Vanadium Redox Flow Batteries

Nomenclature

Symbol	Definition	Units
$C_{DEG(n)}$	Costs of Degradation of ES technologies at the instant n	[£]
C_{ESS}	Capital Cost of Investment in ES devices	[£]
C_{OBJ}	Limit of the Investment Cost of the Project	[£]
CRF	Capital Recovery Factor	N/A
CT_1	Cycling Lifetime of ES1	[cycles]
CT_2	Cycling Lifetime of ES2	[cycles]
D	Total Number of Days of Analysis	[days]
$\frac{df}{dt}$	Rate of Change of the Electrical Frequency	[Hz/s]
$E_{CAP\_ES1(n)}$	Energy stored within ES1 at the instant n	[MWh]
$E_{CAP\_ES2(n)}$	Energy stored within ES2 at the instant n	[MWh]
$E_{ES1\_IN(n)}$	Total Energy Entering ES1 at the instant n	[MWh]
$E_{ES1\_IN(n)}$	Total Energy Entering ES2 at the instant n	[MWh]
$E_{ES1\_LOSS(n)}$	Energy Losses of ES1 at the instant n	[MWh]
$E_{ES2\_LOSS(n)}$	Energy Losses of ES2 at the instant n	[MWh]
$E_{ES1\_OUT(n)}$	Total Energy Leaving ES1 at the instant n	[MWh]
$E_{ES3\_OUT(n)}$	Total Energy Leaving ES2 at the instant n	[MWh]
E_{FM_MAX}	Energy Requirements for Maximum Frequency Deviations at the instant n	[MWh]
E_{KIN}	Kinetic Energy	[J]
$E_{OF(n)}$	Energy Absorbed by the System for High-Frequency Support at the instant n	[MWh]
$E_{OF\_ES1(n)}$	Energy Absorbed by ES1 for High-Frequency Responses at the instant n	[MWh]

$E_{OF\_ES2(n)}$	Energy Absorbed by ESs for High-Frequency Responses at the instant n	[MWh]
$E_{OF\_REG(n)}$	Energy Reduced from RG for High-Frequency Responses at the instant n	[MWh]
$E_{REQ\_OF(n)}$	Response Requirement for High-Frequency Support at the instant n	[MWh]
$E_{REQ\_UF(n)}$	Response Requirement for Primary Frequency Support at the instant n	[MWh]
$E_{RES\_ES1(n)}$	Energy Reserves from ES1 for the Maximum Frequency Deviations at the instant n	[MWh]
$E_{RES\_REG(n)}$	Energy Reserves from RG for the Maximum Frequency Deviations at the instant n	[MWh]
$E_{UF(n)}$	Energy Delivered by the System for Primary Frequency Support at the instant n	[MWh]
$E_{UF\_ES1(n)}$	Energy Delivered by ES1 for Primary Frequency Responses at the instant n	[MWh]
$E_{UF\_ES2(n)}$	Energy Delivered by ES2 for Primary Frequency Responses at the instant n	[MWh]
$E_{UF\_REG(n)}$	Energy Delivered by RG for Primary Frequency Responses at the instant n	[MWh]
$E_{WM\_ABS(n)}$	Energy Absorbed by the ESS from the Wholesale Market at the instant n	[MWh]
$E_{WM\_ABS1(n)}$	Energy Absorbed by ES1 from the Wholesale Market at the instant n	[MWh]
$E_{WM\_ABS2(n)}$	Energy Absorbed by ES2 from the Wholesale Market at the instant n	[MWh]
$E_{WM\_DIS(n)}$	Energy Discharged by the ESS in the Wholesale Market at the instant n	[MWh]
$E_{WM\_DIS1(n)}$	Energy Discharged by ES1 into the Wholesale Market at the instant n	[MWh]
$E_{WM\_DIS2(n)}$	Energy Discharged by ES2 into the Wholesale Market at the instant n	[MWh]
$E_{WM\_REG(n)}$	Energy Traded by RG in the Wholesale Market at the instant n	[MWh]

f_0	Nominal System Frequency	[Hz]
i	Interest Rate on the Investment	[%]
$I_{FM(n)}$	Income of the System from the Frequency Response Market at the instant n	[£]
$I_{WM(n)}$	Income of the System from the Wholesale Market at the instant n	[£]
J	System Inertia	[Kg·m^2]
LT_{ES1}	Manufacturing Lifetime of ES1	[years]
LT_{ES2}	Manufacturing Lifetime of ES2	[years]
$M_{1(n)}$	Binary variable for Primary Frequency Equations	N/A
$M_{2(n)}$	Binary variable for High Frequency Equations	N/A
n	Data Sampling Interval	N/A
N	Total Number of Intervals in the Sample Data	N/A
$Na-NiCl_2$	Sodium-nickel chloride	N/A
P_{DEG_ES1}	Degradation Price of ES1	[£/MWh]
P_{DEG_ES2}	Degradation Price of ES2	[£/MWh]
P_{E_ES1}	Price of the Energy Component of ES1	[£/MWh]
P_{E_ES2}	Price of the Energy Component of ES2	[£/MWh]
$P_{FM(n)}$	Market Price of Frequency Response at the instant n	[£/MWh]
P_{GEN}	Power Generated within the Electricity Network	[MW]
P_{LOAD}	Load Consumed within the Electricity Network	[MW]
P_{P_ES1}	Price of the Power Component of ES1	[£/MW]
P_{P_ES2}	Price of the Power Component of ES2	[£/MW]
$P_{REG(n)}$	Total Power Generated from RG at the instant n	[MWh]
PT	Project Lifetime Horizon	[years]
$P_{WM(n)}$	Wholesale Market Price at the instant n	[£/MWh]

R_{E_ES1}	Energy Rating of ES1	[MWh]
R_{E_ES2}	Energy Rating of ES2	[MWh]
R_{P_ES1}	Power Rating of ES1	[MW]
R_{P_ES2}	Power Rating of ES2	[MW]
SD_{ES1}	Daily Self-Discharge Rate of ES1	[%]
SD_{ES2}	Daily Self-Discharge Rate of ES2	[%]
SOC_{ES1_MAX}	Maximum Allowed State of Charge of ES1	[%]
SOC_{ES2_MAX}	Maximum Allowed State of Charge of ES2	[%]
SOC_{ES1_MIN}	Minimum Allowed State of Charge of ES1	[%]
SOC_{ES2_MIN}	Minimum Allowed State of Charge of ES2	[%]
T_{PER}	Sample Data Rate	[seconds]
T_{REG}	Time Length for Secondary Frequency Response	[minutes]
TSR	Total System Revenue	[£]
X_1	Integer Auxiliary Factor for ES1	N/A
X_2	Integer Auxiliary Factor for ES2	N/A
η_{ES1_CH}	Charging Efficiency of ES1	[%]
η_{ES2_CH}	Charging Efficiency of ES2	[%]
η_{ES1_DIS}	Discharging Efficiency of ES1	[%]
η_{ES2_DIS}	Discharging Efficiency of ES2	[%]

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Chapter 1. Introduction

1.1. Background

Electricity and heat production are responsible for the largest single source of global greenhouse gas emissions and Governments, from all over the world, are making efforts to decrease these emissions by decarbonizing, among other strategies, the energy supply through the continuous inclusion of renewable generation in the energy mix [1]–[3]. In the United Kingdom (UK), for instance, the target was set to achieve 15% energy consumption from renewable energy sources by 2020 and to reach net-zero greenhouse gas emissions for the whole economy by 2050 [4], [5]. Other countries, such as Germany and Japan, have established this objective to 45% and 22%-24%, respectively, by 2030 [6], [7]. Figure 1.1 shows the share, from renewable energy sources, in the gross final energy consumption of the European Union (EU) countries in 2016 and their respectively target by 2020 [8], [9].

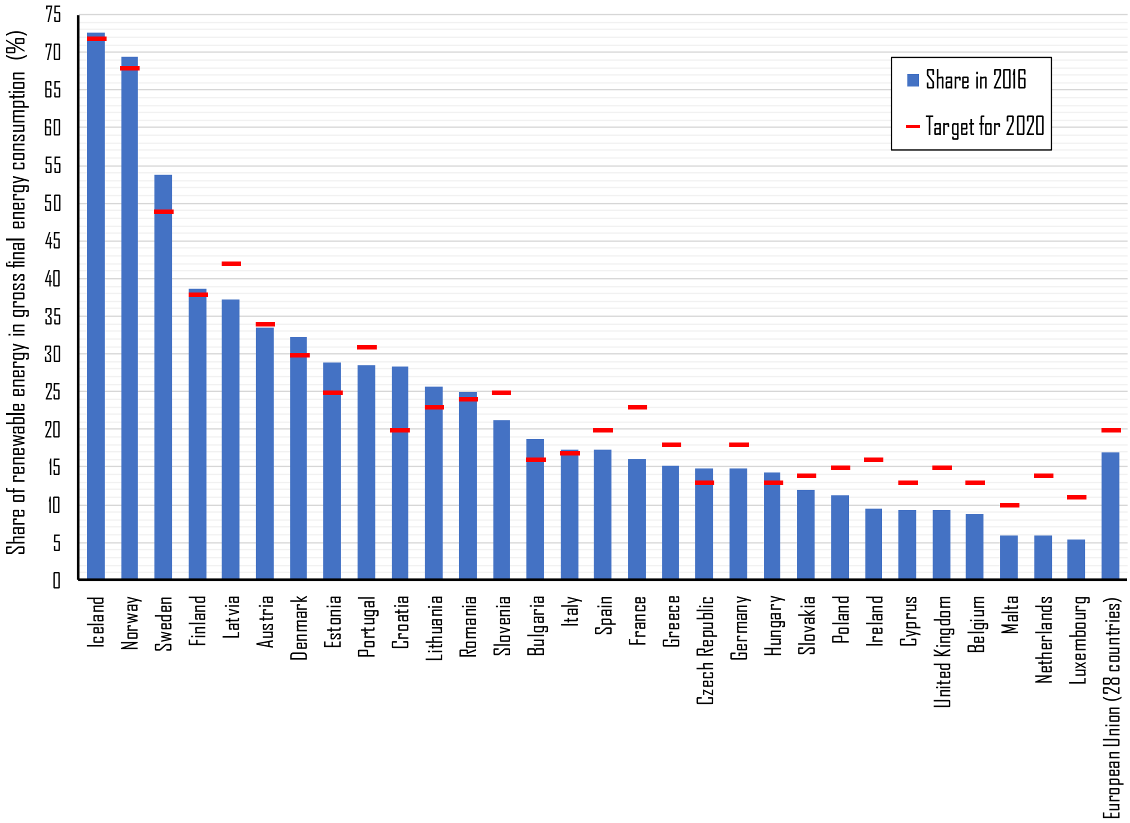

Figure 1.1. Share of renewable energy in EU member states and the targets for 2020

Although increasing sustainability is a key goal for governments and, in particular, power networks, it is also important to mention that energy sustainability is part of a more holistic energy transition which not only includes the environmental sustainability of energy systems but also takes into account the security of supply (i.e. energy security) and the accessibility to this supply in an affordable, safe and reliable manner (i.e. energy equity) [10]–[12]. This energy transition from fossil-fuel dependant systems to low-carbon grids involves managing energy security, energy equity and environmental sustainability and constitutes the Energy Trilemma [10]. Figure 1.2 presents a graphic of the three core dimensions of Energy Trilemma and their relationship.

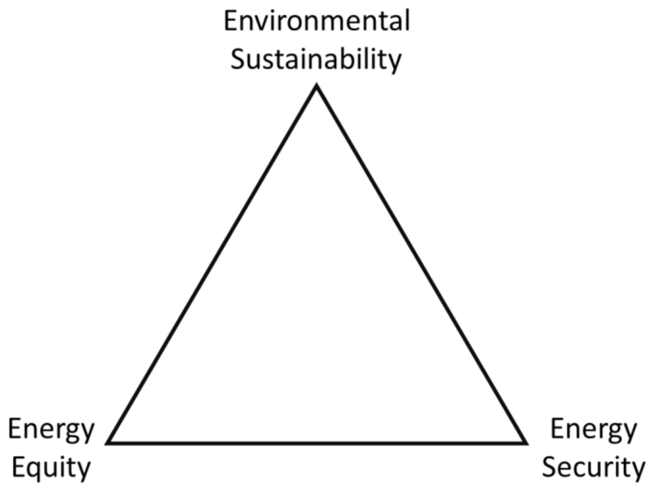

Figure 1.2. Energy Trilemma

Achieving the balance among all the Energy Trilemma dimensions is challenging and requires the joint efforts and collaboration from all the energy actors. One example to understand this complexity could be the need to increase the base load in an electrical grid. If the baseload of this network, for instance, is having difficulties to cover the minimum level of demand, one of the solutions that grid operators could consider is to increase the number of generation sources to rise the baseload levels. This approach solves the problem, at low cost, when the additional generation sources that are contracted by network operators come from fossil-fuel power plants. Nevertheless, contracting these generators increases the fossil-fuel dependency of the network and, consequently, it affects one of the Energy Trilemma dimensions: Environmental Sustainability. This example briefly illustrates part of the importance of considering the Energy Trilemma in decision-making process of energy systems and briefly exemplify the relationship and balance that is required to exist among the dimensions. Reaching a future with low-carbon grids involves, for all the stakeholders of energy systems, to be engaged in the process and to collaborate in achieving the balance within the three dimensions of the Energy Trilemma.

A key player of the transition to low-carbon grids that supports the Environmental Sustainability dimension of the Energy Trilemma are Renewable Generators (RGs). RGs produce renewable energy that comes, directly or indirectly, from natural sources or movements and that are considered to be replenished by nature [13]. Nevertheless, although RGs introduce renewable energy into the electrical network, they are a more expensive technology than fossil-fuel generators, such as Coal Plants, and impose techno-economic challenges to the network [14]–[18]. Due to the nature of the primary source, renewable power stations, such as wind farms, present intermittent outputs which involve a more rapid less predictable fluctuation of generation over time scales from minutes to hours. At low-penetration levels, this might not represent a problem for electricity networks as the variable production of energy from renewable sources can be easily absorbed within the variability of the load [16]. At high-penetration levels, however, the fluctuating output of RGs can produce greater ramp-rates (i.e. higher rates in which RGs are changing the output power), inter-hour variability (i.e. greater changes in power outputs of RGs between consecutive hours), and scheduling errors (i.e. larger gaps between forecast power generation and actual power production of RGs) which can, ultimately, lead to the distortion of the grid-balance between power generation and load demand. This not only could compromise the electricity provision to households, industries and other grid-users (i.e. affecting the energy security component of the Trilemma) but also could create or increase the cost to system operators and all grid-participants to solve balancing problems (i.e. affecting the energy equity component of the Trilemma).

Electricity System Operators (ESOs) are facing part of the challenges arising from the inclusion of RGs into the electricity network by procuring balancing services in liberalized deregulated markets, such as frequency response service or fast reserve service, in order to increase the levels of long-term and short-term energy reserves in the grid, from a mix of different sources. With this strategy, ESOs aim to ensure electricity networks being ready to react when unforeseen power excursions occur as depicted, for instance, in Figure 1.3.

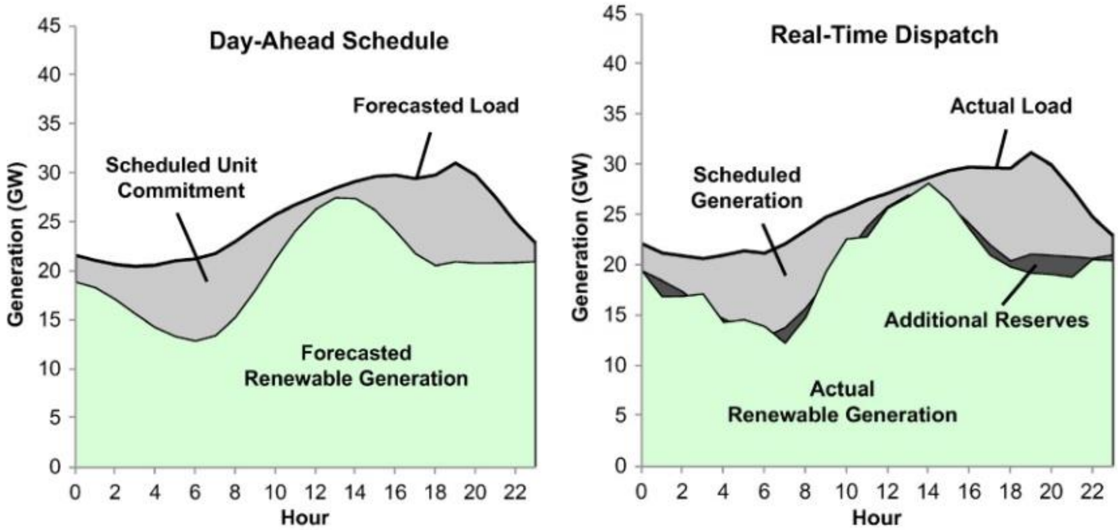

Figure 1.3. Example of the additional reserve requirements caused by the intermittency of RGs [15]

The balancing services of ESOs are not exclusively utilized to reach an equilibrium between power production and load consumption in electricity networks but they are also applied to enhance the security and quality of the energy across the entire system. For instance, ESOs could procure energy reserve services to match the actual power generation with demand while also requesting to generation providers for the provision of reactive power service in order to keep the voltage levels across the network within regulatory boundaries. At present, generation providers deliver the balancing services of electricity networks from a range of conventional sources, as in gas or coal power stations, from eco-friendly energy sources, as in Solar or Wind Farms, or alternatively by using smart grid solutions such as Energy Storage (ES) Devices or Demand Side Response (DSR). As the target of many governments is to achieve a cost-effective transition to a low-carbon future and there is a high expectation of the increase of renewable generators into the grid, ES devices, currently and most likely in the future, has arisen (and will further emerge) as a key technology of power systems with the potential to support future system integration of RGs and it will probably be extensively distributed/applied throughout the electrical network [19][20].

Alternatives to ES devices for facing future power systems are network reinforcement and DSR management [21]. Unlike network reinforcement, DSR provides flexibility to the system as grid-users reduce, increase, or shift their electricity demand in response to signals or incentives from network operators and to support the network operation (e.g. balancing services). DSR and ES devices are both technologies that can facilitate the integration of RGs, reduce extensive network reinforcements from their current situation, and support grid-users to be financially benefited from energy markets while reducing their carbon footprint. In this research, the focus was put into Energy Storage devices, but it is acknowledged the potential of DSR for the future integration of RGs and the transition of power networks into low-carbon grids.

1.2. Energy Storage Technologies

The electricity network is a complex interconnected system divided into a number of stages and composed of multiple elements and participants. Grid-connected ES devices are technologies with the unique characteristic of playing the role of two grid-elements: generators and loads. This occurs since they are capable of storing amounts of energy at one instant for their later utilization. At present, ES technologies can capture electricity in a variety of forms including gravitational potential, chemical and thermal energy. For instance, battery energy storage devices, such as Lithium-ion batteries, convert electrical energy from the electricity network into chemical potential energy during the charging process and transform it back to the original state during discharging process.

ES devices present a large number of technical and economic factors that could make them suitable for certain applications. Energy-dense ES technologies, for instance, have been largely utilized for various grid-applications, including frequency response, energy reserves and peak shaving [22]–[26]. Nevertheless, to date, there is no single ES device with characteristics that allows them to cover the majority of applications. Moreover, their widespread deployment has also been limited due to their relative high investment cost [27]. ES devices are still expensive technologies that require large capital investments to be integrated into electricity networks.

The inclusion of ES devices in electricity networks has a lot of potential to support with the decarbonization of this system and the integration of renewable generators. Although charging and discharging energy with ES devices is not necessarily a process that involve renewable energy within the grid, these technologies can also be used, for instance, together with Renewable Generators to smooth the power output of the system or to better manage their fluctuating energy production towards avoiding the spill of renewable energy. The widespread deployment of ES technologies will be achieved in electricity network when these devices are able to be entirely aligned with the Energy Trilemma. This not only involve reducing the high investment costs required for acquiring ES technologies but also enhancing the value of these devices with other techno-economic factors such as adding more revenue streams, improving operation and control, increasing the number of services provisions and enhancing their functioning performance, among others.

The scientific community is making continuous efforts to increase the value of ES for power systems. Starting from the design at planning stage, a number of studies are looking to optimize the size of ES devices, in terms of power and energy ratings, and their operation for grid applications so that investment costs can be reduced [28]–[32]. In the context of minimizing the size and investment costs of ES technologies, it is important to also understand and quantify all techno-economic factors that can create significant contributions to the future value of ES technologies and to what extent is lacking in the target of these studies.

1.3. Techno-economic Factors Influencing the Value of ES devices

The value of ES technologies could be influenced by several techno-economic factors which can increase the revenues that can be acquired by ES technologies, reduce the capital costs for acquiring ES devices or enhance the operational performance of ES technologies. These factors not only encompass internal features of ES technologies that can intrinsically affect the manufacturing costs and operational performance of ES devices but also external parameters that could influence or limit the grid-connected operation of these technologies, the policy and regulatory ground in which they are being applied, and the revenue streams from which they can obtain economic benefits. The latter refers to the income acquired by ES devices under different energy markets while the operational factors involve the control and operation strategies that allow ES technologies to participate in certain grid applications while maximizing revenues. The policy and regulatory ground refer to the rules that are required to be complied by ES technologies in order to be allowed the operation.

Based on the area in which they can impact the value of ES devices, the techno-economic factors of this work have been in grouped into four categories as follows:

- Market Interactions for ES Technologies: Energy Storage devices are capable of participating in multiple energy markets which could lead to diverse control and operation characteristics and requirements, statutory regulations, and payment structures. These factors play an important role in the value of ES technologies since they could affect, to a large extent, the income of generation providers from using these devices and the ES sizing design. The policies and regulations of certain market interactions, for instance, could represent for ES technologies to restrict their normal operation window to meet energy reserves requirements. This not only will produce drops in the profitability potential of ES technologies in specific moments but also could influence the required power and energy ratings of these devices in order to meet regulations, thus increasing the capital cost of investment of ES devices for generation providers and investors. It is acknowledged by the author, however, that considering future market prices could further help to investigate the influence of this factor for the potential value of ES devices. In this work, market prices prognostic was not taken into account since, for long-term project horizons, as in ES sizing design analysis and investments, predicting market price changes is a complex task which still will not be accurate in periods over years. Nevertheless, this improvement is considered as future work to be carried out from this thesis.

- Economic Parameters of ES Technologies: The economic parameters of ES technologies not only refer to the manufacturing prices of these devices for the power and energy components but also to the interest rates that are determined for investment projects in ES devices. The economic parameters are factors that have a direct influence in the capital costs that generation providers and investors are going to pay when purchasing an energy storage system (ESS). Reducing the power and energy component prices of ES devices, for instance, could represent for generation providers and investors either lower investment expenses on these devices or the ability to perform more actions with a larger ESS.
- Technical Characteristics of ES Technologies: These factors refer to internal technical features of ES devices and it encompasses parameters of design such as cycling lifetime, charging/discharging efficiency, daily self-discharge and operation window. These technical parameters shape the performance that ES devices are going to present when operating. Therefore, enhancing technical features of ES technologies not only would represent lower prices of

manufacturing and sales of these devices but also an improved operation when performing grid applications for generation providers.

- Technology Selection of ES Devices: Different ES technologies present a large variety of technical and economic features which could made them more or less suitable for operating under certain conditions or regulations. Energy-dense ES devices, for instance, could produce greater income for generation providers in applications with a large-energy requirement. Moreover, mixing ES devices have the potential of enhancing drawbacks in their individual features while also presenting the advantages of each technology. This makes the selection of ES devices an important factor to consider for generation providers and investors towards achieving higher revenues while meeting grid regulations for specific applications and market interactions.

Understanding and quantifying the techno-economic factors influencing the present and future value of ES technologies not only could help REG providers and investors with key information that can be used to further increase the income from these devices but also could support with the forthcoming adjustments of regulation for policy makers and regulators, and with specific areas for technology developers to focus towards improving features of ES devices.

1.4. Research Objectives

The primary aim of the research presented in this thesis is to investigate the techno-economic factors that influence the future value of grid-connected ES technologies. The main research objectives are:

- To design and develop a comprehensive framework that allows, during the planning stage of renewable generation providers and investors to perform techno-economic assessments on the design of ES devices when connected to the grid.
- To investigate, determine and quantify the factors that affects the sizing design of ES technologies and their ability to maximize revenues when applied by REG providers in multiple market applications.

- To develop methods for calculating the optimal sizing design of ES technologies while the revenues of the system are maximized for the provision of multiple market applications.

The achievement of these objectives could contribute to the widespread deployment of ES technologies by:

- Incentivising REG providers and investors to consider ES investment projects by presenting profitable cases that involve multiple market applications in which ES technologies can participate on their own or in conjunction with Renewable Generators.
- Presenting to policy makers and regulators the impacts that regulatory and non-regulatory schemes could have on REG providers, thus motivating future adjustments and improvements in policies and regulations.
- Indicating to technology developers the economic and technical characteristics of ES devices that could require a priority of enhancement towards reducing ES investment costs while increasing their operation performance.
- Motivating ES Selling Companies to expand their products range of ES devices and to include hybrid combinations as alternatives for offering to customers.

1.5. Thesis Outline

The rest of this thesis is structured as follows:

- In Chapter 2, the literature review of this research is presented. This chapter describes the grid applications in which ES technologies could add value, the energy markets that could govern the operation requirements and payment schemes for ES devices, the main types of ES devices alongside with their individual features, and the state of art of sizing design and techno-economic analysis of ES technologies. This permits to identify the current gaps in the knowledge that can be undertaken by this work.
- The functional specifications for developing a techno-economic assessment framework are described in Chapter 3. Regulatory schemes of different grid applications are, first, addressed to determine the conditions and revenue streams in which ES technologies are required to operate. Then, the design foundations for the techno-economic assessment framework are defined. This

includes system configuration in which ES technologies are implemented, the operation responsibilities of the whole system, and the specifications and assumptions required to device such a framework.

- In Chapter 4, the development of the techno-economic assessment framework is presented. This involves the formulation of framework models that allows to meet the requirements and conditions established in Chapter 3. The simulation of these models not only permits to quantify the revenues that can be achieved by REG providers when using a particular ESS but also allows to carry out sensitivity analyses to understand the factors that affect these revenues and the design of ES devices at present and future.
- Chapter 5 and Chapter 6 perform techno-economic assessments of ES devices by applying the framework models developed in Chapter 4. These assessments are focused on examining the present and future value of ES based on factors influencing potential incomes of REG providers when using ES devices. These factors include diverse market participation of ES devices, operation schemes, ES technology types, ES economic features and technical characteristics of ES devices.
- Chapter 7 presents a critical discussion of the results and findings of the present work and their broader implications. The thesis ends up in Chapter 8 with the conclusion, key findings, contributions and future work of this research.

Chapter 2. Literature Review

2.1. Introduction

With the increasing penetration of RGs into the grid, Electricity Networks could face techno-economic challenges that require the use of smart cost-efficient solutions. ES devices are key instruments that could support with this transition from conventional power systems into low-carbon grids. Although they are a flexible technology, the costs for investing in ES devices are still relatively high which call for solutions to minimize costs while maximizing the value of these technologies. This could involve the use of ES devices in different grid applications and energy markets which can add value not only to generation providers when covering multiple grid requirements but also could help to increase revenues from using these ES technologies. In this context, due to their nature and requirements, a number of applications could benefit from applying grid-connected ES devices. A review of grid-applications in which ES technologies can provide support is addressed in Section 2.2. Since the economic yield for REG providers from using ES technologies depends, to a large extent, on the energy market interactions and conditions in which these devices are applied, Section 2.3 introduces current energy markets that govern the electricity industry in Great Britain (GB). Other factors that influence the value of using ES devices are also the internal characteristics of these technologies. Section 2.4 presents the most relevant ES devices that could be utilized by REG providers to interact in multiple markets and it summarizes the individual economic and technical features of each ES device. Chapter 2 concludes reviewing and critical discussing the state of art around the design of grid-connected ES technologies and techno-economic factors influencing its value towards identifying the limitations and current gaps in knowledge.

2.2. Grid Applications for Energy Storage Technologies

ES technologies have the capability to support electricity networks with a number of grid applications. The spectrum of applications, in power systems, can cover from fast power quality to energy management requirements [33], [34]. This involves, depending on the application, timescales of response ranging from less than a second to several hours. The following subsections present a brief description of grid-scale applications that could benefit from incorporating ES devices.

2.2.1. Load Levelling

The electricity demand changes throughout the day presenting periods of low-demand and high-demand. Load levelling is a grid-application that aims to flatten the daily load demand [35]. For this reason, the strategy for ES devices is based on storing energy during low-demand periods and discharging power at high-demand periods. This will prevent or reduce the use of additional supply from peaking power plants and potential expenses in new grid-infrastructure investments [34]. In load levelling, the ES devices must be capable of dispatching energy in timescales ranging from minutes to hours as the flattening periods could last a relatively long time. Figure 2.1 shows the basic concept of load levelling where the peaks and valleys of the demand are addressed by ES devices. In this way, the power generation profile can remain as flatten as possible.

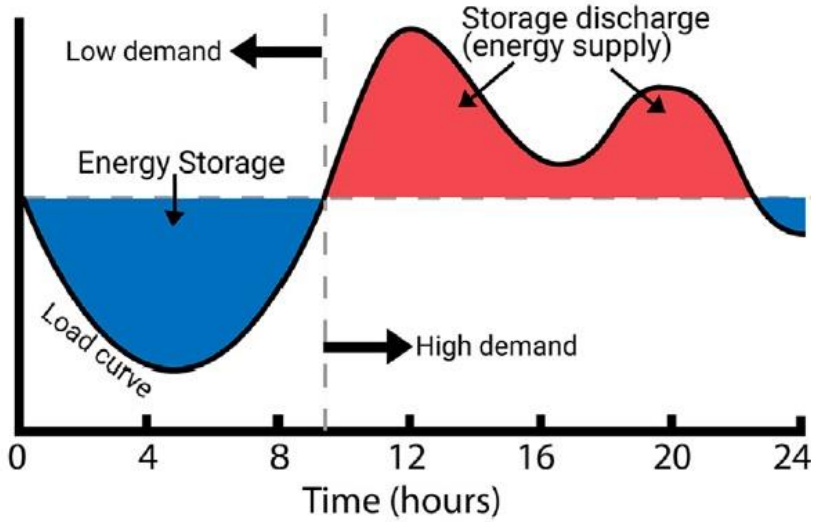

Figure 2.1. Load levelling concept using ES technologies [35]

2.2.2. Peak Shaving

In peak shaving, the objective is mainly focused on reducing the peak-demand in the electricity network [34]. Similar to load levelling, the strategy when using ES devices relies on storing energy at low-demand periods so that power discharge can be carried out during periods of high peak-demand. Although peak shaving requirements can be met through ES devices, there are also other alternatives for providing this application such as demand side response [36]. All these peak shaving solutions help to avoid installing new generation capacities and, therefore, incurring in expensive investments for stakeholders. Figure 2.2 shows, for instance, the periods in which the ES devices charge and discharge energy to address peak-demand. Unlike load levelling in Figure 2.1, here ES devices are only focused on the high peaks of demand. This represents, for the power generation of the grid, additional efforts for dealing with not completely flatten load curves.

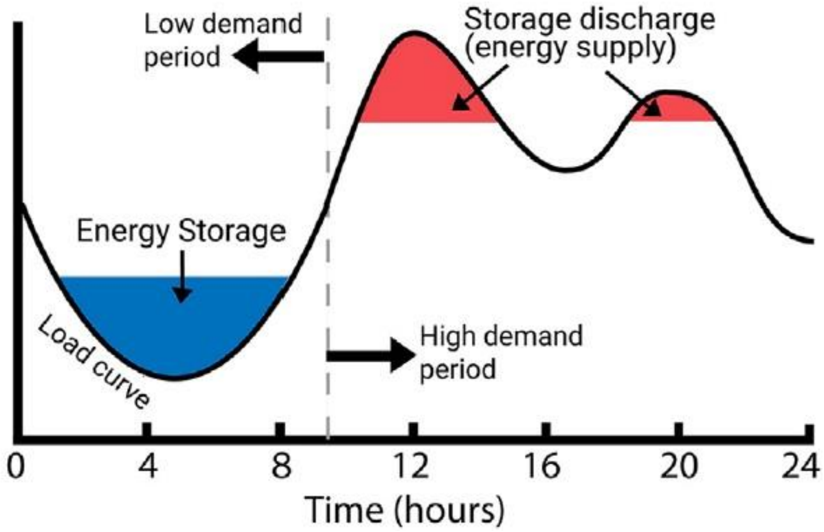

Figure 2.2. Peak shaving concept using ES technologies [35]

2.2.3. Energy Arbitrage

Energy Arbitrage is mainly focused on the economic benefits that the interested parties can obtain when performing this application. Here, although ES technologies present a similar behaviour as load levelling or peak shaving applications, they are operating based on the energy market prices rather than load demands. Energy Arbitrage, within electricity networks, refers to the trading of energy where electricity is purchased at one price and sold at a different price in order to obtain income [37]. This trade generally takes place at off-peak hours for buying low-price energy and during peak hours for selling the high-price energy back to the energy market. This application is not exclusive for ES devices as it can also be achieved by participants performing demand side response when load changes are stimulated by energy market prices. As the income in Energy Arbitrage relies on the daily variation between buying and selling prices, it makes sense that ES technologies with high round-trip efficiencies and low-prices of power and energy to be considered as candidates for this application.

Although, at present, performing Energy Arbitrage, on its own, might not be profitable for ES technologies [26], [38]–[40], there are several studies that have demonstrated not only the stand-alone potential of this application but also its benefits when operating in conjunction with other applications [37], [41]–[45]. This is of importance for REG providers, for instance, as an additional income is likely to be achieved from performing energy arbitrage if the mutual operation with other applications are well-established and allowed by grid-regulations.

2.2.4. Load Following

In load following, ES technologies must provide response to both load and electric generation deviations within a specific area of the network [46]. The advantage of ES devices for this application is that they are a flexible technology and, in most cases, present faster response than conventional rotary generators. The drawback, however, is the limited storage capacity of most of ES technologies which, for certain periods, could save less energy than required [35].

2.2.5. Integration of Renewable generation

Renewable generators might present a variable and uncertain behaviour which could lead to the formation of gaps between their actual generation and what is expected from them [35]. This becomes especially challenging as higher penetration levels of renewables are continuously been introduced into the grid. In this sense, ESSs can be utilized to support RGs with this interconnection as they have the capability to back up, stabilize, or smooth the power output of the generators [47]. For this application, according to [34], it could be beneficial for ES devices to have high-power large-energy capacity i.e. ES devices applied for the provision of services during several hours with power levels from 1 to 100MW, depending on the application.

2.2.6. Power Quality

The provision of good power quality refers to delivering energy with pure noise-free sinusoidal shapes, voltage within limits, stable power flow, high power factor, low levels of harmonic distortion, and frequency under tolerances [35], [46]. When low-quality of power is introduced into the grid, it could compromise sensitive devices connected to this electricity network. As the required type of response for enhancing power quality in power systems could range from few seconds to around one minute, ES devices could be applied as a potential technical solution when they present high-quality power output, fast-response and high cyclability [35]. Figure 2.3 shows an example where a power quality problem is caused by a 50V voltage spike but this problem is rapidly absorbed by an ES technology reaching 1/60 second total time duration of this event.

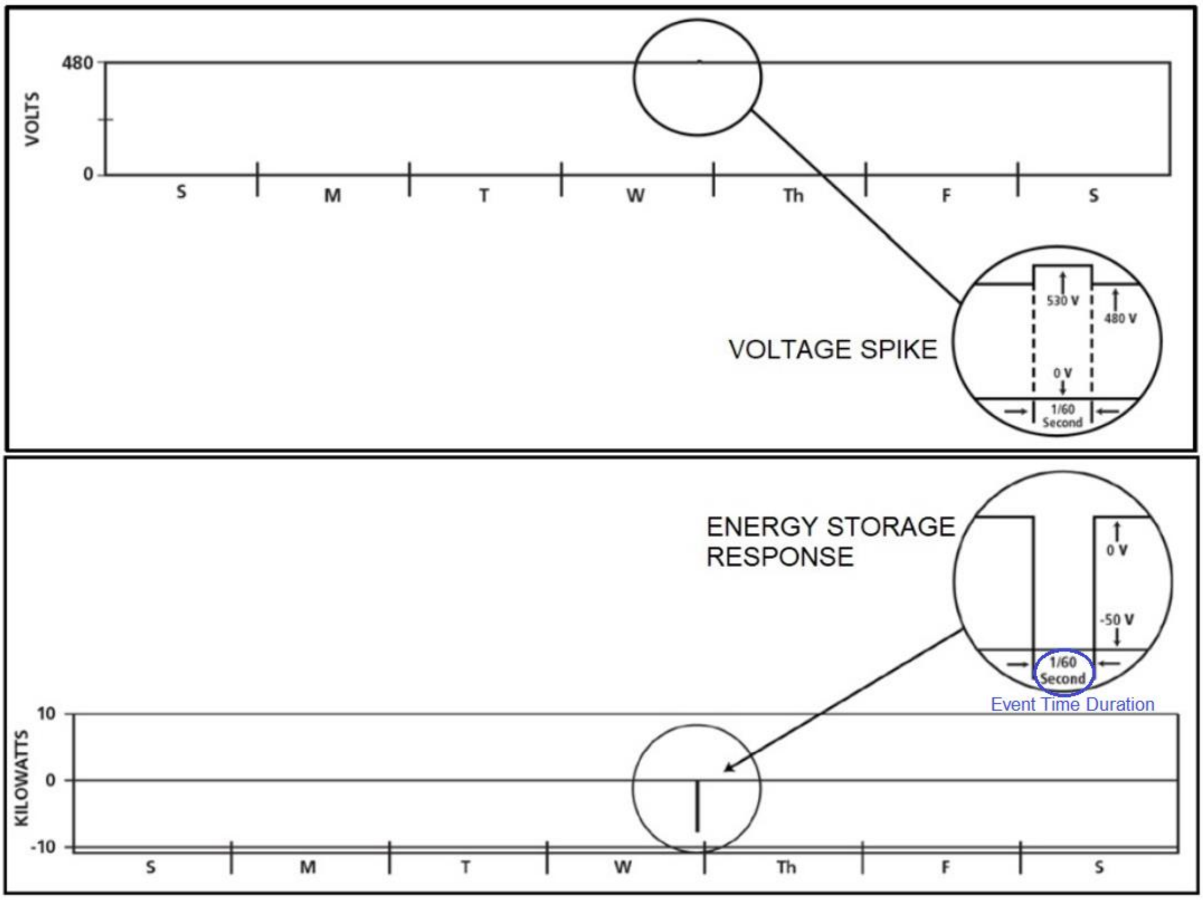

Figure 2.3. Example of power quality problem and the ES response [46]

2.2.7. Spinning Reserve

Spinning Reserve is the generation capacity that is ready to be utilized by the ESO for facing unexpected conditions [48]. For security reasons, all electricity networks must have a certain level of online reserves that can be utilized during emergencies such as generation unit failures. As these type of problems could present different timescale requirements, ES devices should maintain, for this application, a certain level of charge and be able to respond for various minutes up to few hours [47]. Alternatively, ES technologies could have the capability to provide fast-reactions to events requiring energy reserves while maintaining this response until back-up generators are ready to operate.

2.2.8. Voltage Control

In all electricity networks, the voltage must be kept within certain limits throughout the system to avoid the damage of grid-connected devices [48]. In GB, for instance, these limits are established within ±10% and ±6%, depending on the voltage level. As there exist a number of elements, connected into the grid, which present a similar behaviour as inductor and capacitor electric circuits, the management of reactive power flows is highly important for ESOs towards ensuring the voltage level at specific locations. ES devices are a promising technology for this application as they have the capability to support grid-voltage regulation by providing/absorbing real or reactive power into the system [47]. Unlike conventional methods, such as power transformer tap-changers, ES devices are able to deliver very fast-response in fine steps and can be allocated at different points of the grid (i.e. not only, for instance, in Transmission or Distribution Substations as is the case of tap changers of transformers).

2.2.9. Frequency Control

In power systems, there must always be a match between the power generated (P_{GEN}) and the demand consumption (P_{LOAD}) in order to, among other things, prevent the system frequency from facing harmful disturbances [31]. System frequency is the number of cycles per second of alternating current and, depending on the country, it must be maintained as close as possible to 60Hz (e.g. United States) or 50Hz (e.g. United Kingdom). Although the frequency stability depends on balancing load-generation, the inertial response is also an important property that plays a role in this context. The inertial response represents the release of kinetic energy (E_{KIN}) stored in the inertia of the rotating masses of grid-connected generators and it has a stabilizing effect over the grid-frequencies [49]. The system imbalance ($P_{GEN} - P_{LOAD}$), the system inertia (J), and the rate of change of the frequency ($\frac{df}{dt}$) are all related by the, so called, Swing Equation [50]. As frequency variations are relatively small compared to the nominal system frequency (f_0), the simplified swing equation can be expressed as:

$$\frac{dE_{KIN}}{dt} \approx \mathrm{J} \cdot f_0 \frac{df}{dt} \approx P_{GEN} - P_{LOAD} \tag{2.1}$$

Since the system frequency is aimed to be as stable as possible in electricity networks and generators/loads are not usually able to modify the power immediately, Equation 2.1 expresses that frequency deviations are initially determined by the system inertia. Due to this inversely proportional relationship between the rate of frequency change and inertia, electricity networks are exposed to face drastic frequency changes whenever the system inertia is low. This makes higher values of inertia desirable for power generators as they will provide more time to the grid for reacting in the event of frequency deviations. In the case of renewable generation such as solar farms and wind farms, however, these generators might present lower or negligible inertias in comparison with conventional synchronous generators [51]. Therefore, when high-penetration levels of renewable power plants are present, the electricity networks are likely to suffer significant reductions on the total inertia and, thus, they could become unstable if no solutions take place.

ES technologies are potential candidates to deliver grid-frequency support due to the ability of these devices to store power in energy reserves and the very fast-response times they present whenever required [52]. The basic operational concept for ES devices under this application is to absorb real power from the electricity network when over-frequency events arise and to discharge real power for under-frequency events. In GB, the provision of frequency response could fall into three categories depending on the reaction time as follows (See Figure 2.4):

- Primary Response: In this response, active power must be provided within 10 seconds from the beginning of an under-frequency event and must be sustained for an additional of 20 seconds [53]. Here, ES devices require a fast-response capability to deliver a response within 10 seconds. Therefore, ES technologies with high power density and low-price of power, such as supercapacitors, might become an attractive option. Additionally, due to the number of occurrences, it could also play a role for ES technologies to present large cycle lifetime for this service.
- Secondary Response: In this response, active power must be delivered within 30 seconds since the beginning of the under-frequency incident and this must endure up to 30 minutes [53]. Although fast-response capabilities are not essentially required in this category, ES technologies could also contribute with this service by presenting large-energy capacity to sustain a response for 30 minutes. This could make ES devices with high energy-density and low-price of energy, such as vanadium redox flow batteries, interesting candidates for this application. In addition, depending on the time for maintaining the reserves, it could also be valuable for ES technologies to present low self-discharge values.
- High frequency Response: The response for high frequency events is based on reducing active power within 10 seconds since the beginning of the incident and this must be maintained indefinitely [53]. For this application, ES technologies

with fast-response abilities could provide support by absorbing real power from the grid. Depending on the duration of the event, different energy capacities could be required from ES technologies.

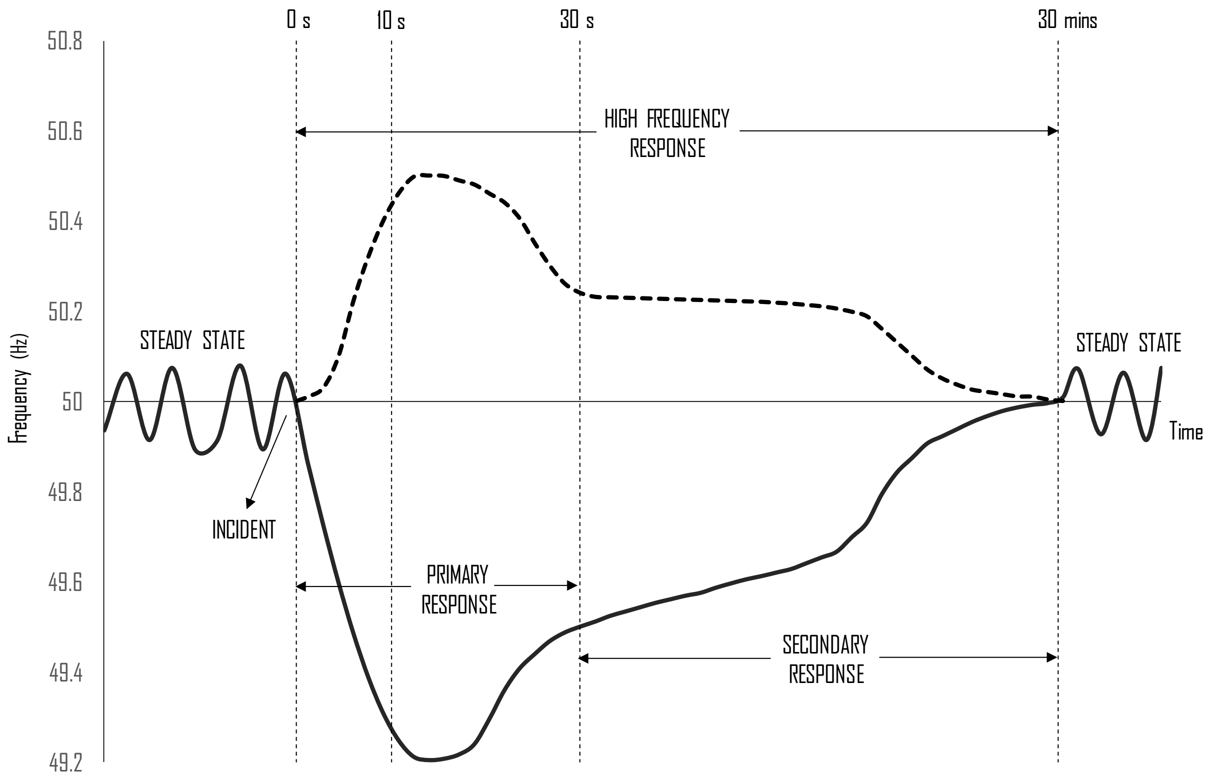

Figure 2.4. Response times and intervals for frequency support in GB

As system inertia determines the initial rate at which frequency changes after an event and since renewable generators, such as wind farms, present very low or negligible inertia, the very fast-response and flexibility characteristics of most ES devices makes these technologies an interesting alternative to stabilize the frequency of the system. Although they might present a relatively low energy capacity, there are ES devices that can actually provide support for long-term incidents while other could be utilized at first until back-up system reserves are activated.

In GB, frequency response is part of the balancing services and, depending on the service, they could be remunerated for availability (£/h), nomination (£/h), window initiation (£/window), tendered window revision (£/h) or utilization (£/MWh). The GB National Grid, in the financial year 2017/2018, has spent around £933 million for balancing services (£31 million more than 2016/2017) where 13% of these costs were solely destined to frequency response services [54]. This shows the potential that this application could represent for ES technologies in economic terms. Figure 2.5 shows that, in the financial year 2017/2018, frequency response is the balancing service with the highest economic impact for the GB National Grid in comparison with the rest of balancing services excluding balancing mechanism (BM) constrains (covering 43% of the total expenditure).

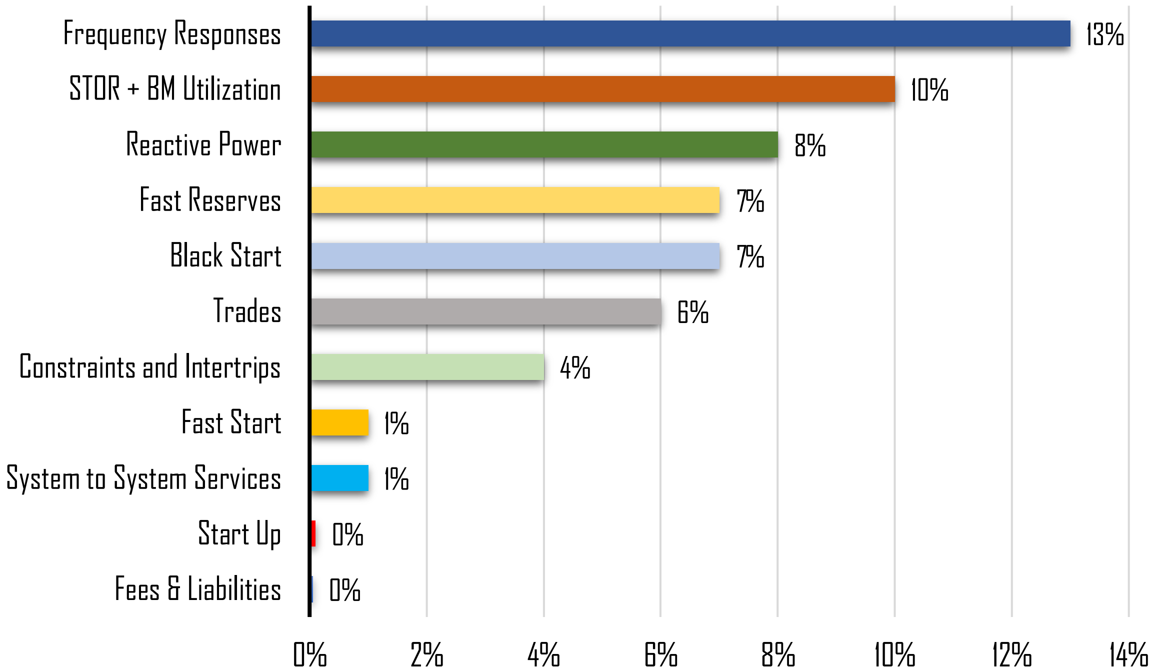

Figure 2.5. Summary of GB Balancing Services Costs in 2017/2018 (excluding BM Constraints) [54]

2.3. Energy Markets

The majority of grid interactions are procured by the system operators through energy markets. Each energy market shows specific features involving tendering processes, bilateral contracts, technical and operational requirements, and remuneration schemes. Although the present research takes into consideration the markets in GB, similar deregulated electricity markets and commitments exist in many other countries around the world and the models of this thesis are developed to be able to consider other market conditions, in particular, energy market prices (see Chapter 4). In GB, the electricity market is a complex structure designed to ensure the achievement of the Energy Trilemma and it is composed of different markets and government policies [55]. These markets can be divided into four big categories: retail market, capacity market, Wholesale Market and balancing services market. The next subsections present an overview of these markets in GB.

2.3.1. Retail Market

The electricity retail market, in GB, allows end-consumers to choose the power supplier based on the offered prices and benefits, thus promoting competition and innovation in the electrical products and services [56]. In this market, electrical companies obtain energy from the Wholesale Market and sell it to their final customers, such as homes and business, under different payment schemes. Since these retail companies could offer to the clients a range of variable tariffs or fix-term tariffs, the payments and income are defined by the individual power consumption of each customer and the tariffs in which they are on. For instance, according to [57], 91% of customers that switched their retail company, in 2017, were concerned about the economic savings. At present, as final consumers in the retail market are also able to produce their own power (e.g. using Solar Panels), the deployment and utilization of ES devices, such as Electric Vehicle (EV) batteries, could be of high importance for them in order to reduce and manage their power consumption from the grid. This could be achieved, for instance, by absorbing with ES devices the surplus of power from their embedded generators for later utilization or by performing energy arbitrage with the grid.

2.3.2. Capacity Market

The capacity market, introduced in GB by the Electricity Market Reform (EMR), was developed anticipating the future increase of intermittent renewable generators and inflexible nuclear generation and its main objectives are to enhance the reliability of supply, minimize the possibility of blackouts and incentive new capacity investments into the electricity network [58]. Here, market participants are determined through capacity auctions and their payments are guaranteed through Capacity Agreements. The revenue stream of the capacity market is considered to be steady and predictable and it could also be complemented through income from other energy markets such as the Wholesale Market and the balancing services market [59], [60]. Failure to deliver electricity obligations, however, will incur in penalties for the participants which are set to be 1/24th of the participant's annual capacity payment.

Due to the ability of storing energy, ES devices are potential technologies that could also participate in this market. However, since the de-rating factors of ES devices (i.e.

ES technologies maintaining energy stored to ensure security of supply contribution of duration-limited storage at times of system stress), used by the ESO to determine the amount of reliable capacity of each participant, are very strict in the capacity market regulations for short-duration storage, large-energy capacity ES devices could be considered suitable candidates for contributing in this market [60]. Table 2.1 presents the calculated de-rating factors of UK National Grid in December 2017 for limited duration storage which was developed based on analysis of its availability during stress events.

Final De-Ratings Per Duration in Hours	"2018/19"	"2021/22"
Storage Duration: 0.5h	21.34%	17.89%
Storage Duration: 1h	40.41%	36.44%
Storage Duration: 1.5h	55.95%	52.28%
Storage Duration: 2h	68.05%	64.79%
Storage Duration: 2.5h	77.27%	75.47%
Storage Duration: 3h	82.63%	82.03%
Storage Duration: 3.5h	85.74%	85.74%
Storage Duration: 4h +	96.11%	96.11%

Table 2.1. "CM De-Rating Factors Proposed for Duration-Limited Storage Class in the 2018/19 T-1 and the 2021/22 T-4 Auctions" [61]

2.3.3. Wholesale Market

The GB Wholesale Market is where the power exchange occurs to balance generation with consumption. It is structured by generation providers, investors and Traders, ESO, market regulators, and consumers [62]. Generation providers refer to power stations that produce or import energy and inject it into the market. Market Consumers are the companies, such as large-scale industries or retail companies, that buy the energy from the Wholesale Market. Traders and investors, such as banks or trading houses, are businesses that are mainly focused on trading. The role of ESO, in GB, is taken by the National Grid while the Government Regulator for all electricity markets is assumed by the Office of Gas and Electricity Markets (OFGEM).

In the Wholesale Market, there are different instances at which electricity trading can take place. In long-term trades between energy buyers and sellers, the contracted prices are not necessarily in accordance with the, so called, day-ahead market prices and they are usually private between companies [63]. The day-ahead market is where the match between generation and demand is mostly guaranteed based on the offers from the generation providers and the day-ahead demand estimations and bids [64]. Unlike the capacity market, the prices in the Wholesale Market are not fixed and they could differ in a half-hour basis, known as Settlement Periods. The price fluctuations for each Settlement Period are mainly driven by the costs of coal, costs of carbon and closely related to the costs of gas since, at present, fossil-fuel dependent power stations are still the main marginal source of generation in GB [63]. When unexpected changes in generation or demand arise from the day-ahead forecasts, the intraday market is the one responsible of facing the imbalances by allowing electricity trading one hour beforehand. Although the intraday market is close to real time, there still exist balancing issues for shorter-periods. For these instants, system imbalances and power quality problems are managed by the GB National Grid through balancing mechanisms and services [64]. It is noteworthy that Wholesale Market participants are obligated to pay cash-out prices (i.e. imbalance prices) when failing to comply with the contracted delivery. These cash-out prices are based on the costs incurred by the National Grid to balance the system at that time [62].

ES devices are technologies that can be applied to support balancing issues in the Wholesale Market while increasing the efficiency and reliability of the system [39], [42]. They can individually provide direct services (e.g. load following or peak shaving), be used together with other solutions (e.g. power peaking plants or grid reinforcements) or contribute indirectly by supporting market participants (e.g. renewable output power smoothing). As Wholesale Market prices are clear indicators of the balancing condition of the electricity network, wholesale market interactions with ES devices, for instance, could be considered as an option for generation providers to support and reduce system imbalances while also making income. It is important to mention, however, that, in the UK, generation providers producing renewable energy are not entirely part of the wholesale market scheme since they are paid based on contracts for difference (CfD). CfD is a policy developed by the UK Government to incentivise low-carbon electricity generation. In this scheme, REG providers are paid a flat (indexed) rate for the electricity they produce over a 15-year period [65]. Although CfDs are the norm in the UK for renewable generators, it is important to mention that, in this research, REG providers are considered to be interact in the wholesale market as other traditional generation mechanisms for the following reasons:

- To develop a methodology that can be applied to any energy market from around the world which might not have this incentive scheme.
- Since the results from applying CfD policy does not change by a significant extent the results that can be obtained by applying wholesale market prices (as demonstrated in Chapter 5).
- To simulate future scenarios in which CfDs are no longer part of the regulation for REG providers.

In this context, there is a large number of studies addressing wholesale market interactions with ES technologies where, in some cases, revenues were achieved depending on the system conditions, strategies, price spread, market regulations, time horizons, and ES technology characteristics [37]–[42], [66]–[69].

2.3.4. Balancing Services Market

The aim of the Balancing Services, also known as Ancillary Services, is to guarantee the continuous balance, stability, security, and quality of the power across the whole network through numerous applications and strategies. The balancing market permits ESOs not only to match demand with supply in a minute by minute basis but also to recover part of the costs incurred by this balancing activity [54]. In GB, the balancing services are grouped into six categories:

- Frequency Response: The main purpose of this service is to maintain the system frequency within statutory limits (i.e. 50Hz ±1%) and operational limits (i.e. 50Hz ±0.4%) [53]. The strategy to achieve this control is based on three classes: Mandatory Frequency Response (MFR), Firm Frequency Response (FFR), and Enhanced Frequency Response (EFR). The latter is the dynamic power response delivered by generation providers and Market Participants to enhance the management of system frequency in a second by second basis. For this service, the participants must be able to reach 100% power response within one second of the occurrence of frequency deviation events. In the case of MFR and FFR, depending on the type of service, participants could provide primary frequency response, secondary frequency response, high-frequency response or a combination of them. Section 3.2 provides a further description of both services, including payment schemes, since they are an integral part of this research.

- Reserves: Electricity network reserves are additional power sources that can be accessed by the ESO to face unexpected changes in demand and supply. The provision of this balancing service can occur as power generation increments or demand reductions and, depending on the specific conditions such as response times and energy reserve levels, it can be subdivided in four services: Fast Reserves, Short Term Operating Reserves (STOR), Demand Turn Up, Super SEL (Stable Export Limit), and BM start up [70]. Except for the latter, the participants of these services can be paid based on availability fees (£/hour), nomination fees (£/hour), or actual utilisation payments (£/MWh). In the case of BM start up service, there are only two payment schemes: BM start up payment (£/h) and hot stand-by payment (£/h).
- System Security: In this service, the ESO buys or sells electricity from balancing mechanisms, by trading energy or through contracts [70]. These operations include intertrips services for facing system fault events, system-operator to system-operator services for trading energy with overseas connections, black start services for helping the network to recover from total or partial shutdowns, and constraint management services for dealing with congested networks.
- Trading: In advance of balancing mechanisms, the ESO trades power exchange contracts, negotiate bilateral contracts (forward trading), or creates energy balancing contracts to achieve forecast energy requirements [70].
- Reactive power: As voltage could be controlled through the flow management of reactive power, the ESO requires strategies to inject or absorb reactive power to/from the grid in order to maintain a stable voltage within the whole electricity network. In this context, the Obligatory Reactive Power Service (ORPS) and the Enhanced Reactive Power Service (ERPS) are both balancing techniques in which the ESO is able to request to generation providers and other participants to inject or consume reactive power towards maintaining the grid voltage levels within limits [70]. In the ORPS, depending on the power production capacity, generation providers might be obligated to participate in this reactive power scheme as determined by the GB Grid Code. The reactive power from these participants could occur as an actual reactive power response or in the form of power reserves. In the case of ERPS, it is a non-mandatory scheme which allow generation providers and other applicants, that are not part of ORPS scheme,

to also contribute with the provision of reactive power while receiving economic benefits [70].

- Demand Side Response (DSR): In DSR service, the users modify their energy consumption as response to grid requirements determined by the ESO. During peak times, for instance, the participants can help flattening the demand curve by reducing or shifting their energy utilization. This service is useful for users to reduce energy costs while helping with the environment.

2.4. Types of Energy Storage Devices

Energy storage devices refer to technologies that are capable of charging, storing and discharging energy. In electricity networks, grid-connected ES devices can provide greater flexibility and control than other technologies as they can absorb power directly from the grid or from other elements, such as embedded generators, and discharge it back to the system at different times when required or beneficial. Due to the diverse properties and characteristics, certain ES technologies could be considered to be more suitable for some applications while not being adequate for other applications [64]. This makes the selection of ES devices an important process to carry out when analysing the feasibility of using ES technologies for specific applications. The characteristics of these devices could include different power ratings, energy capacities, reaction times, round-trip efficiencies, self-discharge rates, among others. As the individual features of different ES technologies have been largely reviewed and examined by numerous studies, the present work has summarized and curated the main properties of these devices in Table 2.2. These characteristics are of great importance when sizing ES technologies as they not only include technical parameters of ES devices but also their economic features, such as prices for the power and energy component of a particular ES technology.

Technology	Cost of Energy* ($/kWh)	Cost of Power* ($/kW)	Energy Density (Wh/l)	Power Density (W/l)	Round Trip Efficiency (%)	Self-Discharge (% per day)	Response Time (ms)	Cycle Lifetime (100% DoD)	Lifetime (years)	Maturity ***
VRFB	150-1000 [71] 280-290 [72]	600 [73]	Around 50 [74]	0.15 W/cm^2 [74]	70-85 [75], [76]	0.1-0.4 [77]	Few [78]	Over 10,000 [74]	10-20 [73]	Demonstration [73]
Supercapacitor (SC)	6800 [48]	100-300 [79]	1-30 Wh/kg [74]	100 [74]	52-96 [80]	5-20 [48], [77]	Under 10 [77]	500,000 [81]	15 [77]	Demonstration [25]
Lithium-ion	250-500 [74], [82]	159-212 [77]	200-550 [74], [82]	1,000-4,000 [74]	Over 93 [74]	0.1-0.3 [77]	20 [78]	1,000-10,000 [82]	5-15 [74]	Demonstration [73]
Lead-Acid	50-265 [77], [83]	159-212 [77]	30-100 [77], [83]	10-500 [77]	63-90 [74]	0.13-0.6 [74]	3-5 [77]	1,000-1,800 [48], [46]	5-15 [48]	Mature [73]
Sodium-Sulphur	350-742 [77], [84]	159-350 [77], [85]	100-250 Wh/kg [78]	260 W/kg [78]	75 [84], [85]	Around 10 [77]	3-5 [77]	4,500 [46], [84]	15 [46], [84]	Commercial [73]
Sodium–Nickel Chloride Batteries	650 [76]	3,500 [76]	95-120 Wh/kg [76]	150 W/kg [82]	85-90 [78]	Around 15 [82]	20 [78]	3,000 (80% DoD) [78]	-	Commercial [86]

Nickel-Cadmium	400-2,400 [83]	500-1,500 [82]	15-75 Wh/kg [82], [83]	50-1,000 W/kg [83]	60-70 [78]	0.2-0.6 [82]	-	Under 3,500 [48][78]	10-20 [82], [83]	Commercial [25]
PHS	5-75 [77], [85]	500-2,000 [73]	0.25-1.5 [77]	0.5-1.5 [82]	75-82 [77], [75]	0.005-0.02 [77]	2-10 minutes [73]	Over 13,000 [84]	30-50 [77], [75]	Mature [86]
CAES	3-80 [77], [75]	500-1,750 [75]	3-6 [82]	0.5-2 [82]	40-70 [87], [88]	0.5-1 [77]	3-12 minutes [77], [83]	Over 10,000 [75]	20-30 [75]	Mature [25]
TES**	3-100 or more [74], [82]	200-300 [82]	80-500 [82]	-	30-72 [74], [82]	0.05-1 [82]	2.5 minutes [74]	-	10-40 [82]	Mature** [73]
FES	1,000-5,000 [73], [82]	250-350 [82]	20-200 [77], [82]	1,000-2,000 [82]	90-95 [82],[85]	100 [77], [82]	4 [84]	Over 100,000 [78], [73]	15-20 [82], [84]	Mature [73]
LAES	-	1,000-2,000 [86]	97 [86]	-	50-70 [86]	-	-	Over 100,000 [86]	Over 20 [86]	Demonstration [86]

* Conversion Rate: £1 = $1.25 and €1 = $1.06
** Depending on the specific thermal technology.
*** Levels of Maturity from higher to lower: Mature, Commercial, Demonstration

Table 2.2. Specific Characteristics of Energy Storage Technologies

In order to choose potential candidates for particular applications, the authors in [89] have introduced a comparison among different ES technologies based on the output power and discharge time of these devices. This is expressed in Figure 2.6 where ES devices could fall into three categories of application: Uninterruptible Power Systems (UPS) and Power Quality, Transmission and Distribution (T&D) Support and Load Shifting, and Bulk Power Management. For instance, here, high-power SC could be considered potential candidate for power quality applications and for T&D support, such as primary response and high frequency response, while Pumped-Hydro could be a suitable device for bulk power management, such as long-term system reserves.

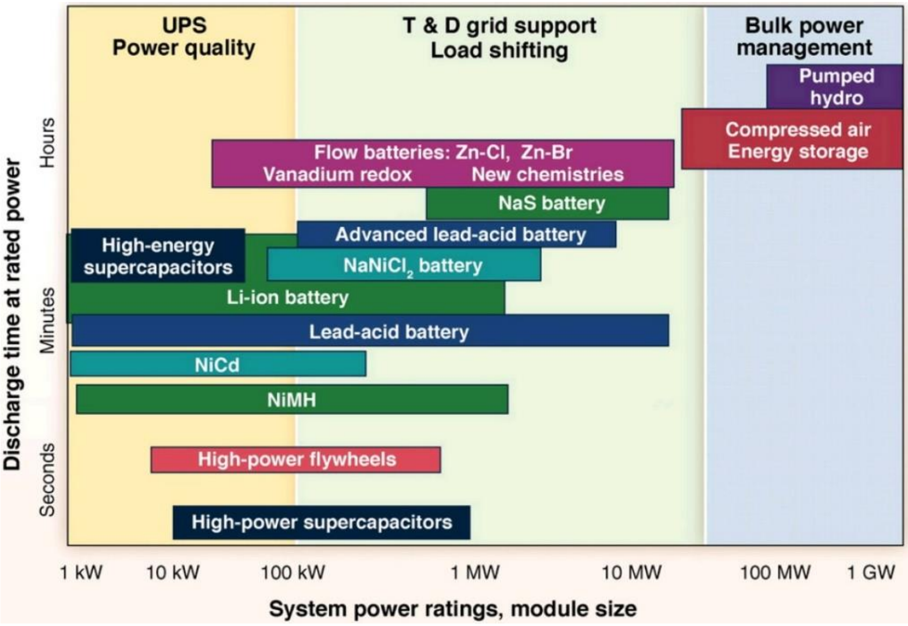

Figure 2.6. Power rating and discharge duration at rated power [89]

In the present work, the research utilises the ES characteristics values from Table 2.2 applying values around the average of the limits for each feature range (more details are described in Section 3.4) and has focused on electrochemical storage technologies (i.e. battery devices) and Supercapacitor storage technologies since these devices have also potential, in the future, of improving technical characteristics, have higher maturity, decreasing their commercial price and they are flexible with very short response times when required. The study includes all ES technologies presented in Table 2.2 with the exception of Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES), Thermal Energy Storage (TES), Flywheel Energy Storage (FES), and Liquid Air Energy Storage (LAES). The former three technologies (i.e. PHS, CAES, TES and FES) were not considered in this study since they are already at a high maturity level while still presenting higher responsive times than electrochemical storage devices responsive times. This limits their flexibility of response, thus, affecting the future value analysis approach that is considered in the present study based on ES frequency responses and ES multiple market interactions. In the case of LAES, the lack of access to current information restricted its inclusion in the present study, but it is acknowledged by the author the potential of this technology for supporting grid-applications and multiple market interactions in the future.

2.5. Sizing of Energy Storage Technologies

The main problem for the widespread deployment of ES devices in electricity networks is the relative high costs of these devices in comparison with other conventional technologies [27]. ES devices are still expensive technologies that require a large capital investment to be integrated into the grid. This has led to a large number of studies around the sizing of ES technologies which not only helps to design ES systems for specific requirements but also to reduce the potential investment costs for these devices. The sizing design of ES devices can be performed by generation providers, investors or any interested party during the planning stage of an investment project and it consists on determining the power and energy ratings of a particular ES device or multiple ES technologies for covering specific applications [90]. This ES sizing comes along with the capital cost of investment required for acquiring such a design and, depending on the study, with the potential revenues that can be acquired for performing those services with this system.

Extensive research has been conducted on sizing ES technologies when applied for supporting the integration of renewable generators into electricity networks [90]-[99] and for the provision of different grid-applications [99]-[140], such as frequency support or voltage control. For achieving an optimal ES design, these works have used a large variety of strategies and techniques, including Discrete Fourier Transform (DFT) and other frequency-domain methods, forecasting techniques, deterministic algorithms, heuristic methods, among many others. Although they have achieved the ES sizing objective while meeting application requirements, a large number of these studies left out the calculation of potential incomes that ES technologies can obtain when providing support. In [91], for instance, the authors proposed a method for sizing ES devices when applied for mitigating the forecasting error of Wind Farms based on DFT and the Discrete Wavelet Transform (DWT). In this work, although the sizing design of ES devices was accomplished by decomposing the wind forecast error into different time-varying periodic components, the potential income of the REG provider from this improvement were not explicitly described. There also exist, however, studies in which the economic benefits of using ES technologies are established from different revenue streams. In [92], for instance, the authors considered a more economical approach for designing an ESS. Here, ES technologies were used to support Wind Generators with the provision of primary frequency response and high frequency response while also taking into account not only the income from delivering frequency service but also the income achieved from increasing the power production of the system generators. The authors in [93], instead, exploit the use of liquid air energy storage (LAES) technologies by expanding the number of grid applications to reserve services and energy arbitrage. Table 2.3 summarized the gaps in science that were found during literature review that requires to be addressed.

KEY COVERED AREAS	**STUDIES PERFORMED**										
	[91], [94], [95], [96]	[97], [98], [99], [100], [101], [102]	[103], [104], [105]	[106], [107], [108], [109]	[110], [111]	[112], [113], [114], [115], [116], [117], [118], [119], [120]	[121], [122], [123]	[124], [125], [126], [127], [128], [129], [130], [131], [132], [133]	[134], [135]	[92], [136]	[93], [137], [138]
Sizing ES devices	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Hybridization of ES	✓			✓	✓						
ES to integrate RGs in electricity network	✓				✓	✓	✓		✓	✓	
ES Market Participation		✓			✓		✓		✓	✓	✓
ES interacting in Multiple Markets									✓		✓
ES Revenue Streams		✓			✓		✓		✓	✓	✓
Technical ES Features	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ES Selection			✓						✓		
Regulatory Schemes					✓					✓	✓

Table 2.3 Key areas covered by ES researches

As presented in Table 2.3, the research around the design of ES devices present significant findings in terms of sizing methodologies when these technologies are applied for specific applications in conjunction with RG or on its own. Although this is clearly an essential area to focus which can contribute to redue the investment costs of ES devices while improving the operation of the system, there are also other aspects that must be considered and investigated. Most of the literature, as shown in Table 2.1, is exclusively participating in a single market interaction with ES devices even though these technologies are flexible and can be utilized for multiple market interactions. Moreover, a number of works are only limited in developing methods and techniques to design ES systems without taking into account potential revenue routes and ESO regulations in which these devices participate when grid-connected and that are able produce incomes. There are also authors that construct their study around one specific technology which restrict the potential for all interested parties of applying alternative options for the same application scheme.

An important consideration that is lacking in most of studies is carrying out techno-economic analysis when sizing ES technologies involving not only technical features of ES devices but also ES economic features and, as mentioned above, potential revenue streams, technology selection, and multiple market interactions. Studying the current and future value of ES technologies requires to take into consideration all techno-economic factors within research methodologies, simulations, assessments and analysis. In this context, the vast majority of studies shown in Table 2.3 excluded performing sensitivity analysis of the different ES techno-economic factors which can play a role when assessing a comprehensive ES value. Applying sensitivity analysis to the technical and economic factors of ES is valuable to study the effects of addressing and enhancing different factors around ES technologies which could lead to important findings for many interested parties.

As mentioned above, a large number of studies does not integrate ES economic benefits from market participation and multiple market interactions, does not address technology selection by applying and comparing diverse ES devices, does not consider regulatory schemes although grid-connected ES devices must also follow regulations, and the potential of hybridizing an ES system is not taken into account in many studies. Moreover, all these techno-economic factors, analysed in conjunction under the same conditions, could play an essential role in examining the present and, most importantly, the future value of ES technologies. These isolated gaps and in combination are acknowledged and addressed by the present work to investigate the future value of grid-connected ES technologies.

2.6. Discussion and Conclusion

Energy storage devices are technologies that could support the electricity industry to face the challenges arising from the transition of electricity networks into low-carbon grids. In this chapter, a plethora of grid-applications and services, in which ES devices can be applied, were examined. Each application could be addressed by different Grid Members, such as generation providers, to assist the system with specific challenges, including power quality, spinning reserves or peak shaving, and they all present their own operational features. In GB, for instance, the support from frequency response turned out to be one of the highest expenses for the National Grid during 2017/2018.

Since ES devices are still expensive technologies, it is important to understand the revenue routes in which the benefits from these devices could be potentially exploited when participating in energy markets. Thus, the present literature also reviewed the Energy Markets, in GB, where ES devices could participate and receive economic benefits for service provision. The literature presented ES technologies with a large number of technical and economic strengths and important drawbacks. At present, there is no single ES solution able to cover all the features required for grid-applications and multiple market interactions at low cost. This not only makes the sizing design of ES devices an essential step when investing in these technologies but also raises questions about the potential of hybridizing ESSs with diverse types of devices in terms of income and applications coverage.

The biggest barrier for the widespread implementation of ES technologies is related to the high cost of investment of these devices. Reviewing the state of art regarding the design of ES technologies was also an essential part for the present work. Although important improvements have been achieved when sizing ES technologies during the planning stage of ES investment projects, the literature review showed significant gaps and limitations which are summarized below:

- Revenue Streams and Market Participation:

  The majority of studies presented methodologies for sizing ES technologies for specific grid-applications leaving out potential revenues that ES devices could obtain from market participation. These works rather focus exclusively on the ES design from a technical point of view and mainly considering costs of design. Although this is clearly important for generation providers and other interested parties when planning the acquisition of ES technologies, the lack of economic analyses has also limited these studies from evaluating potential incomes for ES devices that could help enhancing their value for projects and investments, thus compromising ES proliferation. The inclusion of multiple revenue streams for ES devices that comes from participating in an energy market (e.g. Frequency Market) could be a significant factor worth studying and likely to increase the current and, specially, the future value of ES devices for the Electricity Industry.

- Multiple Market Interactions:
  A large number of studies around sizing design of ES technologies that takes into account grid-applications and energy market participation are focused in applying ES to perform or support services using single market interactions. Although this contributes to increase the value of ES devices for diverse grid members, it also restricts the flexibility that ES devices have, for instance, in performing interactions within multiple markets. The present and future value of ES technology can be further increased if these devices are able to exploit their flexibility to reach higher incomes from interacting and benefiting from multiple markets. Taking into account that purchasing ES technologies is an expensive investment, it could be desirable for investors, generation providers and other interested parties to expand and maximize the utilization of these devices. Research is still required for using ES devices to deliver grid-services while participating in multiple market interactions.
- Selection of ES technologies:
  In the majority of studies, the sizing design of ES technologies is addressed for a specific ES device that was chosen from the beginning or that is not compared with alternative ES solutions. A number of these works developed methodologies and analysis around only one technology, helping to increase the potential value of that particular ES device. While this is important when grid members are interested in a specific ES technology, there might also exists other ES technologies that might present greater benefits for the same tasks. The literature showed a range of ES devices with a large number of

features which show diverse strengths and weaknesses depending on the use within the power network. The current state of the art for designing ES systems and the future value of ES devices could benefit from developing technology-independent methods for sizing ES devices so that technology selection analyses can be made to evaluate ES technologies that could better meet system requirements in terms of investment costs, service provision, market participation and returns. In this context, technology selection could potentially benefit from also including cases with hybrid ES combination that can be used to address and expand market interactions while meeting requirements.

- Regulatory Schemes of ES Grid-Applications
  Most of the methods for sizing ES devices have been developed for assigned applications under specific grid requirements. However, there are significant gaps around the design and analysis of using ES technologies under different regulatory schemes. The regulatory scheme in which ES is participating not only determines the operational responsibilities of the ES system but also the potential revenues that can be achieved from using such as system. It is likely for generation providers and other interested parties to achieve greater incomes from specific policies than in other schemes. Studying the design and use of ES technologies under the most profitable circumstances will help to promote the current and future value of these devices to grid members, thus boosting the widespread deployment of ES technologies within the Electricity Industry.
- Economic and Technical Features of ES technologies:
  Besides achieving the design of ES technologies, the majority of these works neglect the potential impacts and enhancements that could be produced by the economical characteristics of these devices. Taking into account the internal factors of ES devices could help technology developers to strategically address the efforts to enhance these devices, thus increasing their potential future value within the Electrical Industry.

The current and future value of ES technologies is not only influenced by the intrinsic technical features of these devices, which clearly play a key role in their performance during operation and in their lifetime duration, but also by other techno-economic factors that were described as gaps in the literature review above. The future value of ES technologies could potentially be enhanced if studies and developments of these devices are more comprehensive by also addressing economic factors, markets participation and interactions, revenue streams, and regulatory schemes which all are part of the normal operation of grid-connected ES systems. In brief, these factors have the potential to reduce ES sizing costs, increase ES utilization during operation, increase profitability, and improve technical intrinsic characteristics of ES devices. Filling these research gaps, as discussed during this section, could also promote different electricity industry actors to further take into account the benefits of applying ES technologies while also contributing to their widespread deployment. It is important to mention that taking into consideration techno-economic factors of ES devices involves not only to describe these factors but also to investigate the future effects in the ES value when improvements and developments are achieved for each factor. This aspect involves putting into futuristic scenarios the ES devices and it is considered as a key element in this study. The present research aims to address the research limitations in the knowledge by designing, developing and implementing a techno-economic assessment framework which allows generation providers, investors, technology developers, among others, to achieve a comprehensive view of ES technologies by understanding and quantifying the factors influencing the present and future value of ES devices.

Chapter 3. Techno-Economic Assessment Framework Design

3.1. Introduction

The main aim of this work is to investigate the techno-economic factors influencing the future value of grid-connected ES technologies. For the achievement of this objective, this research designs, develops and implements a framework that allows to carry out assessments on ES technologies from the planning stage. This framework could be composed of various models in order to address knowledge gaps determined in Chapter 2: sizing and examining ES devices when applied under different operational and regulatory schemes for multiple market applications and including in the analysis diverse types of ES technologies and ES combinations.

Chapter 3 presents the foundations of the techno-economic assessment framework of this research. This framework is composed of models in which ES technologies are applied by REG providers for the interaction in multiple market: Frequency Market and Wholesale Market. These models are designed to be applied during the planning stage of Investment Projects of ES devices and have the capabilities to find maximum income for REG providers and the optimal sizing design of ES technologies for achieving this income. To understand the context and requirements in which the framework models are based, this chapter introduces, first, the required regulations and characteristics to participate in different frequency service schemes: MFR and FFR. Following this, the system configuration, system operation, specifications and assumptions are presented as part of functional specifications of the techno-economic assessment framework. The chapter concludes describing the inputs required by these models and the outputs produced after running the simulations.

3.2. Mandatory and Non-mandatory Frequency Response

In GB, all Generation Stations, including REG providers, are subject to the compliance of the GB Grid Code as a condition of connection under the Connection and Use of System Code (CUSC) at CC 6.3.7 [139]. Here, the Mandatory Frequency Response (MFR) service is presented as a compulsory requirement for certain type of generators, depending on the size, location and contractual agreement, that aims to be connected to the electricity network and it involves the automatic change of their output power and energy reserve capabilities as response to specific detrimental frequency changes [53], [140]. Table 3.1 presents the classification of generation providers in GB based on their Power Capacity and System Operator assigned by their location.

Size	National Grid	Scottish Power	Scottish Hydro Electricity Transmission
Small	< 50 MW	< 30 MW	< 10 MW
Medium	≥ 50 MW and < 100 MW	–	–
Large	≥ 100 MW	≥ 30 MW	≥ 10 MW

Table 3.1. Generators Size Definition for the provision of MFR in GB

For participants under the GB National Grid, the regulations dictate that grid-connected large-scale power stations are all obligated to deliver frequency services which could include primary frequency response, secondary frequency response, high frequency response or a combination of them [53], [140]. In case of medium-scale generators, they might also be required to comply with MFR services depending on their individual contractual agreements. On the other hand, small-scale power stations are not part of this frequency service. In the present research, it has been considered, as later explained in Section 5.2, a 50MW wind generation provider and a 50MW solar generation provider since this represents, under UK regulations, the minimum generation level in which generation providers might be required to participate in the MFR services. Although, generators with smaller generation capacity could have been selected for them to avoid participating in a mandatory scheme, it is important to mention that the present research takes into account the future value of ES technologies which involves investigating the effects of regulatory schemes. In particular, a 50MW generation plant represents a realistic scenario in which the provider could potentially be forced to deliver MFR services or, depending on its contractual agreements, could be free from this regulatory scheme while being able to consider its participation in other non-mandatory grid services. This generation level allows to create comparable scenarios regarding mandatory and non-mandatory regulations under the same conditions. It is also noteworthy that different regulations in this context can apply to other countries and this is considered in the present study when developing the methodology described in Chapter 4.

For mandatory frequency response, the minimum power requirement that all Power Stations must deliver for the provision of this service are established according to the minimum frequency response requirements for a 0.5Hz frequency-deviation, depicted in Figure 3.1. In cases where the frequency changes of the electricity network are lower than 0.5Hz, the active power response from generation providers are calculated as a direct proportion of the minimum frequency requirement profile of Figure 3.1. When frequency deviations of the system are, instead, greater than 0.5Hz, the response from Power Stations for MFR services must be greater than or equal to the limits of the minimum frequency requirement profile of Figure 3.1. generation providers are also engaged within the MFR to guarantee energy reserves for:

- Addressing the potential provision of Secondary Response, if determined by the ESO, for the greatest frequency deviation up to 30 minutes.
- Providing a response corresponding to 0.5Hz frequency-deviations in order to face the most onerous cases of sudden frequency changes.

This whole procedure is applied in this study to determine the response requirements expected from REG providers when participating in the mandatory scheme MFR.

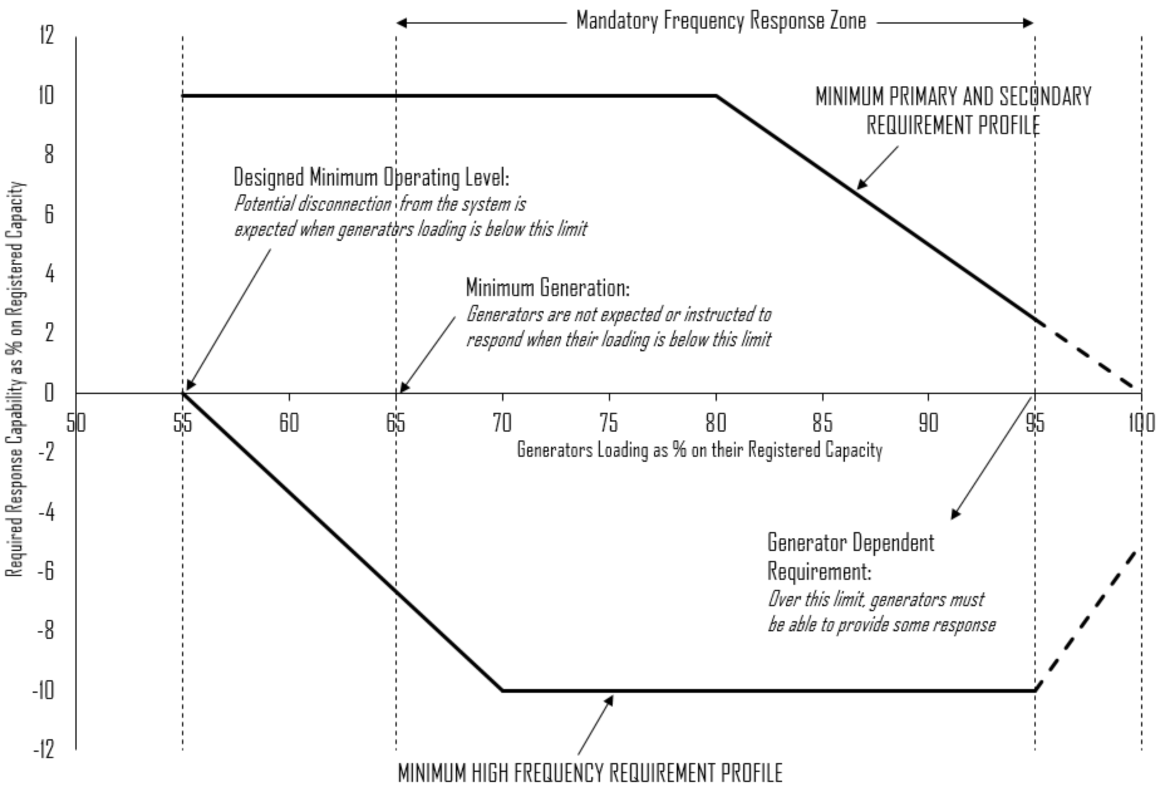

Figure 3.1. Minimum Frequency Response Requirements for 0.5Hz grid-deviations under MFR-scheme

There also exists a non-mandatory frequency scheme which is addressed to Power Stations who want to contribute with primary response, secondary response, high frequency response or their combination and are not part of the MFR service. Unlike the MFR scheme, Firm Frequency Response (FFR) is a non-mandatory scheme open to all generation providers as long as they meet requirements [141]. The most relevant technical requirements for the FFR service are:

- generation providers are free to submit their desired service tenders, but they must consider a minimum response of 1MW. This could be achieved by using a single unit or through multiple devices. This feature is of importance when considering ES technologies since they can be applied in FFR services in conjunction with REGs or other ES devices.
- In order to avoid penalties, Power Stations must be ready to reach their tendered frequency response capability whenever instructed by the ESO. For this requirement, most of the generators under this scheme might need to run part-loaded during their operation.
- FFR Participants must have a suitable operational metering and pass the pre-qualification assessment.
- The Power Stations must communicate via automatic logging devices.
- When frequency response under FFR scheme are continuously provided on a second by second basis, they are known as Dynamic Frequency Response (DFR). For delivering DFR, the participants must able to operate in frequency sensitive mode when required by the ESO. This means that Power Stations must operate in accordance with ESO instructions, proportional to Figure 3.1, in order to deliver primary response, secondary response, high frequency response or any of their combinations.
- Power Stations can also participate in the FFR scheme through static responses. In non-dynamic frequency response, generation providers must activate, through automatic relays, a fixed MW capacity triggered by specific frequency deviations.

The selection of the final FFR participants involves online tender processes carried out every month by the ESO. The pre-qualified contestants are entitled to apply for a single month or multiple months of service. This represents a significant difference with the mandatory scheme MFR as, here, Power Stations can decide to stop their participation in the FFR scheme if this is not suitable with their interests.

3.2.1. Payment Process for MFR and FFR schemes

The mandatory frequency response scheme remunerates the participants in two ways: for the actual utilization of their energy and for their capability to provide the service when instructed [140]. These remuneration-systems are stipulated in Section 4.1.3.8 of the CUSC and they are known as response energy payment (REP) and holding payment respectively. Although holding prices (£/h) are submitted by generation providers each month, only the approved bids by the ESO are entitled to receive the payments [139], [140]. The holding payment-system is not considered in this work as its information is limited. Instead, we take into account REP (£/MWh) since it remunerates the actual provision of MFR service and the payments can be calculated according to Section 4.1.3.9A of the CUSC i.e. based on the real service provided and the reference price obtained from the Market Index Data (MID) [139]. It is important to mention that, while not considering holding payments reduces potential additional incomes that generation providers can obtain, this revenue stream is a constant value which: 1) does not affect simulation results and 2) does not modify the comparison of results since the same logic was applied for all the scenarios and regulatory schemes.

The remuneration system for the FFR service also considers payments for the actual response of energy as in the MFR service. There also exists additional payments for generation providers, such as availability fees, window initiation fees, nomination fees and tendered window revision fees [141]. With the exception of REP where the actual power provision is remunerated, all of the FFR payment schemes seek to compensate the participants for following ESO instructions and for maintaining their availability to provide a response as occurs in MFR. In order to compare both MFR and FFR services under the same rules, due to the lack of information on the rest of payments, and because simulations are not affected by constant payments, the present work focuses exclusively on actual frequency response payments. This comparison of regulatory schemes, under the same payment conditions, could provide important signals of the benefits that ES devices could achieved when supporting REG providers with different frequency services. However, it is again acknowledged that higher revenues could be further reached by REG providers when a full range of payments is considered but this additional revenue stream represents a constant value that does not affect the findings of the present research.

Both, MFR and FFR payments for actual responses are constantly changing since they depend on the market prices which changes in a 30-min basis. Based on the frequency market price trajectory decreasing every year (e.g. the prices stood around £22/MW/hr in 2015-16 while decreased to £15-£18/MW/hr in 2016-17), there exist concerns about future scenarios where REG is not able to benefit from frequency services [142]. The challenge, here, is the difficulty of predicting what will occur in this context taking into account all the actors playing a role in these potential changes such as new market entrants, new non-contracted assets being constructed, load-demand behaviour, large-scale market participants stepping out. Figure 3.2 presents a prediction of [143] for the prices of frequency response which clearly depicted a drop from current values.

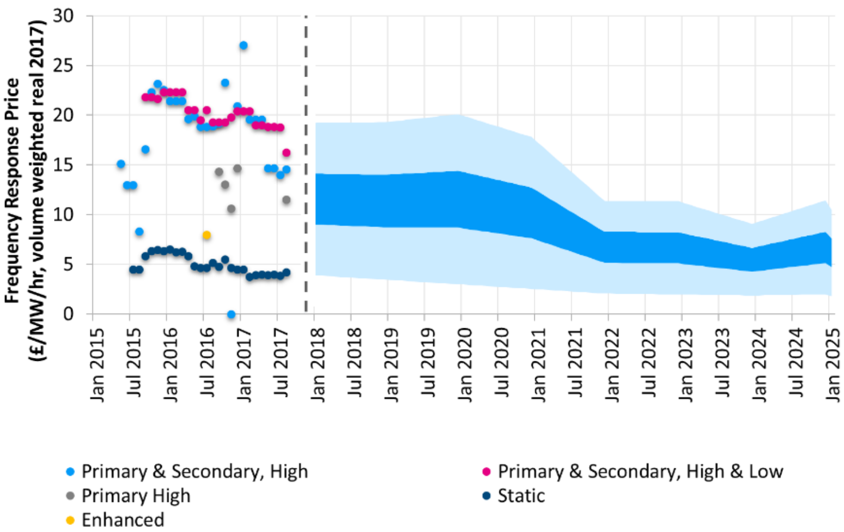

Figure 3.2 Prediction of Prices in Frequency Response Markets [143]

As seen in Figure 3.2, it is highly important for REG providers not to remain static and to expand their range of market interactions when using ES technologies so that the highest income possible can be reached. This, in turn, will also increase the value of ES devices for the present and future. The present study takes into account multiple market interactions using ES technologies to achieve the highest income possible for REG providers. In this approach, generation providers can also minimize their risks of participating in only one energy market (e.g. frequency market) with their ES system since they are also capable of profiting from a different market (e.g. wholesale market) instead (if this is more convenient). The methodology allows the study a flexible behaviour of ES devices to address the most convenient interaction to achieve higher incomes which could, ultimately, disregard one market if this is not profitable and mandatory. However, it is acknowledged by this research that potential future energy market prices have not been considered due to their unpredictability explained above. It rather focused on allowing flexibility to ES devices to be able to access to the highest profit for REG providers.

3.3. System Configuration

At transmission level, generation providers utilizing renewable sources, such as Solar and Wind Farms, are able to participate in the Wholesale Market and, depending on the electricity network regulations, they could also be allowed to support the system, simultaneously, with various grid-services remunerated from different markets. In the present work, the framework models that will permit the assessment of the techno-economic factors influencing the value of ES technologies take into account ES devices integrated to REG providers for the provision of multiple market applications and aim to maximize the economic benefits of the whole system while optimizing the ES sizing design.

The complete system, depicted in Figure 3.3, is made of a medium to large-scale REG provider looking to incorporate a single ES device or two different ES technologies for a partial or complete provision of frequency response while also participating in the wholesale market. The potential combination of ES devices is composed of one energy-dense technology, named ES1, and one power-dense technology, named ES2. The main objective of this system is, ultimately, to maximize the Total System Revenue (TSR), during a project duration scope, for REG providers by exploiting the income from both, wholesale market and frequency market, using an optimal ESS design. As the main cost drivers of this optimization problem are the ES power and energy ratings, the outputs of the framework models are fundamentally achieving the minimum sizing design of ES technologies which are complying with system requirements for delivering frequency services while also interacting with the wholesale market.

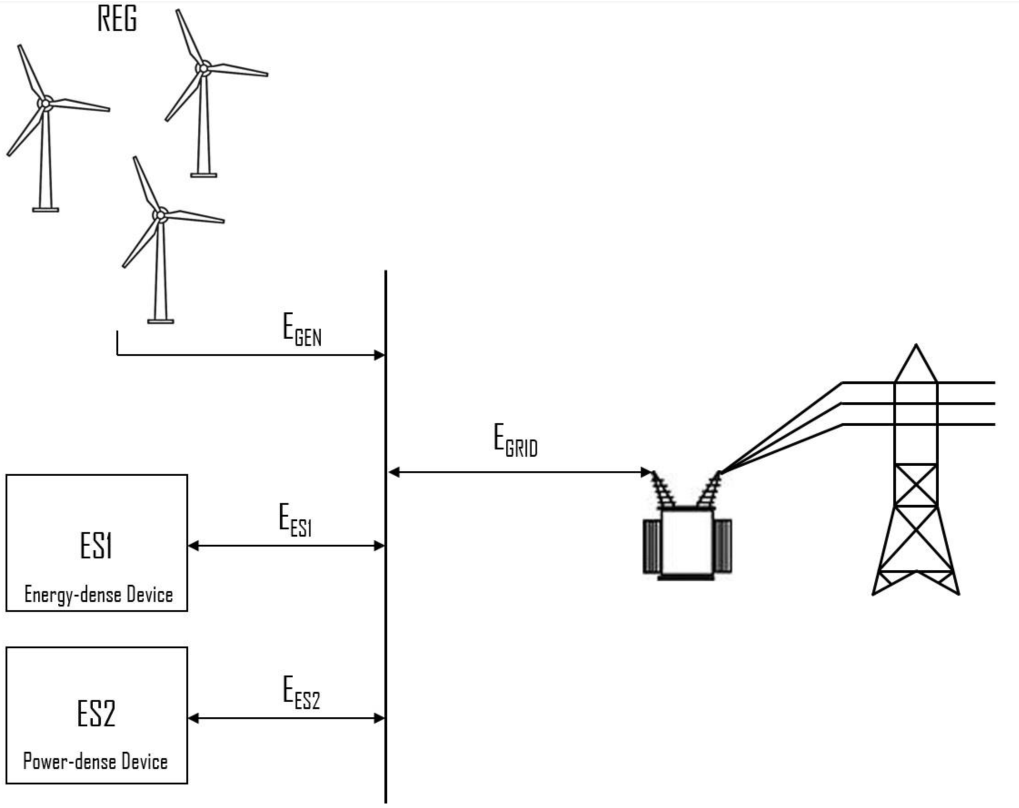

Figure 3.3. System Description for Framework Models

3.4. System Operation

The normal operation of the REG provider presented in Figure 3.3, without using ES devices, is to inject into the electricity network as much power as possible from its renewable generators. This generation process is assumed to occur exclusively under the Wholesale Market. If REG provider is, however, engaged under the MFR service or participating in the FFR service, it is then necessary from its RGs to curtail the output power so that power reserves can be assured for facing secondary frequency response (i.e. up to 30 mins provision) and, in the solely case of MFR service, for addressing situations of maximum frequency deviations. For instance, Figure 3.4 presents a two-months period of the actual power generation that is achieved by a 50MW Wind Farm when participating in the MFR service. As depicted in this figure, whenever the wind power production from this REG provider exceeds the minimum generation level required, by regulation, to deliver MFR, a gap is formed between the actual power generation and the maximum power that is available. This gap represents the energy reserves of this machine for the provision of frequency response for the most onerous cases of frequency change (i.e. for 0.5 Hz deviations) and to support with high frequency events.

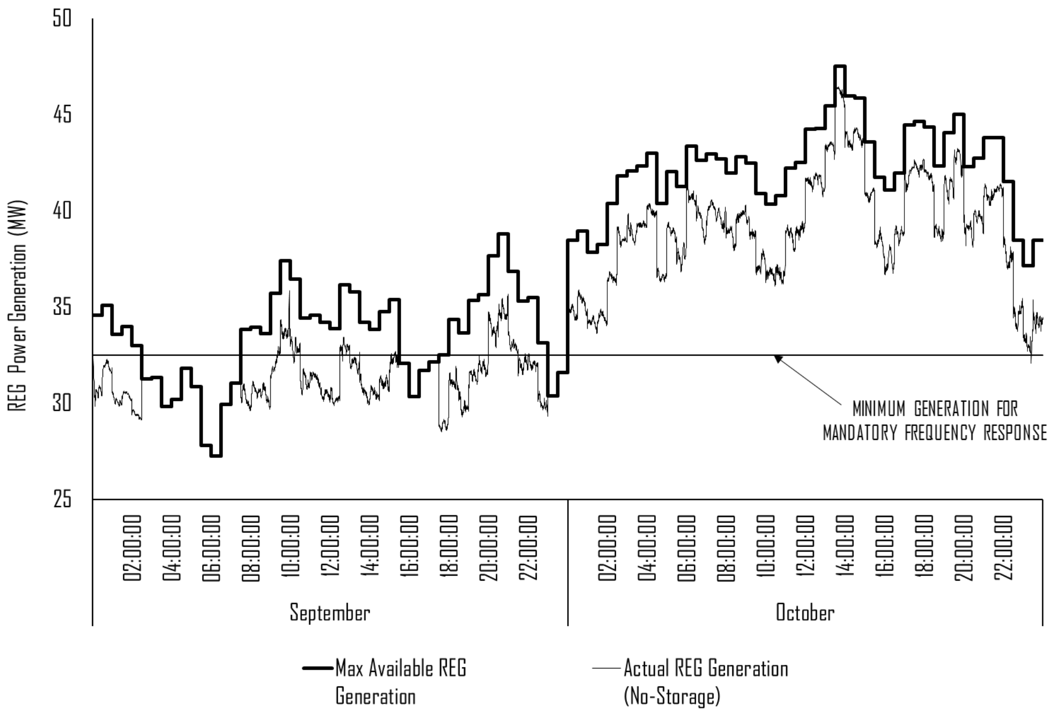

Figure 3.4. Maximum Available and Actual Power Generation of a 50MW Wind Farm participating in MFR

The use of ES devices could contribute with Power Stations by allowing their RGs to generate closer to their maximum available power while meeting frequency support requirements. This changes the operational behaviour of the whole system depending on the responsibilities assigned to ES technologies. In this research, three operational processes, described below, are considered for REG providers when using energy storage devices.

3.4.1. Provision of MFR and Wholesale Market Interaction with RG and ES

In this operational process, the MFR support could proceed either from renewable generators, energy-dense storage technologies (ES1), power-dense ES technologies (ES2) or from any combination of them. These three elements are considered to be active players, under this operational process, for the mandatory provision of primary frequency response and high frequency response of REG providers. Regarding the energy reserves required for the potential provision of secondary response, the MFR regulation establishes a 30-mins delivery of service for the highest possible frequency deviation. For this reason, RG and ES1 are the only elements taken into account in this task as power-dense ES devices are still expensive technologies for storing large amounts of energy.

In the MFR service, the regulation dictates the degree and conditions in which power response must be met by each participant. This allows to formulate an optimization problem considering RG as an active player for frequency support. For FFR service, however, the degree of response is not determined based on regulations but rather by the accepted offers of Power Stations. This creates an unbonded limit for generators which disrupts the achievement of the solution from the optimization problem. For that reason, FFR services are not considered under this operational approach.

Under MFR regulations, Power Stations are also allowed to do other grid-applications and market participation as long as this is not interfering with the provision of MFR [140]. If mandatory frequency response were only addressed by RG, interacting with the wholesale market would be limited due to the nature of generators. With the inclusion of ES1 and ES2, however, a flexible interaction with wholesale market and frequency market is now achievable for REG providers, leading to potential enhancements on their total income. In this operational process, interacting with the wholesale market with ES devices is restricted to occur exclusively in the direction of frequency services or in moments where the frequency support is not required so that the MFR service is not compromised by these actions.

This operational process involving the active participation of RG, ES1 and ES2 for the provision of MFR service and wholesale market interaction represents one framework model named Three Players Model. The complete participation required by each active element in this framework model is summarized below:

Activity	ES1 Energy-dense device	ES2 Power-dense device	RG Renewable Generator
Primary Frequency Response	✓	✓	✓
Secondary Frequency Reserves	✓	-	✓
ES Wholesale Market Interaction	✓	✓	-

Table 3.2. Three Players Model: Elements participation

3.4.2. Provision of MFR and Wholesale Market Interaction with ES

In the previous section, the operational process for REG providers to deliver MFR service while also interacting, in a flexible manner, with the wholesale market was defined using three active players (i.e. RG, ES1 and ES2). In the operation mode of this section, the same market applications as in Three Players Model are also addressed in this operational process but using, in exclusivity, ES devices as active elements. This means that RGs are solely dedicated in introducing energy in the wholesale market (which could occur under common wholesale prices or through CfDs depending on grid regulations at that moment) while ES1 and ES2 are in charge of meeting all MFR primary response and high frequency response requirements. Here, both ES devices are also allowed to interact in the wholesale market in the direction of frequency services or during times where frequency support is not required. Regarding energy reserves for the potential provision of secondary response and to face the most onerous cases of frequency deviation, in this operational process, ES1 becomes the element assuming the complete responsibility as RG is now a passive element.

This operational process involving the active participation of ES1 and ES2 to provide MFR service while also interacting with the wholesale market represents a framework model named, by the author, as MFRA Model. The complete participation required by each active element in this framework model is summarized in Table 3.3.

Activity	**ES1** **Energy-dense device**	**ES2** **Power-dense device**	**RG**
Primary Frequency Response	✓	✓	-
Secondary Frequency Reserves	✓	-	-
ES Wholesale Market Interaction	✓	✓	-

Table 3.3. Two players model for MFR and Wholesale Market Interaction: Elements participation

3.4.3. Provision of FFR and Wholesale Market Interaction with ES

In this operational process for REG providers, the generators are considered passive elements of the system while ES technologies are active players for participating in a non-mandatory frequency scheme and to interact in the wholesale market. As in the previous operational process, here, ES1 and ES2 are both in charge of delivering primary response and high frequency response and they are also able to interact with the wholesale market in the same direction of the frequency response or when frequency support is not provided. One of the main operational differences with the MFRA Model is, however, that ES1 takes full responsibility of the energy reserves for secondary response when primary frequency response is decided to be delivered (i.e. not taking into account the worst cases of frequency change as dictated by MFR regulations). This is due to the degree of independence that REG providers have under this FFR service. Nevertheless, if primary frequency response is decided to be delivered, the minimum response that can be provided by REG provider as established by FFR regulations must be at least 1MW. This event creates a conditional constraint in the operational process that must be considered during the modelling stage.

This operational process involving active participation of ES1 and ES2 to provide FFRA service while also interacting in the wholesale market represents a framework model named FFRA Model. The complete participation required by each active element in this framework model is summarized in Table 3.4.

Activity	**ES1** **Energy-dense device**	**ES2** **Power-dense device**	**RG**
Primary Frequency Response	✓	✓	-
Secondary Frequency Reserves	✓	-	-
ES Wholesale Market Interaction	✓	✓	-

Table 3.4. Two players model for FFR and Wholesale Market Interaction: Elements participation

Despite the aforementioned differences, both MFRA and FFRA Models present a similar remuneration scheme and technical operation, allowing the analysis of their benefits and making mutual comparisons. This could provide important information not only for generation providers and technology developers to evaluate the influence of these factors in the value of ES devices but also for policy makers and regulators to observe and measure the impact, for ES devices and RGs, of mandatory and non-mandatory frequency regulations and wholesale market interactions.

3.5. Specifications and Assumptions

The modelling of each operational process of REG provider, presented in Section 3.4, requires a number of hypotheses to achieve simple, feasible and realistic models. The following specifications/assumptions are considered to develop the Framework Models of the present work:

- All framework models take into account REG providers that are connected to transmission level in GB.

- The renewable generators of a REG provider are assumed to be concentrated at single locations on the electricity network (i.e. not distributed and spread out across a feeder).
- In the Three Players Model, while RG, ES1 and ES2 could participate in primary and high frequency response, only the former two elements are capable of addressing energy reserves for secondary frequency response and for facing the worst cases of frequency deviations. In MFRA and FFRA Models, however, ES1 becomes the unique element of REG provider system that is in charge of this regulatory task.
- In all the Framework Models involving Mandatory Frequency Response, the power requirements are always met in order to avoid penalties from the ESO.
- In all Framework Models, it is assumed that generators are, at all times, allowed to inject their power production into the wholesale market and that there is no market restriction for ES technologies regarding the amount of energy they can trade in the Wholesale Market. It is acknowledged, however, there might be effects and limitations, in reality, for REG providers when large amounts of energy are aimed to be introduced in this market.
- ES technologies applied in each framework model must be able to respond as fast as the MFR and FFR regulations dictate. This means reaching their rated power within 10 seconds. Based on Table 2.2 and Figure 2.6, this condition is achieved by most of ES devices except for bulk storage technologies such as pumped-hydro, CAES and TES. This research is focused, however, exclusively in electrochemical ES technologies (i.e. battery devices) and Supercapacitor storage technologies.
- The technical characteristics considered for each ES technology are derived from Table 2.2 regarding cost of energy ($/kwh), cost of power ($/kW), roundtrip efficiency (%), self-discharge (%), cycle lifetime (100% DoD) and lifetime (years). When the value of a specific technical characteristic is unique, a value around this limit is the one applied to the methodology while values that are within large ranges are chosen utilizing a number around the average of these limits. For features in which the feature specifies above a certain limit, the value considered involved over a half the minimum limit. It is important to mention, however, that varying the values within each range was applied to explore the

effects of enhancing these characteristics as sensitivity analysis. The only exception occurs with Sodium–Nickel Chloride batteries in which the prices used for simulations are not based on Table 2.2 but rather from actual information of the Test-Bed of Newcastle University. Further details in this ground could be confidential and will require the authorization from Newcastle University to be accessed.

- It is assumed for all framework models a power to energy ratio limited up to 10 for each ES technology in order to discard solutions with unrealistic ES ratings. This restriction can be adjusted, however, if different ratios are to be accepted within the analysis.
- The minimum sampling interval (T_{PER}) of this method is assumed to be the same as the one located in the grid-frequency data because this represents the shortest period from all input data of the system (i.e. $T_{PER} = 15s$ in GB).
- All variables of each framework model are treated as positive numbers unless otherwise stated.
- In all models, the modifications in the manufacturing prices for the power and energy components of ES technologies are assumed to be linear when sizing these devices. In reality, these prices might not present such a behaviour due to the economy of scale and other industrial factors. Nevertheless, the prices of ES components are based on information acquired from the literature as shown in Table 2.2 and they could be effective when building optimization models and to achieve reliable simulation outcomes through deterministic algorithms.
- In all the models, it has been assumed a 100% state of health (SOH) and a constant SOC that can reach its upper and lower limits for each ES technology evaluated throughout their complete lifetime. The present work assumed not to consider degradation effects of ES devices which require extensive research in laboratory testing and circuit modelling with high computational efforts. Instead, this improvement is collocated as the next step for the present work.
- The system operation in all framework models is assumed to have no effect on the electricity prices throughout the project lifetime. In this regard, an extensive study would be required to analyse the potential impacts of embedding many medium and large-scale ES devices on the electricity markets and this is beyond the scope of this work. This also involves that market price changes in the future

were not considered part of the present research because it requires economic studies with inner information from all the actors of the markets and predictions that, still, might not be accurate based on the number of factors that play a role for these changes. Instead, this work takes into account historic market prices to perform simulations which could create significant scenarios to analyse the influence for ES technologies of the factors describe in Section 1.3.

3.6. System Inputs and Outputs

The techno-economic framework models of this work are developed around different operational process for grid-connected REG providers applying ES devices for multiple market applications and they require a number of specifications and assumptions. The main purpose for these models, however, is to achieve the highest income for REG providers taking into account performing frequency response while also interacting with wholesale market through ES technologies. This makes the TSR, at the end of a project scope, one of the key outcomes of the simulations in each model. As the main cost drivers of the framework models are the power and energy ratings of ES technologies, the optimal sizing of these devices is also one of the outcomes obtained from simulating the framework models. The sizing design of ES devices could involve, depending on the economic benefits, a single unit, a hybrid energy storage system (HESS) or none using ES technologies. This means, for instance, that the framework models are not forced to deliver a hybrid combination of ES devices if this not the most profitable option.

The required inputs for all framework models are divided into five parts: Renewable Generation Profiles, Energy Markets Data (i.e. wholesale and Frequency Market), Grid-Frequency Profiles, and Economic and Technical Parameters of ES technologies. The latter refers to the intrinsic characteristics of each ES device regarding charging and discharging efficiencies, state of charge (SOC) limits, cycling lifetime and daily self-discharges. The economic parameters include the Interest Rate when investing in ES devices, the Investment Project Lifetime, the Maximum Investment Target (when required), and the ES power and energy components costs. The complete overview of all framework models for both, inputs and outputs, is presented in Figure 3.5.

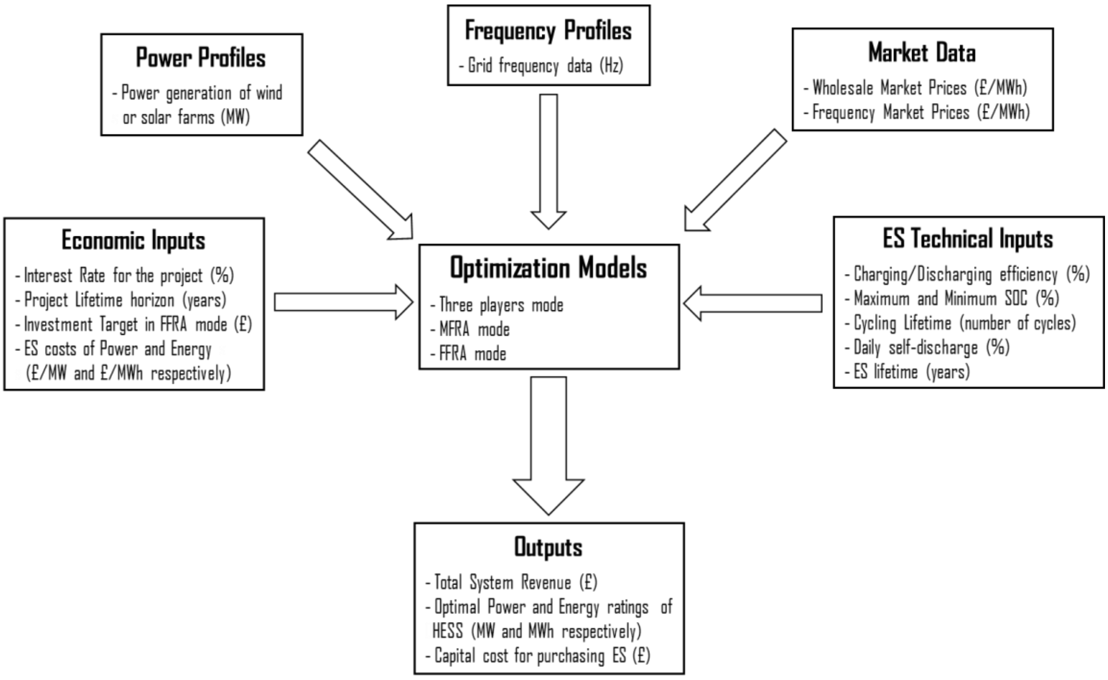

Figure 3.5. Overview of inputs and outputs of the optimization models

The simulation of all models not only provides the maximum income that can be reached by REG providers when using ES technologies for frequency services and wholesale market interactions but also the optimal sizing design of ES devices to achieve those revenues. In addition, the simulation outcomes also include the capital costs for investing in these ES technologies. The simulation outputs for all framework models are aimed to be achieved by using deterministic methods since their solutions are reliable. For that reason, the development phase of this work, presented in the next chapter, aims to establish linear relationships among the objective function and constraints for all framework models. Except for the FFRA Model in which it might be required a conditional constraint to ensure a frequency response of at least 1MW, the rest of models could contain linear non-conditional constraints that can be addressed through linear programming (LP). In the case of FFRA Model, the model solution could be achieved, instead, using a mix-integer linear programming (MILP) method.

3.7. Conclusion

This chapter presented the design of a techno-economic assessment framework which will allow the study of factors influencing the value of ES technologies. The framework was determined to contain three models, named Three Players, MFRA and FFRA, in order to cover different operational processes in which REG providers could apply ES devices for interacting with multiple markets: Frequency Market and Wholesale Market. Since all framework models are addressing frequency response, the first part of this chapter described the grid requirements for REG providers to participate in mandatory and non-mandatory frequency schemes (i.e. MFR and FFR services). Although in this work, the remuneration system for REG providers depends on the payments achieved by their actual frequency response, it is acknowledged that there also exist different types of payments which could ultimately boost the outcomes of this framework. The lack of information and access to private sources were, however, the reasons for assuming this simplification.

From all framework models, Three Players Model and MFRA Models show similarities since, aside from the capability of interacting with the wholesale market through ES devices, they both consider a mandatory frequency scheme for REG providers. The difference is, however, based on the active elements allowed to address the provision of MFR. While frequency support is exclusively delivered by using ES devices in the MFRA Model, in the Three Players Model, the renewable generators are also able to provide MFR. This will allow the explanation of the benefits for REG providers from operating ES technologies and RGs, all together, for frequency services and wholesale market interaction. Meanwhile, the FFRA and MFRA Models could permit the study of the advantages of using, in exclusivity, ES devices for interacting with the wholesale market and frequency market under mandatory and non-mandatory schemes. These schemes comparison will not only be beneficial to analyse the value of ES devices for REG providers and investors but also for policy makers and regulators who can evaluate potential improvements in regulations.

The outcomes of all framework models provide the highest income that REG providers can achieve when using ES devices for frequency services and wholesale market interactions. This income is accompanied by optimal ES sizing designs which, in turn, will create savings, for REG providers and investors, in the capital investment required to purchase such a system. The framework models are aimed to be developed with linear relationships among the objective function and system constraints in order to allow the calculation of reliable solutions.

Chapter 4. Development of Framework Models

4.1. Introduction

In this chapter, the framework models required for the techno-economic assessment of the factors influencing the present and future value of ES devices are developed. All models are built following energy market application requirements, payment structures, system configuration, operational processes, specifications and assumptions described in Chapter 3. Since the main goal, in all models, is to achieve the highest revenue for REG providers when applying ES devices to support with Frequency Services (either MFR or FFR) and for also interacting in the wholesale market, the Objective Function (OF) for the Three Players Model, MFRA Model, and FFRA Model is presented as a common piece in Section 4.2. This OF is based on the revenues and expenses that REG providers incur when taking part of multiple markets (i.e. Wholesale and Frequency Market) and for the acquisition investment and degradation of ES technologies. As the main cost driver of the OF is the power rating and energy rating of ES devices, the solution of all framework models is fundamentally determining the optimal design for each technology. The possibility of using multiple ES devices, for REG providers, is also taken into account within the framework models but the models' outcomes will only deliver the most profitable alternative for the system. Therefore, the feasibility of hybridizing the ES system is implicit in the solution of these models. Section 4.3, Section 4.4 and Section 4.5 described the model development for the Three Players Model, MFRA Model, and FFRA Model respectively.

4.2. Objective Function of Framework Models

All framework models consider an ES investment project that aims to rise Total System Revenues (TSR) of a REG provider for specific time horizon (PT). The calculation of this TSR depends on:

- Income from the Wholesale Market ($I_{WM(n)}$),
- Income from the Frequency Market ($I_{FM(n)}$),
- Investment costs of purchasing ES devices (C_{ESS}), and
- Energy Storage degradation costs ($C_{DEG(n)}$)

For each sampling interval (n), the income $I_{WM(n)}$ and $I_{FM(n)}$ and the costs $C_{DEG(n)}$ are all added up until the total number of samples (N) is reached. This summation value, in days, is then escalated to an annualized income by taking into account the maximum number of days of the input data (D). In the case of ES capital costs C_{ESS}, however, the annualization is achieved using the capital recovery factor (CRF). This method is an effective cost analysis tool applied when businesses and investors, in engineering and other fields, are looking to determine the success of their investments [144], [145]. CRF allows to calculate the present value of successive annual payments of an investment over a fixed amount of time. Extensive studies involving energy storage and economic factors utilizes the CRF method to assess investments [146]–[150], and in this work, it was considered to represent for REG providers their annual payment carried out to invest in purchasing the ES system (i.e. ES capital costs C_{ESS}). Since all investments are subject to interest rates each year which could come from the debts with banks or from the value representation of that investment in an specific period, the CRF method applies and interest rate on investments (i) over a fixed amount of time. In this case, the amount of time is allocated based on the expected project lifetime determined by REG providers or investors:

$$CRF = \frac{(1+i)^{PT} \cdot i}{(1+i)^{PT} - 1} \tag{4.1}$$

The objective function, for all the models, is presented below:

$$TSR = PT \cdot \left(\frac{365}{D} \sum_{n=n_0}^{N} \left(I_{WM(n)} + I_{FRQ(n)} - C_{DEG(n)} \right) - C_{ESS} \cdot CRF \right) \tag{4.2}$$

In Equation 4.2, the capital costs for purchasing an ES system, whether single unit or a hybrid combination, is obtained based on the design of ES technologies as shown in Equation 4.3. This design is expressed in terms of power ratings for ES1 (R_{P_ES1}) and ES2 (R_{P_ES2}) and their energy ratings (R_{E_ES1} and R_{E_ES2} respectively).

$$C_{ESS} = X_1 \cdot \left(R_{P\_ES1} \cdot P_{P\_ES1} + R_{E\_ES1} \cdot P_{E\_ES1} \right) + X_2 \cdot \left(R_{P\_ES2} \cdot P_{P\_ES2} + R_{E\_ES2} \cdot P_{E\_ES2} \right) \tag{4.3}$$

Where,

- P_{P_ES1} and P_{E_ES1} are the prices of the power and energy components of ES1

- P_{P_ES2} and P_{E_ES2} are the prices of the power and energy components of ES2

X_1 and X_2 are included in this study as auxiliary factors for ES1 and ES2 respectively. These factors are established during planning stage of the ES project follows:

$$X_1 = \frac{PT}{LT_{ES1}} \tag{4.4}$$

$$X_2 = \frac{PT}{LT_{ES2}} \tag{4.5}$$

In Equation 4.4 and Equation 4.5, the auxiliary factors must be approximated to the highest integer value in the results of the division in order to take into account the acquisition of ES devices according their lifetime and the span of the project. As the manufacturing lifetime of ES technologies (LT_{ES1} for ES1 and LT_{ES2} for ES2) might be different among ES technologies and shorter than the duration scope of the project, the function of these auxiliary factors is to scale the energy and power costs of each ES technology, in Equation 4.3, accordingly. For instance, if a Li-ion battery storage is determined by the manufacturer to have a 5 years lifetime, this ES device could be analysed using the framework models for investment projects of up to 5 years. If the project duration is, however, determined to span 8 years and assuming a 5 years manufacture lifetime, then it will be necessary to include in the calculations a complete new set of Li-ion batteries to address the remaining years of the project. This can be mathematically expressed as a single payment at a double cost thanks to the auxiliary factors (e.g. $X_1 = \|8/5\| = 2$) that are introduced in this work. Figure 4.1 is presented, as an example, to observe the effects of using auxiliary factors on energy component designing costs of various ES devices for different project lifetimes up to 20 years taking into account ES technical characteristics presented in Table 2.2 analysed as described in Section 2.4 and Section 3.5. It is important to mention that the approach of this study only takes into account the manufacture lifetime of ES technologies rather that the potential lifetime of these devices based on their operation. Although this might represent a limitation which could be addressed in future studies that include a function of ES degradation, this research considers a degradation cost using a simple method in which all the energy utilized by each ES device is accounted through a price of degradation. A complete ES degradation function requires the development of complex models that could, for instance, accounts the wear of internal components/chemicals of ES devices due to utilization and aging. Degradation models, for instance, could also require access to specific ES devices for including laboratory work to test actual operation while measuring wear and tear of ES systems. On its own, ES degradation studies could represent a complete research thesis and it has been considered out of the scope of this work. It is acknowledged by the author, however, that this inclusion could help exhibit a more realistic behaviour of ES system while increasing the complexity and conditions of the model.

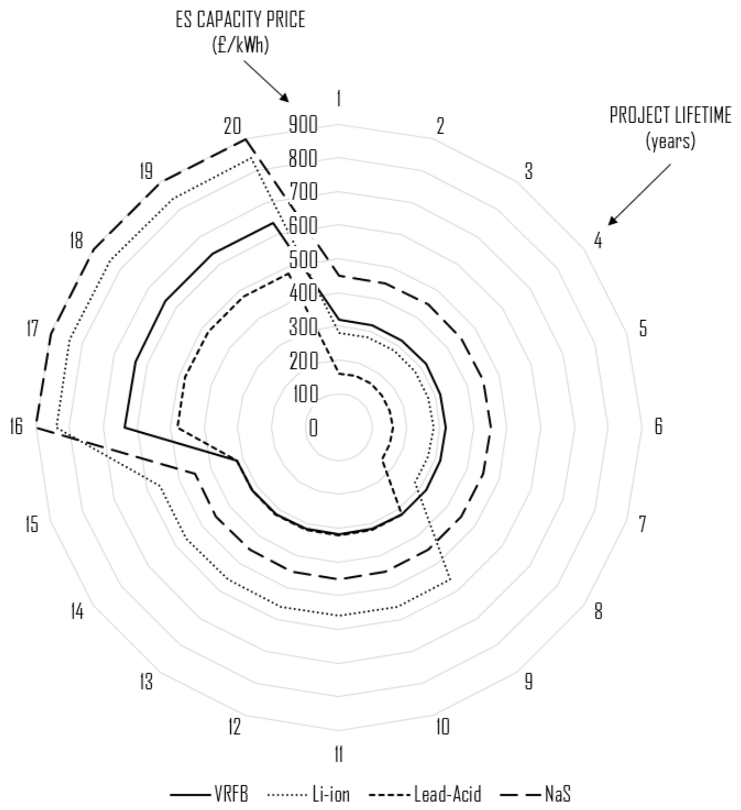

Figure 4.1. Auxiliary Factor Effect on the Energy Component Costs of ES for different Project Lifetimes and based exclusively on ES manufacture lifetime

In Figure 4.1 is possible to observe, for instance, that lithium-ion batteries show a lower cost of energy components than sodium-sulphur batteries for short-term projects. This is because one set of Li-ion batteries is assumed to resist the complete duration of the ES project up to 8 years (as determined in Section 2.4 and Section 3.5). On the other hand, if the lifetime of the project becomes longer, it might be necessary for generation providers or investors to purchase more Li-ion battery sets depending on the remaining time of the project. The auxiliary factor, for a 13-years project example, would now make NaS batteries a cheaper option than Li-ion batteries in the energy components price as the first set of NaS batteries might still be operating after this time. In the context of manufacture lifetime of ES devices, it is noteworthy that the present research carries out sensitivity analyses on this feature to evaluate the future value of these technologies for large range of manufacture years.

4.3. Three Players Model

4.3.1 Frequency Market

In the Three Players Model developed in this work, generation providers can obtain revenues from Frequency Market by delivering energy into the grid when supporting in primary frequency events ($E_{UF(n)}$) or by absorbing energy from the grid for high-frequency support ($E_{OF(n)}$) as follows:

$$I_{FM(n)} = P_{FM(n)} \cdot E_{UF(n)} + P_{FM(n)} \cdot E_{OF(n)} \quad (4.6)$$

Where,

- $P_{FM(n)}$ is the price in the Frequency Market at the instant n.

As this model is composed of three active elements for Frequency Services, the actual response for primary frequency events and high frequency events could proceed from RG, ES1, ES2 or any combination them. This is defined as:

$$E_{UF(n)} = E_{UF\_REG(n)} + E_{UF\_ES1(n)} + E_{UF\_ES2(n)} \quad (4.7)$$

$$E_{OF(n)} = E_{OF\_REG(n)} + E_{OF\_ES1(n)} + E_{OF\_ES2(n)} \quad (4.8)$$

Where,

- $E_{UF\_REG(n)}$ is the primary frequency response from RG at the instant n.
- $E_{UF\_ES1(n)}$ is the primary frequency response from ES1 at the instant n.
- $E_{UF\_ES2(n)}$ is the primary frequency response from ES2 at the instant n.
- $E_{OF\_REG(n)}$ is the high frequency response from RG at the instant n.
- $E_{OF\_ES1(n)}$ is the high frequency response from ES1 at the instant n.
- $E_{OF\_ES2(n)}$ is the high frequency response from ES2 at the instant n.

The present model considers a complete provision of MFR service from REG providers in order to avoid penalties from the ESO. This can be achieved by forcing the system to provide a response for each primary frequency request ($E_{REQ\_UF(n)}$) and each high frequency request ($E_{REQ\_OF(n)}$) with the following constraints:

$$E_{UF(n)} - E_{REQ\_UF(n)} = 0 \tag{4.9}$$

$$E_{OF(n)} - E_{REQ\_OF(n)} = 0 \tag{4.10}$$

The constraints assigned to Equation 9 and Equation 10 also permit to avoid a non-linearity associated with the charging and discharging processes of ES devices. If these constraints are not defined, for instance, there might exist potential solutions, after simulating, in which ES devices are making income from charging and discharging power at the same instant. In Equation 4.9 and Equation 4.10, this creates, however, a contradiction since regulations will determine only one of these actions for a particular moment.

4.3.2. Wholesale Market

In the UK, low-carbon electricity generation providers are paid based on contracts for difference (CfDs). CfDs is a policy measure to incentivise new low-carbon electricity generation based on stabilising the revenue of renewable generators by paying a flat (indexed) rate for the electricity they produce over a 15-year period [65]. As described in Section 2.3.3, this research does not limit the developed methodology to consider CfD as a norm for renewable generators but rather expands the horizons to allow studies considering REG providers participating in the wholesale market as it could be case in other countries or future changes. Therefore, in this model, the income from the wholesale market, for REG providers, was established to proceed from two revenue streams: the power injected into the grid from the renewable generators ($E_{WM\_REG(n)}$) and from the energy traded when wholesale market interactions with ES devices. The market interaction is represented as a positive income for REG providers when the energy is sold into the wholesale market ($E_{WM\_DIS(n)}$) and a negative value (i.e. payment) when the energy is bought from the grid ($E_{WM\_ABS(n)}$) in the wholesale market. This constraint is defined as:

$$I_{WM(n)} = P_{WM(n)} \cdot \left(E_{WM\_REG(n)} + E_{WM\_DIS(n)} - E_{WM\_ABS(n)}\right) \tag{4.11}$$

Where,

- $P_{WM(n)}$ is the Wholesale Market Price at the instant n.

It is important to mention that CfD policy can be applied to this methodology, if required, by establishing a fixed paying rate in $P_{WM(n)}$ rather than being variable throughout the settlement periods.

The following constraints characterise the energy discharged from ES1 ($E_{WM\_DIS1(n)}$) and/or ES2 ($E_{WM\_DIS2(n)}$) and the energy charged from ES1 ($E_{WM\_ABS1(n)}$) and/or ES2 ($E_{WM\_ABS2(n)}$) when performing wholesale market interactions:

$$E_{WM\_DIS(n)} = E_{WM\_DIS1(n)} + E_{WM\_DIS2(n)} \quad (4.12)$$

$$E_{WM\_ABS(n)} = E_{WM\_ABS1(n)} + E_{WM\_ABS2(n)} \quad (4.13)$$

An important restriction to consider in this model is, again, to prevent ES technologies from charging and discharging at the same time. If unrestricted, this event is likely to occur when there is a price difference between the price in the Frequency Market and the price in the Wholesale Market at the same instant. This could create an unrealistic scenario where the REG provider is profiting from two markets without doing any action (i.e. by maintaining an idle capacity with its ES devices). In order to address this issue and, at the same time, guarantee frequency services whenever required, this model includes two conditions that only allows ES devices to interact with wholesale market in the direction in which frequency support is occurring or when no-service is provided:

- If $E_{REQ\_UF(n)} > 0$, then $E_{WM\_\_ABS(n)} = 0$
- If $E_{REQ\_OF(n)} > 0$, then $E_{WM\_\_DIS(n)} = 0$

4.3.3. System Operation and Restrictions

Renewable Generators produce a determined amount of energy during each sample interval. In the present model, this energy is fully distributed between the Wholesale Market and Frequency Market with the following constraint:

$$P_{REG(n)} \cdot \left(\frac{T_{PER}}{3600}\right) = E_{WM\_REG(n)} + E_{UF\_REG(n)} + E_{OF\_REG(n)} + E_{RES\_REG(n)} \quad (4.14)$$

Where,

- $P_{REG(n)}$ is the power generation data from RG at the instant n.
- T_{PER} is the sample data rate in seconds.
- $E_{RES\_REG(n)}$ are the energy reserves in RG for supporting the system with the most onerous case of frequency-deviation.

By regulation, REG providers must be ready to respond to unexpected scenarios with very large frequency deviations by, at least, having energy reserves that allows them to address, if required, the equivalent response to maximum statutory frequency changes (i.e. 0.5Hz deviations) [53]. In the case of extreme over-frequency changes, REG providers able to cover these events without requiring energy reserves since their operational principle is based on reducing generation when needed. This consideration does not affect the economic analysis of this model. For extreme under-frequency changes, however, the strategy in this model is to keep energy reserve levels in the generator ($E_{RES\_REG(n)}$) and/or in the energy-dense storage technology ($E_{RES\_ES1(n)}$) so that the maximum frequency response requirement ($E_{FM\_MAX(n)}$) can be achieved with this backup energy whenever required by ESO. It goes without saying that $E_{RES\_REG(n)}$ will simply complement $E_{RES\_ES1(n)}$ and $E_{UF\_REG(n)}$ if RG and ES1 are already proving primary frequency response during that instant.

$$E_{FM\_MAX(n)} \leq E_{UF\_REG(n)} + E_{RES\_REG(n)} + E_{RES\_ES1(n)} \tag{4.15}$$

Energy reserves of REG providers must also include the ability to provide secondary frequency response which could length up to T_{REG} minutes depending on regulations (e.g. $T_{REG} = 30$ mins in GB). For ES1, these energy reserves are kept within the storage capacity of this technology ($E_{CAP\_ES1(n)}$), at the instant n, by using the next constraint:

$$E_{CAP\_ES1(n)} \geq \left(\frac{E_{RES\_ES1(n)}}{\eta_{ES1\_DIS}}\right) \cdot \left(\frac{T_{REG} \cdot 60}{T_{PER}}\right) \tag{4.16}$$

Where,

- η_{ES1_DIS} is the discharging efficiency of ES1

The charging and discharging efficiencies allow to model the operation of ES devices in which losses are accounted during these processes as it is the case in real systems i.e. not all the energy that is inputted in the ES device actually arrives in the same amount to be stored and not all the energy that is drawn from the ES device reaches in the same amount the final destination. In this work, the storage discharge efficiency is calculated from Table 2.2 by obtaining the square root of the round-trip efficiency. It is important to mention, however, that this represents an assumption considered in this work by applying a constant round-trip efficiency. In reality, the charging/discharging efficiencies are not constant throughout the complete lifetime of the ES devices because of their inner characteristics that create a non-linear charging-discharging behaviour depending on the ES device, circuit features, material, state of health (SOH) and state of charge (SOC). It is acknowledged by the author that this could represent a further improvement to the present work. This assumption has been made, however, in this model and the remaining models developed as established in Section 3.5.

The total energy stored in ES1 and ES2 ($E_{CAP\_ES2(n)}$), for a specific interval, is obtained based on the increments and reductions of energy from the previous capacity state of each device and taking into account their self-discharge losses and immerse charging and discharging efficiencies. These constraints are defined as:

$$E_{CAP\_ES1(n)} - E_{CAP\_ES1(n-1)} = E_{ES1\_IN(n)} - E_{ES1\_OUT(n)} \tag{4.17}$$

$$E_{CAP\_ES2(n)} - E_{CAP\_ES2(n-1)} = E_{ES2\_IN(n)} - E_{ES2\_OUT(n)} \tag{4.18}$$

Being,

$$E_{ES1\_OUT(n)} = \frac{E_{UF\_ES1(n)}}{\eta_{ES1\_DIS}} + \frac{E_{WM\_DIS1(n)}}{\eta_{ES1\_DIS}} + E_{ES1\_LOSS(n)} \tag{4.19}$$

$$E_{ES2\_OUT(n)} = \frac{E_{UF\_ES2(n)}}{\eta_{ES2\_DIS}} + \frac{E_{WM\_DIS2(n)}}{\eta_{ES2\_DIS}} + E_{ES2\_LOSS(n)} \tag{4.20}$$

$$E_{ES1\_IN(n)} = E_{OF\_ES1(n)} \cdot \eta_{ES1\_ABS} + E_{WM\_ABS1(n)} \cdot \eta_{ES1\_ABS} \tag{4.21}$$

$$E_{ES2\_IN(n)} = E_{OF\_ES2(n)} \cdot \eta_{ES2\_ABS} + E_{WM\_ABS2(n)} \cdot \eta_{ES2\_ABS} \tag{4.22}$$

In these constraints,

- $E_{CAP\_ES1(n-1)}$ is the energy capacity state of ES1 at the instant $n-1$.
- $E_{CAP\_ES2(n-1)}$ is the energy capacity state of ES2 at the instant $n-1$.
- $E_{ES1\_IN(n)}$ and E_{ES2_IN} are the energy inputs of ES1 and ES2 respectively.
- $E_{ES1\_OUT(n)}$ and $E_{ES2\_OUT(n)}$ are the energy outputs of ES1 and ES2 respectively.
- η_{ES1_DIS} and η_{ES2_DIS} are discharging efficiencies of ES1 and ES2 respectively.
- η_{ES1_ABS} and η_{ES2_ABS} are charging efficiencies of ES1 and ES2 respectively.
- $E_{ES1\_LOSS(n)}$ are the losses caused by ES1 self-discharge at the instant n.
- $E_{ES2\_LOSS(n)}$ are the losses caused by ES2 self-discharge at the instant n.

In all the models of this research, it has been assumed a 100% state of health (SOH) and a constant SOC that can reach its upper and lower limits for each ES technology evaluated throughout their complete lifetime. This involves that the present work does not consider the degradation effects of ES devices which requires extensive research in circuit modelling (to simulate, for instance, charging/discharging curves) and laboratory testing. Furthermore, such models could become complex and requiring significant efforts from computational software. It is, however, acknowledged by the author that considering aging models for ES technologies that better represent the variable behaviour of the SOH, SOC and charging/discharging process of ES devices could enhance the results of this work and, thus, the analysis of the present and future value of these technologies.

In order to calculate energy losses for each ES device, the theoretical self-discharge rates of ES1 (SD_{ES1}) and ES2 (SD_{ES2}) are applied in the following constraints:

$$E_{ES1\_LOSS(n)} = E_{CAP\_ES1(n)} \cdot \left(SD_{ES1} \cdot \frac{T_{PER}}{24 \cdot 3600 \cdot 100} \right) \quad (4.23)$$

$$E_{ES2\_LOSS(n)} = E_{CAP\_ES1(n)} \cdot \left(SD_{ES2} \cdot \frac{T_{PER}}{24 \cdot 3600 \cdot 100} \right) \quad (4.24)$$

For the ES cost of degradation ($C_{DEG(n)}$), a simple method is applied in this study based on all the energy utilized by each ES device and their respective cost of degradation.

$$C_{DEG(n)} = \left(E_{ES1_{IN(n)}} + E_{ES1_{OUT(n)}} \right) \cdot P_{DEG\_ES1} + \left(E_{ES2_{IN(n)}} + E_{ES2_{OUT(n)}} \right) \cdot P_{DG\_ES2} \quad (4.25)$$

The degradation prices for ES1 (P_{DEG_ES1}) and ES2 (P_{DEG_ES2}) are calculated using the price of the energy component of each technology, their auxiliary factors to scale the system, and their cycling lifetime stated in the manufacturing data of each ES device (CT_1 and CT_2), as follows:

$$P_{DEG\_ES1} = \frac{P_{E\_ES1}}{X_1 \cdot CT_1} \tag{4.26}$$

$$P_{DEG\_ES2} = \frac{P_{E\_ES2}}{X_2 \cdot CT_2} \tag{4.27}$$

Regarding technical constraints of the ES devices, they must take into account all the tasks assigned to each ES technology without exceeding their power ratings. These considerations are defined as follows:

$$\left(\frac{E_{RES\_ES1(n)}}{\eta_{ES1\_DIS}} + \frac{E_{WM\_DIS1(n)}}{\eta_{ES1\_DIS}} + E_{ES1\_LOSS(n)}\right) \cdot \frac{3600}{T_{PER}} \leq R_{P\_ES1} \tag{4.28}$$

$$\left(\frac{E_{UF\_ES2(n)}}{\eta_{ES2\_DIS}} + \frac{E_{WM\_DIS2(n)}}{\eta_{ES2\_DIS}} + E_{ES2\_LOSS(n)}\right) \cdot \frac{3600}{T_{PER}} \leq R_{P\_ES2} \tag{4.29}$$

$$\left(E_{OF\_ES1(n)} + E_{WM\_ABS1(n)}\right) \cdot \frac{3600}{T_{PER}} \leq R_{P\_ES1} \tag{4.30}$$

$$\left(E_{OF\_ES2(n)} + E_{WM\_ABS2(n)}\right) \cdot \frac{3600}{T_{PER}} \leq R_{P\_ES2} \tag{4.31}$$

The energy stored in each ES device also requires a constraint in the model to restrict the maximum and minimum state of charge (SOC) limits allowed by operation control or by the intrinsic characteristics of each ES technology. This represents the operating SOC window of each ES device and is defined as follows:

$$E_{CAP\_ES1(n)} \leq SOC_{ES1\_MAX} \cdot R_{E\_ES1} \tag{4.32}$$

$$E_{CAP\_ES2(n)} \leq SOC_{ES2\_MAX} \cdot R_{E\_ES2} \tag{4.33}$$

$$E_{CAP\_ES1(n)} \geq SOC_{ES1\_MIN} \cdot R_{E\_ES1} \tag{4.34}$$

$$E_{CAP\_ES2(n)} \geq SOC_{ES2\_MIN} \cdot R_{E\_ES2} \tag{4.35}$$

Where,

- SOC_{ES1_MAX}, SOC_{ES2_MAX} are the SOC upper-limits of ES1 and ES2 respectively
- SOC_{ES1_MIN}, SOC_{ES2_MIN} are the SOC lower-limits of ES1 and ES2 respectively

In this work, the SOC is assumed to be constant which, in reality, this might not be the case due to ageing effects on the ES technologies. This represents, however, an improvement that is considered to be included in the future work of this thesis. This enhancement will allow a more accurate and detailed representation of ES device during ES sizing process and, thus, producing important findings in the present and future value of these technologies.

In order to achieve the model results, the Three Players Model can be simulated using linear programming as both, the objective function and the system constraints, present linear relationships. LP is a deterministic optimization method that guarantees to find reliable solutions which, in this case, is to achieve the highest TSR for REG providers and the related sizing design of each ES technology to achieve this income (if applicable). In the present study, GAMS software, equipped with IBM CPLEX solver, was utilized to build and solve this model.

4.4. MFRA Model

Unlike the Three Players Model, MFRA Model takes into account ES technologies of REG providers, in exclusivity, for the provision of MFR service and wholesale market interaction. In this case, RG is now producing power that is only injected into the grid under the wholesale market. This changes its role in the system from being an active element in the provision of frequency response to be a passive player. The advantages of MFRA Model, however, is the ability to examine the use of ES devices addressing, on their own, MFR services while also being able to interact with the wholesale market. Moreover, this model permits, in conjunction with the FFRA Model, to study the benefits for REG providers of participating, with ES devices, in mandatory and non-mandatory frequency schemes.

4.4.1 Frequency Market

REG providers can obtain income from the Frequency Market by producing energy to support the grid with primary frequency response or by absorbing energy to support the grid with high-frequency events as follows:

$$I_{FM(n)} = P_{FM(n)} \cdot E_{UF(n)} + P_{FM(n)} \cdot E_{OF(n)} \quad (4.36)$$

Both, primary response and high frequency response, are met by REG providers by only using two active players: ES1 and ES2. This is defined as:

$$E_{UF(n)} = E_{UF\_ES1(n)} + E_{UF\_ES2(n)} \quad (4.37)$$

$$E_{OF(n)} = E_{OF\_ES1(n)} + E_{OF\_ES2(n)} \quad (4.38)$$

In order to avoid penalties from the ESO, the MFRA Model assure meeting the entire frequency service provision requirement through the following constraints:

$$E_{UF(n)} - E_{REQ\_UF(n)} = 0 \quad (4.39)$$

$$E_{OF(n)} - E_{REQ\_OF(n)} = 0 \quad (4.40)$$

Equation 4.39 and Equation 4.40 are constraints that also restrict ES technologies from charging and discharging at the same time as MFR regulations will only require one of these actions for a particular instant.

4.4.2. Wholesale Market

As in Three Players Model, the income for REG providers from the wholesale market could proceed from the power injected into the grid by the generators and/or from the energy traded by ES devices when interacting in this market. This is defined as:

$$I_{WM(n)} = P_{WM(n)} \cdot \left(E_{WM\_REG(n)} + E_{WM\_DIS(n)} - E_{WM\_ABS(n)}\right) \quad (4.41)$$

A difference of this model with the Three Players Model is, however, that the energy produced by renewable generators is not calculated based on their active actions for frequency response and energy reserves (as it occurs in Equation 4.14) but it is rather obtained directly from the input regarding RG Power Profile, as follows:

$$P_{REG(n)} \cdot \left(\frac{T_{PER}}{3600}\right) = E_{WM\_REG(n)} \tag{4.42}$$

The following constraints characterise the energy charged and discharged from the ES technologies when interacting in the wholesale market:

$$E_{WM\_DIS(n)} = E_{WM\_DIS1(n)} + E_{WM\_DIS2(n)} \tag{4.43}$$

$$E_{WM\_ABS(n)} = E_{WM\_ABS1(n)} + E_{WM\_ABS2(n)} \tag{4.44}$$

The following conditions are also included in this model in order to permit ES devices to interact with the wholesale market only in the direction of the frequency response or when there is no-service delivered. This not only will prevent ES technologies from affecting the provision of MFR service but also from charging and discharging at the same time.

- If $E_{REQ\_UF(n)} > 0$, then $E_{WM\_\_ABS(n)} = 0$
- If $E_{REQ\_OF(n)} > 0$, then $E_{WM\_\_DIS(n)} = 0$

4.4.3. System Operation and Restrictions

In this model, the energy reserves of REG providers for facing the most onerous cases of frequency deviation and to provide, if required, support with secondary frequency events are entirely kept in the energy-dense storage technology, ES1. As in the Three Players Model, the amount of energy to be stored is calculated using the maximum statutory frequency response requirement established by regulation with a duration of up to T_{REG} as follows:

$$E_{FM\_MAX(n)} \leq E_{RES\_ES1(n)} \tag{4.45}$$

$$E_{CAP\_ES1(n)} \geq \left(\frac{E_{RES\_ES1(n)}}{\eta_{ES1\_DIS}}\right) \cdot \left(\frac{T_{REG} \cdot 60}{T_{PER}}\right) \tag{4.46}$$

The storage capacity of ES1 and ES2, for a specific moment, takes into account all of the energy that enters and leaves each ES device in the form of frequency response, wholesale market interaction or self-discharge losses. This is defined as:

$$E_{CAP\_ES1(n)} - E_{CAP\_ES1(n-1)} = E_{ES1\_IN(n)} - E_{ES1\_OUT(n)} \quad (4.47)$$

$$E_{CAP\_ES2(n)} - E_{CAP\_ES2(n-1)} = E_{ES2\_IN(n)} - E_{ES2\_OUT(n)} \quad (4.48)$$

Being,

$$E_{ES1\_OUT(n)} = \frac{E_{UF\_ES1(n)}}{\eta_{ES1\_DIS}} + \frac{E_{WM\_DIS1(n)}}{\eta_{ES1\_DIS}} + E_{ES1\_LOSS(n)} \quad (4.49)$$

$$E_{ES2\_OUT(n)} = \frac{E_{UF\_ES2(n)}}{\eta_{ES2\_DIS}} + \frac{E_{WM\_DIS2(n)}}{\eta_{ES2\_DIS}} + E_{ES2\_LOSS(n)} \quad (4.50)$$

$$E_{ES1\_IN(n)} = E_{OF\_ES1(n)} \cdot \eta_{ES1\_ABS} + E_{WM\_ABS1(n)} \cdot \eta_{ES1\_ABS} \quad (4.51)$$

$$E_{ES2\_IN(n)} = E_{OF\_ES2(n)} \cdot \eta_{ES2\_ABS} + E_{WM\_ABS2(n)} \cdot \eta_{ES2\_ABS} \quad (4.52)$$

The ES losses are calculated in the MFRA Model based on the energy stored in each ES technology and their individual self-discharge rate as follows:

$$E_{ES1\_LOSS(n)} = E_{CAP\_ES1(n)} \cdot \left(SD_{ES1} \cdot \frac{T_{PER}}{24 \cdot 3600 \cdot 100} \right) \quad (4.53)$$

$$E_{ES2\_LOSS(n)} = E_{CAP\_ES1(n)} \cdot \left(SD_{ES2} \cdot \frac{T_{PER}}{24 \cdot 3600 \cdot 100} \right) \quad (4.54)$$

The following constraint is applied in this model to include the ES costs of degradation:

$$C_{DEG(n)} = \left(E_{ES1\_IN(n)} + E_{ES1\_OUT(n)}\right) \cdot P_{DEG\_ES1} + \left(E_{ES2\_IN(n)} + E_{ES2\_OUT(n)}\right) \cdot P_{DEG\_ES2} \quad (4.55)$$

Where,

$$P_{DEG\_ES1} = \frac{P_{E\_ES1}}{X_1 \cdot CT_1} \quad (4.56)$$

$$P_{DEG\_ES2} = \frac{P_{E\_ES2}}{X_2 \cdot CT_2} \quad (4.57)$$

Finally, the model constraints that consider the power and energy limitations of each ES device, for all of their assigned tasks and allowable operational window, are defined as follows:

$$\left(\frac{E_{RES\_ES1(n)}}{\eta_{ES1\_DIS}}+\frac{E_{WM\_DIS1(n)}}{\eta_{ES1\_DIS}}+E_{ES1\_LOSS(n)}\right)\cdot\frac{3600}{T_{PER}}\leq R_{P\_ES1} \quad (4.58)$$

$$\left(\frac{E_{UF\_ES2(n)}}{\eta_{ES2\_DIS}}+\frac{E_{WM\_DIS2(n)}}{\eta_{ES2\_DIS}}+E_{ES2\_LOSS(n)}\right)\cdot\frac{3600}{T_{PER}}\leq R_{P\_ES2} \quad (4.59)$$

$$\left(E_{OF\_ES1(n)}+E_{WM\_ABS1(n)}\right)\cdot\frac{3600}{T_{PER}}\leq R_{P\_ES1} \quad (4.60)$$

$$\left(E_{OF\_ES2(n)}+E_{WM\_ABS2(n)}\right)\cdot\frac{3600}{T_{PER}}\leq R_{P\_ES2} \quad (4.61)$$

$$E_{CAP\_ES1(n)}\leq SOC_{ES1\_MAX}\cdot R_{E\_ES1} \quad (4.62)$$

$$E_{CAP\_ES2(n)}\leq SOC_{ES2\_MAX}\cdot R_{E\_ES2} \quad (4.63)$$

$$E_{CAP\_ES1(n)}\geq SOC_{ES1\_MIN}\cdot R_{E\_ES1} \quad (4.64)$$

$$E_{CAP\_ES2(n)}\geq SOC_{ES2\_MIN}\cdot R_{E\_ES2} \quad (4.65)$$

As mentioned in Section 4.3.3, in this work, the SOC is assumed to be constant which, in reality, this might not be the case due to ageing effects on the ES technologies. This represents, however, an improvement that is considered to be included in the future work of this thesis. This enhancement will allow a more accurate and detailed representation of ES device during ES sizing process and, thus, producing important findings in the present and future value of these technologies.

As the Three Players Model, this model can also be solved using linear programming as both, the objective function and system constraints, present linear relationships. LP is a deterministic optimization method that guarantees to find reliable solutions which, in this case, is to achieve the highest TSR for REG providers and the related sizing design of each ES technology to achieve this income (if applicable). In the present study, GAMS software, equipped with IBM CPLEX solver, was utilized to build and solve this model.

4.5. FFRA Model

From all framework models, FFRA Model is the only one that considers the provision of a non-mandatory frequency service for REG providers. This is of importance to analyse not only the potential benefits of using ES devices in this context but also the potential advantages or disadvantages that non-mandatory schemes could bring to REG providers with ES technologies. In this model, the overall roles of the generator and ES devices are similar as in the MFRA Model:

- RG is considered to be a passive element which only dispatch power into the grid under the Wholesale Market and has no contribution in frequency support.
- Both ES technologies are active players allowed to participate in non-mandatory frequency response while also interacting with the wholesale market.

In the FFRA Model, the generator was not catalogued as an active player since REG providers are free to propose their own, desired, contribution to the FFR service. Unlike MFR service, this principle makes the system responses an unrestricted variable and, in the context of optimisation problems, the generator would take full advantage of this situation creating unrealistic solutions which not only leaves out the use of ES devices but also unbounded problems for the unlimited bids that can be done by RG.

Although the renewable generator is transformed into a passive element when REG providers are delivering FFR services, the unrestricted bids that can be proposed by REG providers for the provision of frequency support still remain as an issue for solving this model. This is because optimization solvers, in an effort to maximize income, will keep increasing the sizing design of ES devices infinitely while exploiting the system freedom to propose and deliver frequency response.

In order to address the issue with unrestricted bids for FFR provision, the FFRA Model includes a decision stage in which REG providers or investors decide the investment limit that they are willing to spend for acquiring ES technologies. This is not informed by regulation but rather established by the generation providers and their targets in investments. In particular, the present research establishes this limit based on the investment calculated using the MFR model so that comparison can be made between their results (see below). As the main decision variables of this model are the energy and power ratings of the ES devices, this decision stage approach is fundamentally allowing the model solution to achieve the optimal highest TSR for REG providers by not explicitly restricting frequency response but implicitly through the size of ES technologies. As constraints, this decision stage is defined as:

$$C_{ESS} \leq C_{OBJ} \tag{4.66}$$

Where,

- C_{OBJ} is the established investment limit of the project

The comparison between MFRA and FFRA Models takes advantage of this investment target requirement. Here, the MFRA Model is solved for a particular set of inputs as presented in Figure 3.5. The solution of this process will produce, among other things, the capital cost required to purchase an ESS that achieves the highest income for REG providers under the mandatory frequency scheme. This cost could then be introduced into the FFRA Model as the investment limit when comparing both framework models. The rest of inputs also remain the same so that both model solutions are compared under the same ground.

4.5.1 Frequency Market

Although the provision of FFR service is an entire choice of REG providers, the process to calculate the income from their actual delivery of frequency response, in the FFRA Model, is the same as in the other framework models. In the Frequency Market, the prices for this service, at the instant n, are multiplied by the actual response, at that instant, of REG providers using ES technologies for supporting with primary frequency events or high-frequency events, as follows:

$$I_{FM(n)} = P_{FM(n)} \cdot E_{UF(n)} + P_{FM(n)} \cdot E_{OF(n)} \tag{4.67}$$

This frequency support could proceed from any of ES device or from their combination:

$$E_{UF(n)} = E_{UF\_ES1(n)} + E_{UF\_ES2(n)} \tag{4.68}$$

$$E_{OF(n)} = E_{OF\_ES1(n)} + E_{OF\_ES2(n)} \tag{4.69}$$

Although REG providers are free to bid their own contribution to FFR service, one of the tender requirements for firm frequency response is, however, to deliver a minimum response of 1MW, whether from a single unit or using multiple aggregated units, whenever a response is delivered. For that reason, this condition only affects the FFRA model when primary frequency response and high frequency response take place from REG providers. The challenge when modelling, however, is that one constraint (i.e.

providing a frequency response of at least 1MW) will always be dependent on the occurrence of another event (i.e. REG providers deciding to offer frequency response at a specific instant), creating in the model conditional constraints.

The drawback of conditional constraints is that they make endogenous problems when solving models with LP. In this context, one approach to model and achieve feasible solutions in problems containing conditional constraints while maintaining linear relationships among the entire model is to apply a technique known as big-M method [151]–[153]. The basic concept of this method is to include artificial binary variables and very large positive limits, allowing the reformulation of the conditional constraints by linear relationships. In this case, these additional elements must affect the system variables that reflects the provision of primary frequency response and high frequency response so that a minimum 1MW dispatched is ensured whenever the response is appointed, as follows:

$$E_{UF(n)} \leq \left(10^4 \cdot \frac{T_{PER}}{3600}\right) \cdot M_{1(n)} \tag{4.70}$$

$$E_{UF(n)} \geq \cdot \left(1 \cdot \frac{T_{PER}}{3600}\right) - \left(10^4 \cdot \frac{T_{PER}}{3600}\right) \cdot \left(1 - M_{1(n)}\right) \tag{4.71}$$

$$E_{OF(n)} \leq \left(10^4 \cdot \frac{T_{PER}}{3600}\right) \cdot M_{2(n)} \tag{4.72}$$

$$E_{OF(n)} \geq \cdot \left(1 \cdot \frac{T_{PER}}{3600}\right) - \left(10^4 \cdot \frac{T_{PER}}{3600}\right) \cdot \left(1 - M_{2(n)}\right) \tag{4.73}$$

Where,

- $M_{1(n)}$ and $M_{2(n)}$ are the artificial M variables

In Equation 4.70, an additional constraint is created in the FFRA Model to limit primary frequency response of REG providers to a very large unrealistic value (i.e. 10 GW) whenever the artificial binary variable $M_{1(n)}$ is equal to 1. The alternative scenario for Equation 4.70 is forcing the primary frequency response ($E_{UF(n)}$) to be 0 whenever the artificial variable is 0 (i.e. $M_{1(n)}$=0). As the solution of this model aims to maximize TSR for REG providers, $M_{1(n)}$ will only be 1 in cases where primary response $E_{UF(n)}$ are required and can be profitable for the system.

Equation 4.71 is the link of this method to ensure $E_{UF(n)}$to be greater that 1MW if the primary frequency response exists. In this equation, whenever $M_{1(n)}$ is 1, the primary response $E_{UF(n)}$ is forced to be greater than or equal to 1. However, in cases where $M_{1(n)} = 0$, the very large value (10^4) forces the right part of Equation 4.71 to be negative, which automatically produce, at least, a zero response for primary frequency events since $E_{UF(n)}$ has been defined as a positive variable. From Equation 4.70, it is known that $E_{UF(n)}$ is going to be 0 whenever $M_{1(n)}$ is equal to 0. Following this logic, the big-M method guarantees the FFRA Model to meet a minimum of 1MW tender requirement whenever primary frequency response is provided by REG providers. The same logic applies, however, for high frequency response with Equation 4.72 and Equation 4.73.

In this model is assumed that, although firm frequency response is not a mandatory requirement by regulation, REG providers will only make bids for frequency service in the direction of grid-frequency. This condition is not only accurate to represent actual grid requirements that ESOs might need to address frequency deviations but also to restrict ES technologies from charging and discharging simultaneously (i.e. avoiding a non-linearity constraint for this purpose).

4.5.2. Wholesale Market

The income for REG providers from the wholesale market proceed from the power delivered by RG into the grid and from the energy traded by ES technologies when interacting with the wholesale market. This process is carried out at each instant n as follows:

$$I_{WM(n)} = P_{WM(n)} \cdot \left(E_{WM\_REG(n)} + E_{WM\_DIS(n)} - E_{WM\_ABS(n)}\right) \quad (4.74)$$

As REG is also playing a passive role in this model, the generator will not contribute with frequency response and system reserves in any case. This makes the energy injected into the grid under the Wholesale Market ($E_{WM\_REG(n)}$) the only responsibility to be considered for the renewable generator. This is defined as:

$$P_{REG(n)} \cdot \left(\frac{T_{PER}}{3600}\right) = E_{WM\_REG(n)} \quad (4.75)$$

The following constraints characterise the energy charged and discharged from the ES technologies when interacting with the Wholesale Market:

$$E_{WM\_DIS(n)} = E_{WM\_DIS1(n)} + E_{WM\_DIS2(n)} \tag{4.76}$$

$$E_{WM\_ABS(n)} = E_{WM\_ABS1(n)} + E_{WM\_ABS2(n)} \tag{4.77}$$

When interacting with the wholesale market, it is also important to prevent ES devices from charging and discharging at the same time due to the price difference between the wholesale market and frequency market. This can be achieved by conditioning the ES technologies to only interact with the wholesale market in the direction of the grid-frequency or in any direction whenever grid-frequency is within statutory limits. This information is processed from the input data of grid-frequency profiles.

4.5.3. System Operation and Restrictions

In the FFR service, REG providers are not obligated to keep energy reserves to face the worst cases of frequency deviations as occurs in Three Players Model and MFRA Model. Nevertheless, they still must ensure energy reserves for addressing secondary frequency response that could follow the actual provision of primary response. This is defined as:

$$E_{CAP\_ES1(n)} \geq \left(\frac{E_{UF\_ES1(n)}}{\eta_{ES1\_DIS}} + \frac{E_{UF\_ES2(n)}}{\eta_{ES2\_DIS}}\right) \cdot \left(\frac{T_{REG} \cdot 60}{T_{PER}}\right) \tag{4.78}$$

The storage capacity of ES1 and ES2, for a specific interval, considers all the energy that enters and leaves each ES device in the form of frequency response, wholesale market interaction or self-discharge loss as follows:

$$E_{CAP\_ES1(n)} - E_{CAP\_ES1(n-1)} = E_{ES1\_IN(n)} - E_{ES1\_OUT(n)} \tag{4.79}$$

$$E_{CAP\_ES2(n)} - E_{CAP\_ES2(n-1)} = E_{ES2\_IN(n)} - E_{ES2\_OUT(n)} \tag{4.80}$$

Being,

$$E_{ES1\_OUT(n)} = \frac{E_{UF\_ES1(n)}}{\eta_{ES1\_DIS}} + \frac{E_{WM\_DIS1(n)}}{\eta_{ES1\_DIS}} + E_{ES1\_LOSS(n)} \tag{4.81}$$

$$E_{ES2\_OUT(n)} = \frac{E_{UF\_ES2(n)}}{\eta_{ES2\_DIS}} + \frac{E_{WM\_DIS2(n)}}{\eta_{ES2\_DIS}} + E_{ES2\_LOSS(n)} \tag{4.82}$$

$$E_{ES1\_IN(n)} = E_{OF\_ES1(n)} \cdot \eta_{ES1\_ABS} + E_{WM\_ABS1(n)} \cdot \eta_{ES1\_ABS} \tag{4.83}$$

$$E_{ES2\_IN(n)} = E_{OF\_ES2(n)} \cdot \eta_{ES2\_ABS} + E_{WM\_ABS2(n)} \cdot \eta_{ES2\_ABS} \tag{4.84}$$

The energy losses of this model are obtained based on the energy stored in each ES device and their individual self-discharge rate as follows:

$$E_{ES1\_LOSS(n)} = E_{CAP\_ES1(n)} \cdot \left(SD_{ES1} \cdot \frac{T_{PER}}{24 \cdot 3600 \cdot 100} \right) \tag{4.85}$$

$$E_{ES2\_LOSS(n)} = E_{CAP\_ES1(n)} \cdot \left(SD_{ES2} \cdot \frac{T_{PER}}{24 \cdot 3600 \cdot 100} \right) \tag{4.86}$$

The costs of degradation take into account all the energy that circulates in each ES technology and their individual cost of degradation:

$$C_{DEG(n)} = \left(E_{ES1\_IN(n)} + E_{ES1\_OUT(n)} \right) \cdot P_{DEG\_ES1} + \left(E_{ES2\_IN(n)} + E_{ES2\_OUT(n)} \right) \cdot P_{DEG\_ES2} \tag{4.87}$$

Where,

$$P_{DEG\_ES1} = \frac{P_{E\_ES1}}{X_1 \cdot CT_1} \tag{4.88}$$

$$P_{DEG\_ES2} = \frac{P_{E\_ES2}}{X_2 \cdot CT_2} \tag{4.89}$$

Finally, the model constraints that consider the power and energy limitations of each ES device, for all of their assigned tasks and allowable operational window, are defined as follows:

$$\left(\frac{E_{RES\_ES1(n)}}{\eta_{ES1\_DIS}} + \frac{E_{WM\_DIS1(n)}}{\eta_{ES1\_DIS}} + E_{ES1\_LOSS(n)} \right) \cdot \frac{3600}{T_{PER}} \leq R_{P\_ES1} \tag{4.90}$$

$$\left(\frac{E_{UF\_ES2(n)}}{\eta_{ES2\_DIS}} + \frac{E_{WM\_DIS2(n)}}{\eta_{ES2\_DIS}} + E_{ES2\_LOSS(n)} \right) \cdot \frac{3600}{T_{PER}} \leq R_{P\_ES2} \tag{4.91}$$

$$\left(E_{OF\_ES1(n)} + E_{WM\_ABS1(n)} \right) \cdot \frac{3600}{T_{PER}} \leq R_{P\_ES1} \tag{4.92}$$

$$\left(E_{OF\_ES2(n)} + E_{WM\_ABS2(n)}\right) \cdot \frac{3600}{T_{PER}} \leq R_{P\_ES2} \tag{4.93}$$

$$E_{CAP\_ES1(n)} \leq SOC_{ES1\_MAX} \cdot R_{E\_ES1} \tag{4.94}$$

$$E_{CAP\_ES2(n)} \leq SOC_{ES2\_MAX} \cdot R_{E\_ES2} \tag{4.95}$$

$$E_{CAP\_ES1(n)} \geq SOC_{ES1\_MIN} \cdot R_{E\_ES1} \tag{4.96}$$

$$E_{CAP\_ES2(n)} \geq SOC_{ES2\_MIN} \cdot R_{E\_ES2} \tag{4.97}$$

As mentioned in Section 4.3.3 and Section 4.4.3, in this work, the SOC is assumed to be constant which, in reality, this might not be the case due to ageing effects on the ES technologies. This represents, however, an improvement that is considered to be included in the future work of this thesis. This enhancement will allow a more accurate and detailed representation of ES device during ES sizing process and, thus, producing important findings in the present and future value of these technologies.

Due to the characteristics of the FFR service, in which the participants are required to propose at least 1MW of response when bidding, and the use of the big-M method, which introduces binary variables into the model, the FFRA model cannot be solved using linear programming as in the rest of the framework models. Instead, in this work, a mixed-integer linear programming (MILP) method using GAMS software and the IBM CPLEX solver is utilized to achieve the simulation outputs of the FFRA Model.

4.6. Conclusion

This chapter has developed models that will allow the techno-economic assessment of the factors influencing the present and future value of ES technologies. All models took into account a REG provider aiming to incorporate ES devices for the participation in multiple markets: Wholesale Market and Frequency Market. In each model, specific considerations, defined in Chapter 3, were applied including active elements of REG provider that are allowed to deliver frequency response and interact with wholesale market, economic and technical constraints to ensure REG providers to comply with specific regulations, the ability of REG providers to keep energy reserves for maximum frequency deviations and secondary frequency response, and the potential of using a HESS if this produces greater income for REG providers. All models were developed with linear relationships among the objective function and system constraints in the form of LP problems, in the case of Three Players Model and MFRA Model, and in the form of MILP problem, in the case of FFRA Model.

In the Three Players Model, the model considers RG as an active player to provide MFR service. As the mandatory frequency scheme determines response requirement, in this model, REG providers are able to apply any of the active elements (i.e. RG, ES1 or ES2) or their combination to achieve service provision while interacting in wholesale market. For MFRA Model, a similar approach as in the Three Players Model is followed with the sole difference of using ES devices, in exclusivity, as active players for the provision of MFR service. Since REG providers are free to offer their services in the FFR service, the approach in the FFRA Model differs from the rest of framework models of this work. Here, the model is built so that the total bids from REG providers for FFR service provision are restricted by defining an investment cost target for acquiring ES technologies. Moreover, the big-M method is also implemented to allow the model having a constraint for a minimum response of 1MW whenever FFR service is provided and to ensure linear relationships among the complete FFRA Model.

Overall, applying the framework models, developed in this chapter, not only will provide specific information regarding maximum TSR of REG providers and ES sizing design but also will permit the study of factors influencing the present value and future benefits when using ES devices. These techno-economic assessments are presented in the forthcoming chapters.

Chapter 5. Framework Assessment of a Three Players Scheme

5.1. Introduction

In Chapter 4, the framework models that will allow the techno-economic assessment of factors influencing the value of ES technologies were developed. These framework models consider REG providers using ES devices for the partial or complete provision of Frequency Services, depending on the model, and for interacting in the wholesale market. In the first model, known as Three Players Model, REG providers could address the provision of MFR service through any of these three players: renewable generators, energy-dense ES device and power-dense ES device. As this framework model is technology agnostic, it can be utilized for a range of different ES technologies. The outcomes after model simulation, aside from the TSR for REG providers, also provide the optimal sizing of ES devices in terms of power and energy ratings. The use of HESS is also implicitly assessed in this model since the solutions could present, if this is the best option, a hybrid ES combination for achieving maximum income.

The main target of the present chapter is to investigate and quantify the techno-economic factors influencing the value of ES devices using the Three Players Model. This model allows to examine the potential effects of utilizing ES technologies in mutual operation with renewable generators to interact with multiple market applications. The chapter is structured, first, to present an initial case in which the value of using ES technologies in conjunction with Solar Farms and together with Wind Farms is assessed. Diverse ES combinations, focused in Electro-chemical Batteries and Supercapacitors, are then utilized to examine, as ES selection process, the best technology in reaching maximum income for REG providers. Following this, multiple sensitivity analyses on the intrinsic technical and economic characteristics of ES devices are examined for present and future ES conditions. The chapter concludes presenting a ranking of the individual contributions on the income of REG provider from each characteristic of ES devices based on their current conditions and future improvements.

5.2. Case Study Description

This initial case study considers a generation provider, with medium-scale renewable generators, forced to participate in a mandatory scheme: MFR service. In this context, investing in ES technologies represents a potential solution for this REG provider to face this mandatory provision of frequency response and to avoid the curtailment of the power output of its RGs. The main target for this REG provider, ultimately, is to achieve the highest income while meeting MFR regulations. The operation strategy, in the Three Players Model, is to utilize RG, ES1 and ES2 to deliver primary response and high-frequency response, RG and ES1 to keep energy reserves, required by regulation, and ES1 and ES2 to further enhance the income of the REG provider in the wholesale market.

In this initial case, the Three Players Model is simulated to obtain the highest TSR for REG providers, throughout 15-years project lifetime, when applying ES devices in mutual operation not only with Wind Generators but also with Solar Generators. By doing this, it is possible to compare the effects of different generation profiles in the system, the consequences that current MFR regulation could have on the income of REG providers and the potential impact of using ES technologies. The inputs to carry out the simulations in this model, described in Section 3.5 and depicted in Figure 3.5, are divided into five groups: power generation profiles, grid-frequency data, energy market prices, economic parameters and ES technical inputs. The actual inputs utilized in this case study are defined below.

5.2.1. Power Generation Profiles

In this case study, the Three Players Model is applied at transmission level and takes into account a 50MW grid-connected Wind Farm. The input power data is a half-hourly wind generation profile acquired from the North East of England and scaled for the purposes of this study. Figure 5.1 presents the representative day of each month based on the half-hourly average of generation.

In Figure 5.1, the minimum generation line represents the lower bound by regulation in which 50MW REG providers might be required to deliver mandatory frequency response i.e. all generation below this limit is not participating in the MFR service.

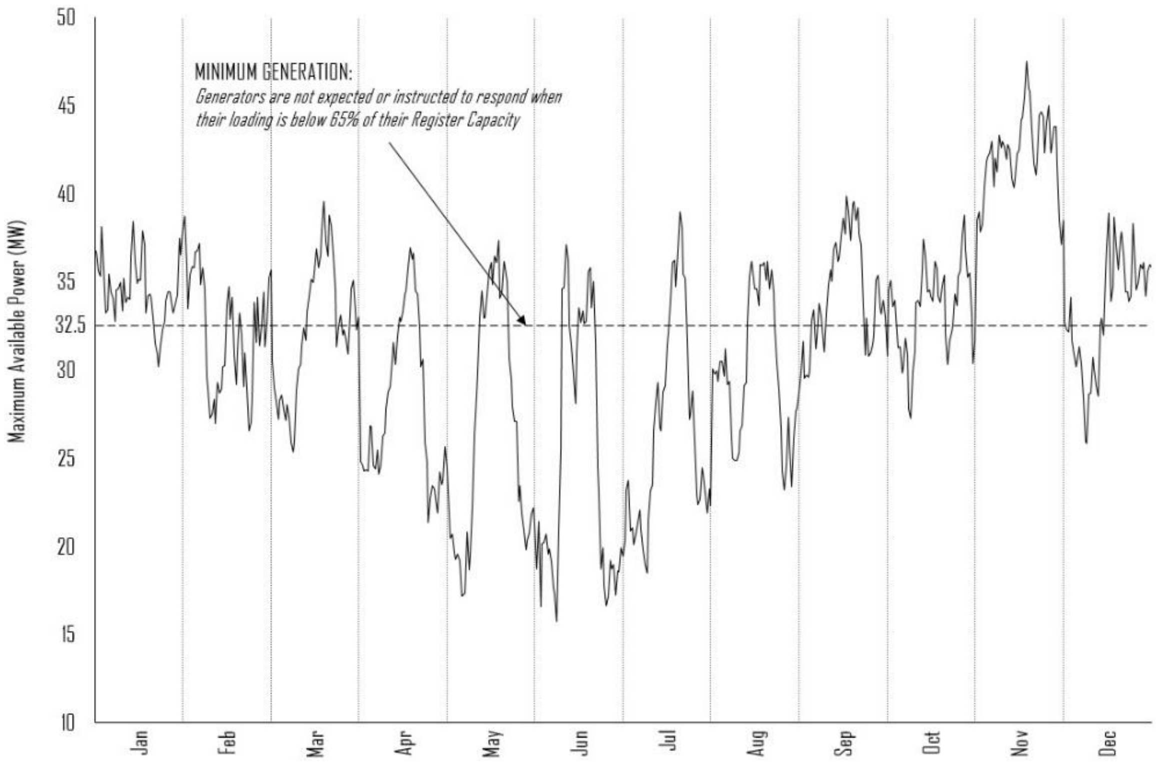

Figure 5.1. Wind Farm – Daily Average Power Generation for each month

For this initial case, the model is also examined using a 50 MW Solar Farm located at Lincolnshire, UK. This data, depicted in Figure 5.2, is obtained based on the hourly averaged solar irradiance data from [154] over a 12-years period from 2005.

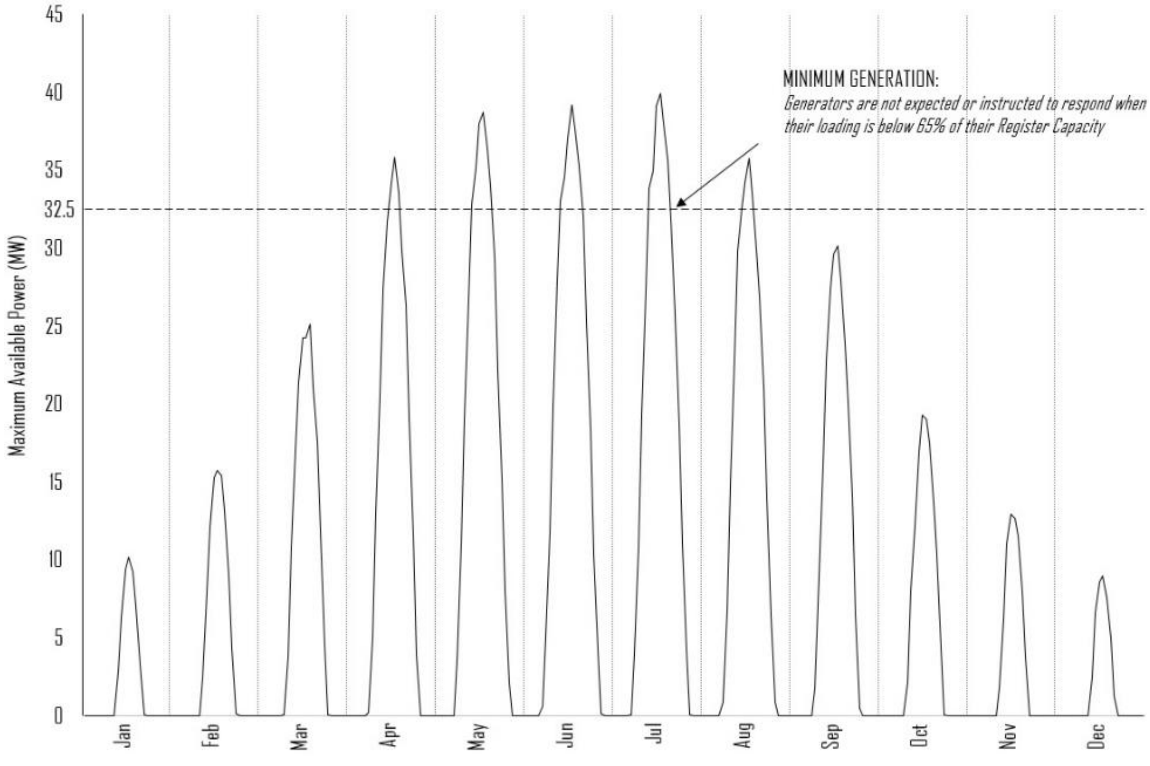

Figure 5.2. Solar Farm – Daily Average Power Generation for each month

5.2.2. Grid-Frequency Data and Market Prices

As the present model is studied under the GB regulations, the grid-frequency data and market index prices are obtained from the Elexon Portal for the year 2017 [155], [156]. In the case of grid-frequency information, the sample time is every 15 seconds. This data is then utilized to calculate frequency requirements for primary response and high frequency response using the procedure described in Section 3.2 (i.e. frequency response must be proportional to frequency-deviations of Figure 3.1). It is important to mention that the rest of input parameters are adjusted to a 15-seconds sample time as this represents the shortest sampling time of all data (T_{PER}). This procedure was previously defined during the design of framework models in Chapter 3.

Figure 5.3 presents part of the grid-frequency profile used in this study for a 6-hours window while Figure 5.4 depicts the power requirements, in November, for renewable generators based on the GB Grid Code and the conditions of the grid-frequency.

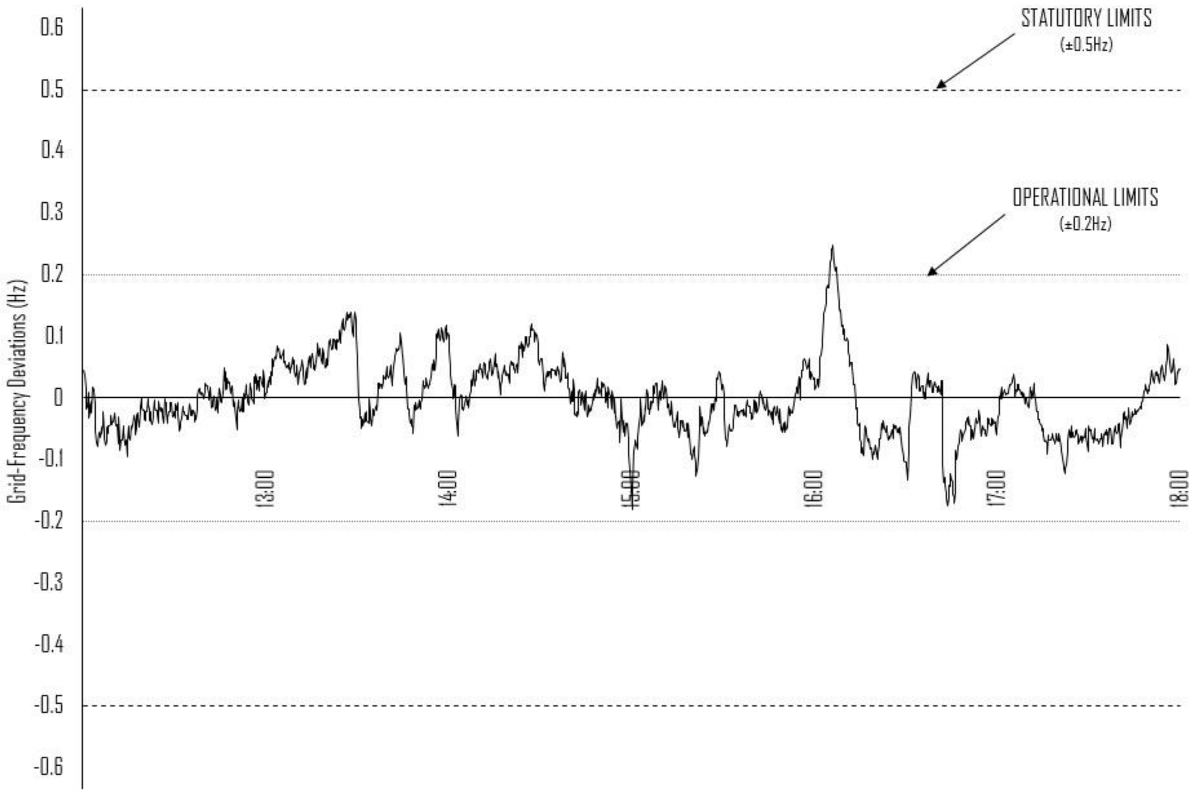

Figure 5.3. Grid-frequency profile during a 6-hours window

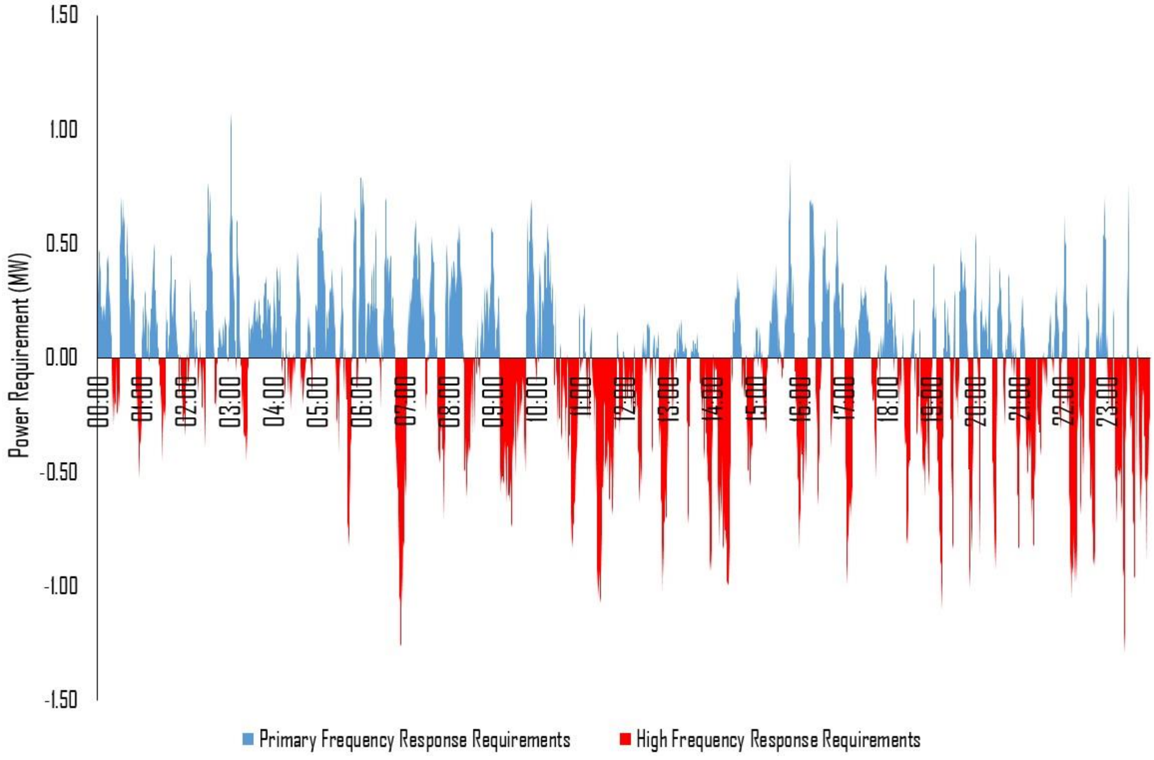

Figure 5.4. Frequency Response Requirements by UK regulation

Regarding the market prices, the sample time follows 30-minutes period as established by the GB market settlement periods. Figure 5.5 presents a half-hourly average of the Wholesale Market short-term spot market prices for each month during 2017.

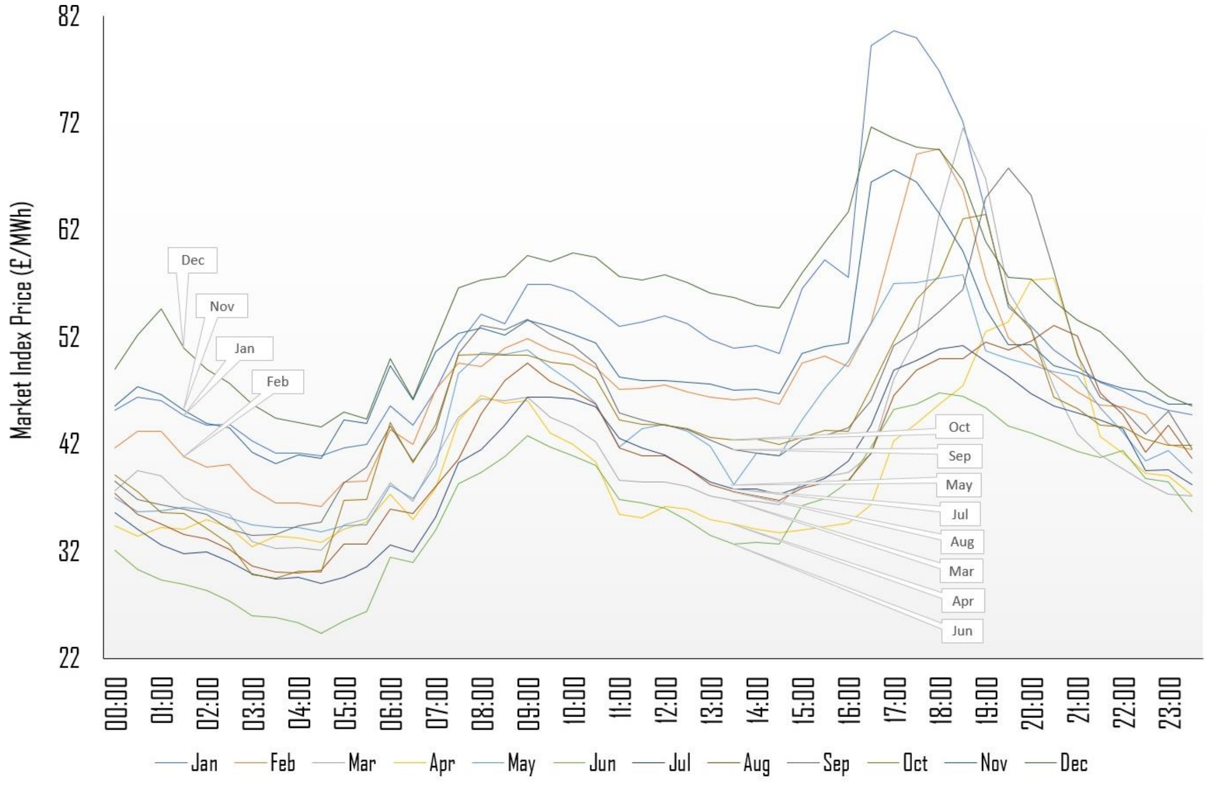

Figure 5.5. Monthly Average of Market Index Prices in 2017

As shown in Figure 5.5, the Wholesale Market prices are likely to achieve the highest value between 1700h to 1900h (i.e. during peak time) while November represents the month that reaches the maximum price in 2017. For this reason, it could be expected that model outcomes from November would result in the most profitable income in comparison with the rest of the months.

5.2.3. Economic and Technical Parameters

The Three Players Model takes into account a potential HESS composed of one energy-dense ES technology and one power-dense ES technology. In particular, for this initial case study, the hybrid storage system is composed of vanadium redox flow batteries (VRFB) and supercapacitors. The technical features utilized in this initial case for these devices are based on the literature review presented in Table 2.2. The maximum and minimum state of charge (SOC) are assumed to have a complete operation window for this case study (i.e. an operation window from 0% to 100%). In reality, this operation window could vary depending on the ES technology characteristics and the operational restrictions. This factor is considered during the sensitivity analysis later on.

The economic paraments of ES technologies refer to the interest rate assumed for the ES investment project and the prices of energy and power components of ES devices. Both, economic and technical paraments of VRFB and Supercapacitors, utilized in this initial case study are summarized in Table 5.1.

	Parameters	VRFB	Supercapacitor
Technical	Charging/Discharging Efficiency (%)	92	90
	Maximum SOC (%)	100	100
	Minimum SOC (%)	0	0
	Cycling Lifetime (cycles)	15,000	500,000
	ES Lifetime (years)	15	15
	Daily self-discharge (%)	0.25	10
Economic	Cost of Energy (£/kWh)	280	5,000
	Cost of Power (£/kW)	700	120
	Interest Rate (%)	3	3
	Project Lifetime (years)	15	15

Table 5.1. Technical and Economic Parameters of Initial Case Study

As shown in Table 5.1, the VRFB technology presents remarkable advantages over supercapacitors referring to the costs of energy component and daily self-discharge. This could potentially make this ES technology suitable for energy-dense applications. Conversely, Supercapacitors (SC) are superior than VRFB in terms of cycling lifetime and costs of power component, making them potentially attractive for power-dense applications.

5.3. Case Study Simulation

As discussed in Chapter 4, the Three Players Model presents a linear objective function and system constraints which allows to achieve its solutions through LP. In this work, the complete model was developed and solved using GAMS software. The present case study not only can provide specific TSR for REG provider and the related ES sizing design to achieve these revenues for a 15-years project duration but also can be used to compare benefits of using ES technologies in conjunction with Wind Generators and together with Solar Generation. Table 5.2 encompasses the main outputs after simulation of this model.

	Total Project Revenue (millions)	**ES Ratings**
Wind Farm	£182.24	VRFB: 3.5MW/1.8MWh Supercapacitor: -
Solar Farm	£47.10	VRFB: - Supercapacitor: -

Table 5.2. Initial Case Study of Three Players Model – Solar and Wind farm Income and ES ratings using UK energy market prices

The outcomes of this case study showed that the 50MW Wind Farm can reach a TSR of £182.24 million by investing in a VRFB technology sized as 3.50MW/1.84MWh. This represents an additional revenue of £135.14 million over the maximum income achieved REG provider using Solar Generation. The model outputs also indicate that this Solar Farm does not require an investment in ES technologies to reach its highest revenue while complying with MFR regulation. This means that mandatory frequency response and energy reserves are fully addressed through Solar Generators reactions and by curtailing the power output of these RGs when required.

For Solar generation providers, both conditions, lower profitability and non-using ES devices, are mainly caused by their reduced power production in compassion to Wind generation providers. In Figure 5.1 and Figure 5.2, it can be visualized, in a clear way, that solar generation is lower than wind generation during most of the time around the year. This principle, in turn, will produce lower income every month for REG providers. Figure 5.6 presents the simulation results for the monthly income of both providers, Solar generation provider and Wind generation provider, for this case study per year.

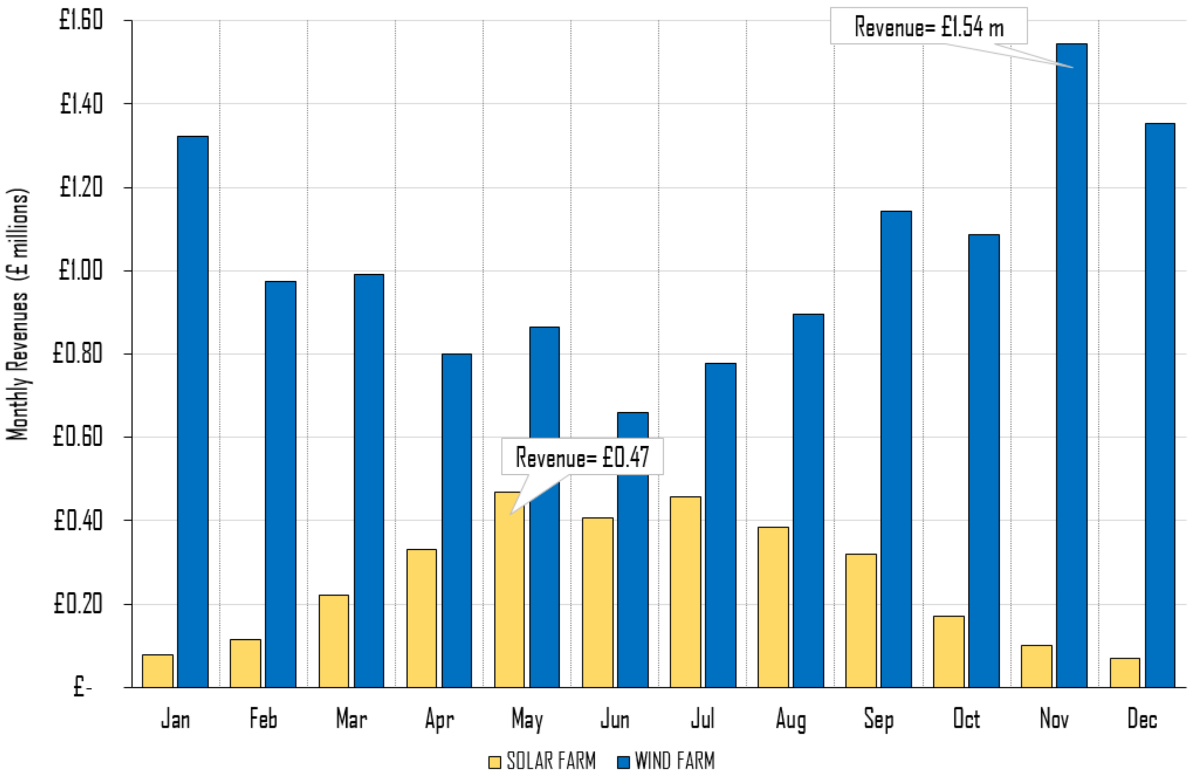

Figure 5.6. Monthly Revenues per year reached by Wind and Solar Farms in Three Players Model when REG providers are participating as common generation plants in the Wholesale Market

It is important to mention that simulation results presented in Table 5.2 and Figure 5.6 were obtained assuming that renewable generation, both solar and wind farms, are participating in the wholesale market and frequency market under the same conditions as other traditional generation plants. As explained in Section 2.3.3 and Section 4.3.3, although contracts for difference is the norm in the UK for REG providers, in this research, REG providers were considered to be interacting in the wholesale market as traditional generation plants in order to present a methodology that could be applied to other markets from around the world in which CfDs does not exist. Nevertheless, it is critical to compare the results in both scenario (i.e. normal wholesale market conditions vs CfDs) to ensure that the findings of this research are valid regarding present and future value of ES technologies.

In the last CfD allocation round in 2019 for the UK [157], a 49.5 MW wind farm (Druim Leathann Windfarm) was a successful applicant with a flat price of 41.611 (£/MWh) in 2012 prices. Taking into account this information to be the fixed payment price input in the Three Players Model, the results obtained, after simulations, are presented in Table 5.3.

	Total Project Revenue (millions)	**ES Ratings**
Wind Farm	£179.14	VRFB: 3.4MW/1.8MWh Supercapacitor: -
Solar Farm	£48.96	VRFB: - Supercapacitor: -

Table 5.3. Initial Case Study of Three Players Model – Solar and Wind farm Income and ES ratings when REG providers are participating with a CfD scheme

The results presented in Table 5.3 show a very small difference in the size of the ES system required and in the TSR that can be reached by the Wind Farm and Solar Farm when considering a common wholesale market participation vs when REG providers are participating using a CfD scheme. This small difference can be further observed when comparing the monthly revenues of the Wind Farm and the Solar Farms in Three Players Model when:

- REG providers are participating as a common generation plant in the wholesale market (see Figure 5.6)
- REG providers are participating with CfD scheme in the wholesale market (see Figure 5.7)

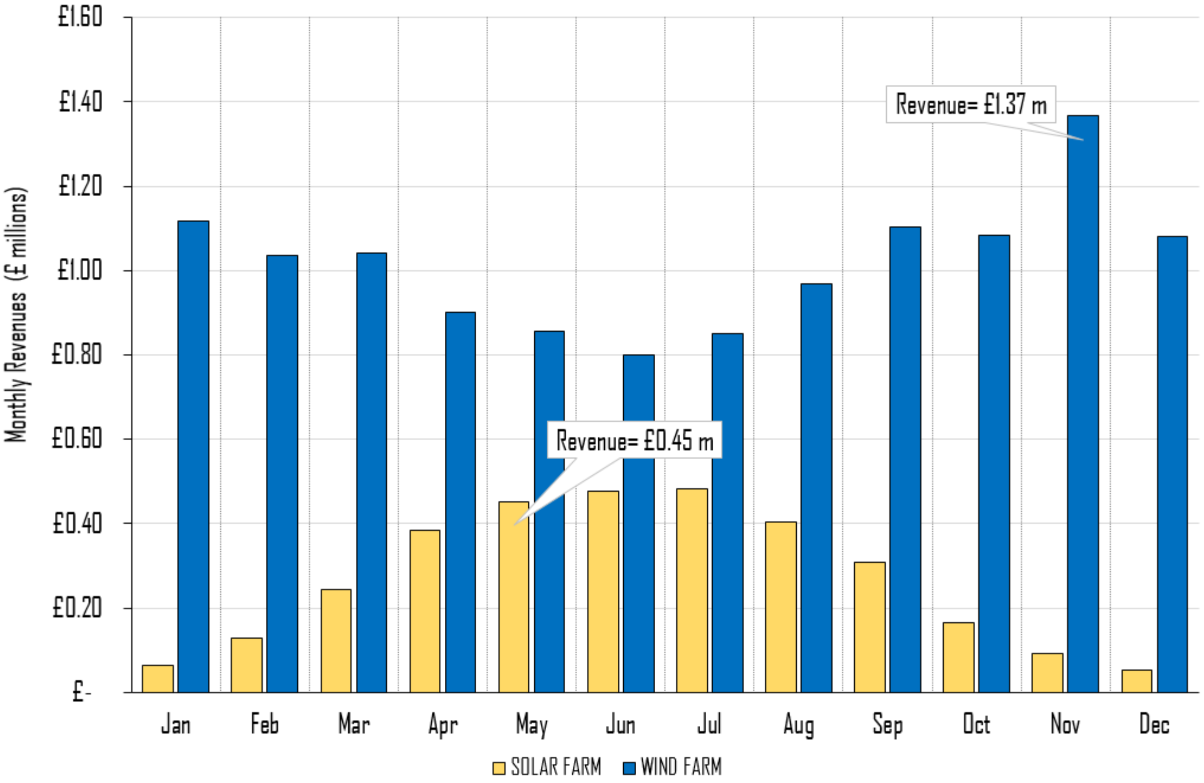

Figure 5.7. Monthly Revenues per year reached by Wind and Solar Farms in Three Players Model when REG providers are participating with a CfD scheme in the Wholesale Market

The simulation results of these two wholesale market participation schemes for REG providers have also shown a very small difference between them regarding the income coming from the ES system and its interaction with multiple energy markets for a 15-year project duration as shown in Table 5.4:

ES Income	REG Participating in Wholesale Market	REG Participating with CfD fixed price	Difference between Schemes
Income from Wholesale Market	$344,320	$355,510	$11,190
Income from Frequency Market	$594,980	$605,300	$10,320

Table 5.4 ES incomes from the wholesale market and frequency market when REG Providers are participating in wholesale market and with a fixed price from CfD scheme

Based on the aforementioned results, this research have shown that a relatively small difference in the TSR of REG providers is driven by the input price used in the Three Players Model when considering a common REG provider participation in wholesale market and when participating with a CfD scheme without affecting the contribution of the ES devices. This means that the techno-economic analysis performed using ES technologies is not affected to a significant extent by the market price input in the Three Players Model. Therefore, the rest of the document is developed taking into account REG providers participating in the wholesale market as common generation plants rather than join in with a CfD scheme.

As described in Section 4.3, the Three Players Model considers a REG provider compromised to meet MFR service. This involves that, aside from supplying power to the wholesale market, a portion of generation is both destined to address frequency requirements and being reduced to maintain reserves able to cover onerous cases of frequency deviation as stipulated by regulation. Moreover, it is important to mention that wind generation profile is not a constant value (i.e. constant 50MW rated capacity) and the market prices are also fluctuating. Therefore, the revenues presented in Figure 5.6 cannot be calculated by simple multiplication of static market price with energy delivered. It is rather obtained by having into account MFR requirements and ES operation as developed in Chapter 4. It is important to mention, however, that load factors are not directly considered within this study models since power generation profiles are inputs of the models and loading factors can be applied from the raw data stage rather than during model development and optimization process.

In Figure 5.6, it can be seen that the Wind Farm reaches the best income of the year during November (£1.54 millions) while the Solar Farm only achieves less than a third of this income during its best month (i.e. £0.47 million during May). However, the lower generation presented by the Solar Farm not only implied a reduced revenue stream from the Wholesale Market but also the inability of profiting from the MFR service during the majority of the months each year. This is because the minimum generation requirement of this REG provider for being engaged in MFR participation is not realised by Solar Generation for seven months, from January to March and from September to December. Figure 5.8 provides the monthly revenues of REG providers exclusively coming from the provision of frequency services in this case study.

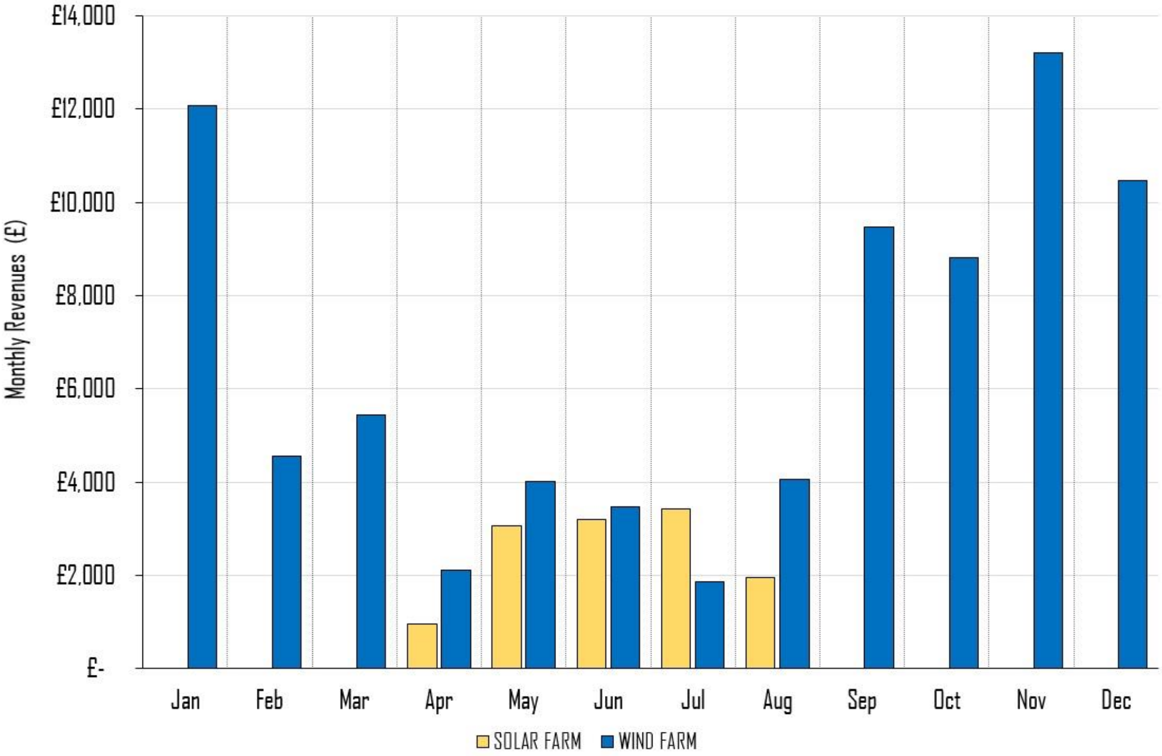

Figure 5.8. Monthly Frequency Income per year reached by Wind and Solar Farms in Three Players Model

As shown in Figure 5.8, the REG provider using Solar Generation is not capable of producing income from frequency services most of the time, with the exception of summer period. For this reason, it is not the best option for REG provider to invest in ES devices to receive support with the MFR service. Interacting with the wholesale market, on the other hand, could still be a possible alternative of this Solar generation provider to exploit the use of ES devices. However, based on the simulation results, interacting with the wholesale market would not be a strong argument on its own to make a full investment for acquiring ES technologies. By assuming a zero-frequency response in the model, it is possible to examine the benefits for REG providers of participating in the wholesale maket exclusively using ES technologies. With this modification, the simulation results returned, for all generation providers, a non-feasibility of applying ES technologies. This makes wholesale market interaction to be considered a benefit that, on its own, is not profitable for REG providers if ES devices are to be acquired only for this purpose.

It is noteworthy that the rest of sections in Chapter 5 are addressed considering only Wind Generation since it allows to study the use of ES technologies in the majority of cases, as shown by the results of the present section.

5.4. Technology Selection

The main goal of this section is to examine the impact that different technologies have on the income of REG providers when collaborating with Wind Generators for providing MFR service and interacting in the wholesale market. The ES technology selection criterion is based on applying a number of ES combinations in the Three Players Model to, ultimately, select the most profitable alternative for REG providers. Table 5.5 summarizes the main characteristics of each ES candidate applied to this model. With the exception of VRFB and Supercapacitors, all of these ES technologies are utilized in Three Players Model as both, energy-dense and power-dense technologies, during the simulations. This makes a total of 31 hybrid ES combinations that were examined for this case study. It is important to acknowledge, however, that further ES technologies and combinations could be analysed using this model as it is ES technology agnostic.

Parameters	NaS	Li-ion	Lead-Acid	Sodium–Nickel Chloride	NiCd
Charge/Discharge Efficiency (%)	87	95	75	85	65
Maximum SOC (%)	100	100	100	100	100
Minimum SOC (%)	0	0	0	0	0
Cycling Lifetime (cycles)	4500	6000	1500	2500	3500
ES Lifetime (years)	15	8	8	15	15
Daily self-discharge (%)	10	0.3	0.2	15	0.4
Cost of Energy (£/kWh)	400	280	180	250	1500
Cost of Power (£/kW)	200	190	180	650	1000

Table 5.5. Technology Selection in Three Players Model – ES Characteristics

Taking into account that model outputs achieves the maximum TSR for REG providers using the most convenient combination of ES technologies, there are multiple cases in which the solution is repeated. This occurs, for instance, when, after assessing a specific ES combination, only a single ES technology is needed by REG providers to reach maximum revenues, but this single technology is also required, on its own, when assessing a different ES combination. For this reason, Figure 5.9 presents the Three Players Model results limited only to the most profitable solutions for REG providers rather than showing all 31 ES combinations.

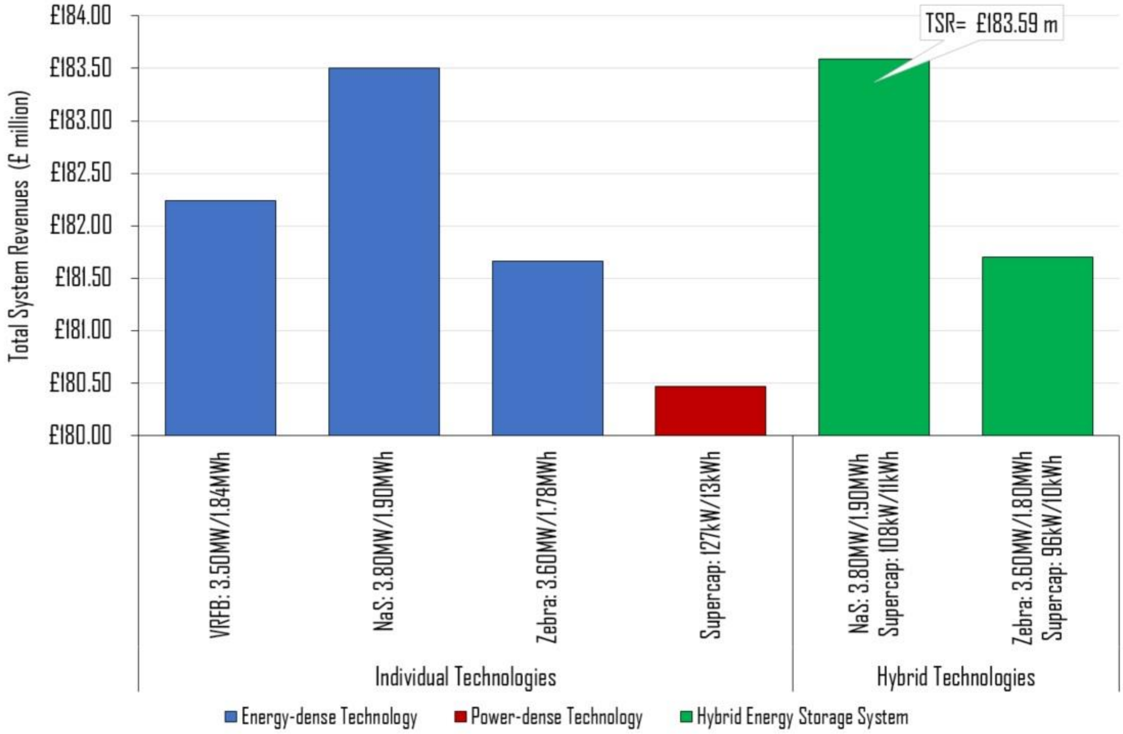

Figure 5.9. Technology Selection – ES Combination Outputs for Three Players Model

As shown in Figure 5.9, the REG provider achieves its highest revenue when investing in a HESS composed of NaS battery and Supercapacitors (i.e. TSR= £183.59 million). This hybrid ES combination provide £3.59 million more revenues for this REG provider than the income achieved using only Wind Generators and £1.35 million more income than considering an individual VRFB battery, as presented in Section 5.3. This makes NaS + Supercapacitor the chosen ES combination for REG provider. In this chapter, the rest of sections are addressed taking into account this HESS combination.

Apart from achieving the best ES combination in terms of income for REG providers, the simulation outputs of this model also show the current potential that relies, for REG providers, on applying multiple ES devices to address multiple market interactions. It is important to acknowledge, however, that hybridizing an ESS could achieve the best outcome in specific cases only as the majority of profitable options for REG providers, in this case, involved the use an individual ES device (see Figure 5.9). The only HESS combinations that were a feasible option to invest for REG providers were:

- NaS + Supercapacitor and,
- Sodium–nickel chloride + Supercapacitors

In both ES combinations, the hybridization of the ESS occurred using Supercapacitors as the power-dense technology. Based on the Three Players Model results for REG providers using NaS batteries and Supercapacitors, the role of the latter ES technology was found to be focused on primary frequency response, high frequency response and wholesale market interaction while NaS batteries were mainly used for energy reserves and high frequency response.

Since energy reserves are required by MFR regulation but do not represent a direct revenue to REG providers, the investment cost for a large-scale NaS technology is high for REG providers and investors. This expense can, however, be compensated by the increment in the wholesale market income that Wind Generators can reach. The simulation results showed that, although ES technologies support REG providers with Frequency Service, the renewable generators still take most of the responsibility to meet MFR requirements. That is the reason why the power and energy ratings of Supercapacitors are relatively small. The contribution of each ES device, expressed as individual income, to the TSR of REG providers is showed in Figure 5.10 over a 15-year period.

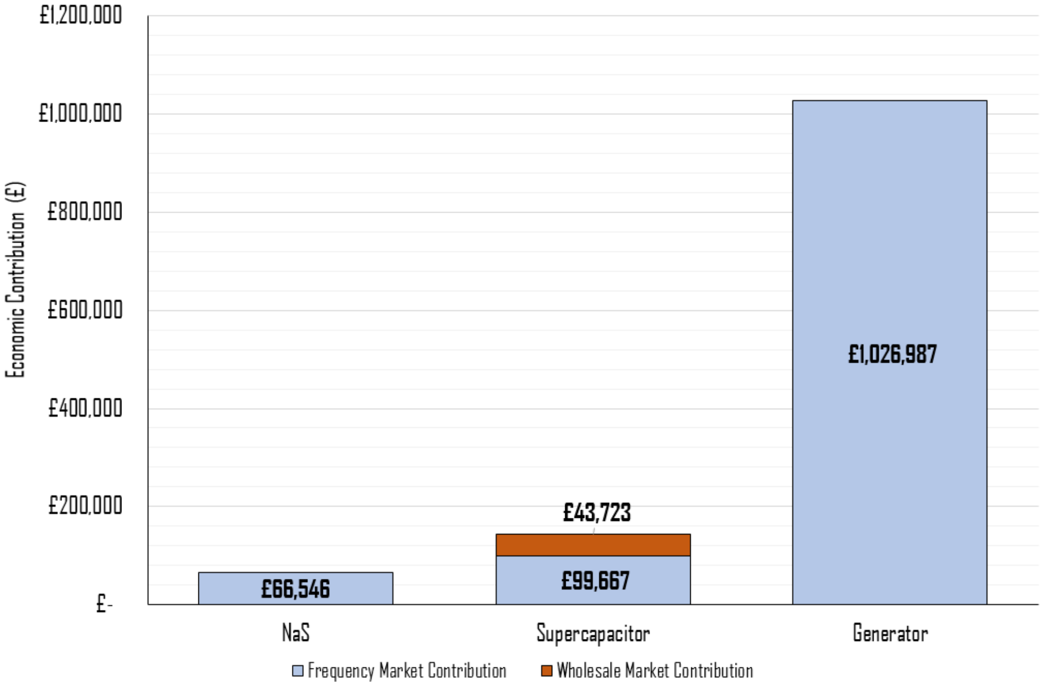

Figure 5.10. Technology Selection - Individual Contributions to Total System Revenues

In Figure 5.10, it is presented not only the individual contribution of each ES device to the TSR of the REG provider but also the market from which the income proceeds. To achieve the highest revenue for the system, the results show that NaS batteries are only interacting with the Frequency Market while supercapacitors are performing interactions in both markets. Figure 5.11 is also introduced in order to have a more detailed representation of the individual contributions of each ES technology from interacting with each market.

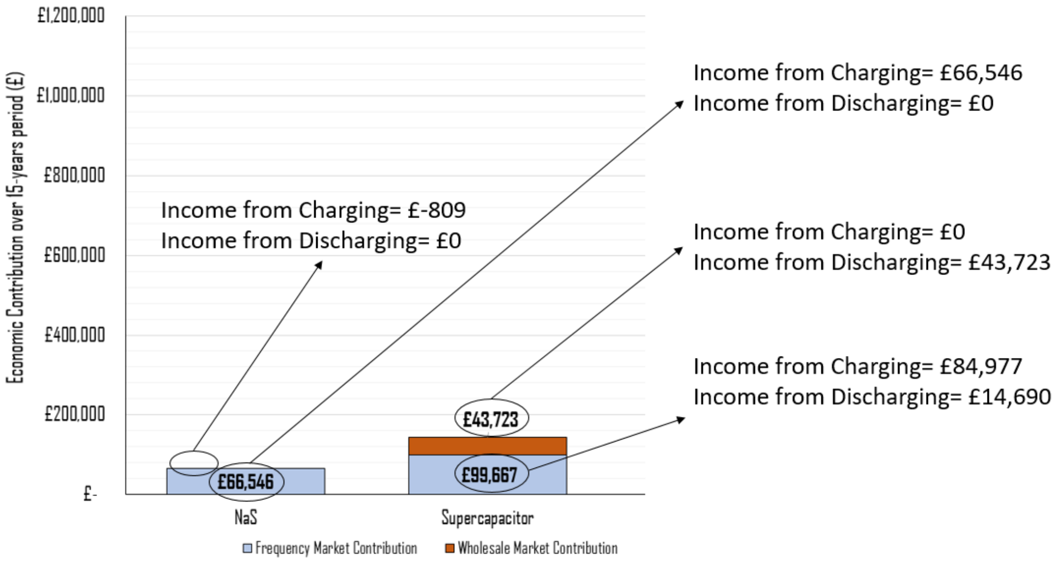

Figure 5.11. Explanation of the Individual Contributions of ES system to the Total System Revenues

The simulation results presented in Figure 5.11 show that the ES system is actually interacting with both markets by taking advantage of the price fluctuation and meeting grid-regulations as developed in the Three Players Model. The advantage does not involve only interacting in the same energy market for charging and discharging tasks, but it also considers the possibility of profiting from other market. In Figure 5.11, for instance, supercapacitor obtains incomes for charging exclusively from the Frequency Market while achieves revenues from discharging in both markets, depending on the most profitable scenario, calculated by the optimization process. It is also important to mention that, for reaching these results, the supercapacitors are required to operate 16,000 cycles per year which represented a total of 273,750 cycles throughout the complete 15-year project scope and an average of 44 cycles per day. By taking into account that the cycling lifetime of a supercapacitor was determined in 500,000 cycles (see Table 5.1), the operation of this device does not exceed its cycling characteristics.

In the Three Players Model simulation results presented in Figure 5.9, it can also be observed that Li-ion and Lead-acid batteries could not reach the maximum revenue for REG providers in comparison with other ES alternatives. This is because of the limited manufacturing lifetime considered for these devices. In both cases, Li-ion and Lead-Acid, the manufacture lifetime is considered to be the lifetime duration of the devices according to the manufacturer and it was determined to 8 years based literature data from Table 2.2 and described in Section 3.5. As the project scope was established to 15 years (see Section 5.2), both ES technologies require an extra investment for a new set of devices which, in turn, increases investment costs. If the project scope were to be, for instance, 7 years then both ES devices would become a more attractive option, on their own, for REG providers. This scenario was tested in the Three Players Model against the best ES combination obtained for a 15-year project (i.e. ES combination of NaS and Supercapacitors) and the simulation results are displayed in Table 5.6. It is important to mention, as described in Section 4.3.3, that the present work does not consider the aging effects of ES devices which requires extensive research in circuit modelling (to simulate, for instance, charging/discharging curves) and laboratory testing. Furthermore, such models could become complex and requiring significant efforts from computational software. It is, however, acknowledged by the author that considering an aging model for ES technologies that better represent the variable behaviour of the SOH, SOC and cycling lifetime of ES devices would enhance the results of this work and, thus, the analysis of the present and future economic analysis of these technologies.

Technologies	**Total Project Revenue (million)**	**ES Ratings**
Lead-Acid	£85.30	Lead-acid: 4.2MW/2.1MWh
Li-ion	£85.36	Li-ion: 3.4MW/1.7MWh
NaS + Supercapacitors	£84.88	NaS: 3.5MW/1.8MWh

Table 5.6. Technology Selection – Outputs from short term project scopes

From Table 5.6, it can be seen that Li-ion and Lead-acid batteries have now become more promising candidates for REG providers to make an investment when looking at a 5-year project horizon. In particular, both results achieved a greater income for Wind generation providers than the hybrid combination of NaS and Supercapacitor which, in this case, only requires an individual NaS battery to achieve the highest revenues. This demonstrates the importance for REG providers and investors of selecting an appropriate set of ES technologies taking into account the lifetime scope of the project and the manufacturing lifetime of these ES devices. This could also be important for technology developers to evidence the impact of improving the ES lifetime when ES devices are applied in multiple market applications.

The remainder of Chapter 5 is presented having selected the best ES combination determined during this section for REG providers: NaS batteries as energy-dense ES technology and Supercapacitors as power-dense ES technology.

5.5. Sensitivity Analysis on ES Economic Parameters

Investigating techno-economic factors of ES technologies involve analysing each key element, described in Section 1.3, that influence the present and future value of energy storage. In this research, the approach followed in Chapter 5 was first to investigate the value of using ES technologies in conjunction with different renewable generators (i.e. Solar Farms and Wind Farms) for REG providers when participating in MFR service while also interacting in the wholesale market. This approach is of importance to understand the value of ES technologies when supporting REG integration from different sources. Moreover, the value of ES technologies was also examined in this work by taking into account technology selection processes. The results of this factor could help different energy actors to visualize the how selecting a specific ES device or a hybrid combination of them is key for decision-making processes that could increase revenues while complying with grid-commitments.

In this Section 5.5, and in Section 5.6, it is analysed the value of ES technologies from the economic factors and inner technology features point of view that directly influence the value of ES devices and, thus, the systems in which these devices are applied. For these sections, the approach followed to examine the present and future value of ES devices is to perform sensitivity analyses to represent current conditions and potential future changes that could occur for these influencing factors.

5.5.1. Impact of ES Prices of Energy and Power components

The prices of the energy and power components of ES technologies are key factors that might influence the TSR that REG providers can achieve when using ES devices and the ES sizing design. The present section carries out a sensitivity analysis on these economic components of ES devices in order to examine their impacts on the income of REG providers. This study takes into consideration a hybrid system composed of a NaS technology and Supercapacitors and the simulation utilizes all the required inputs from November as this represented the most profitable month of the year and for simulation simplicity. As we aim to analyse economic patterns in the simulation outputs for this model, this assumption does not affect the conclusions of the analysis.

The simulation results for the Three Players Model applied in this sensitivity analysis of economic parameters are presented in Figure 5.12. This figure shows the effects of REG provider Income when changing the ES components price for each ES technology individually and for both ES devices simultaneously. These results are all expressed as additional revenues over the TSR that can be achieved by REG provider when non-using ES technologies for the provision of MFR service.

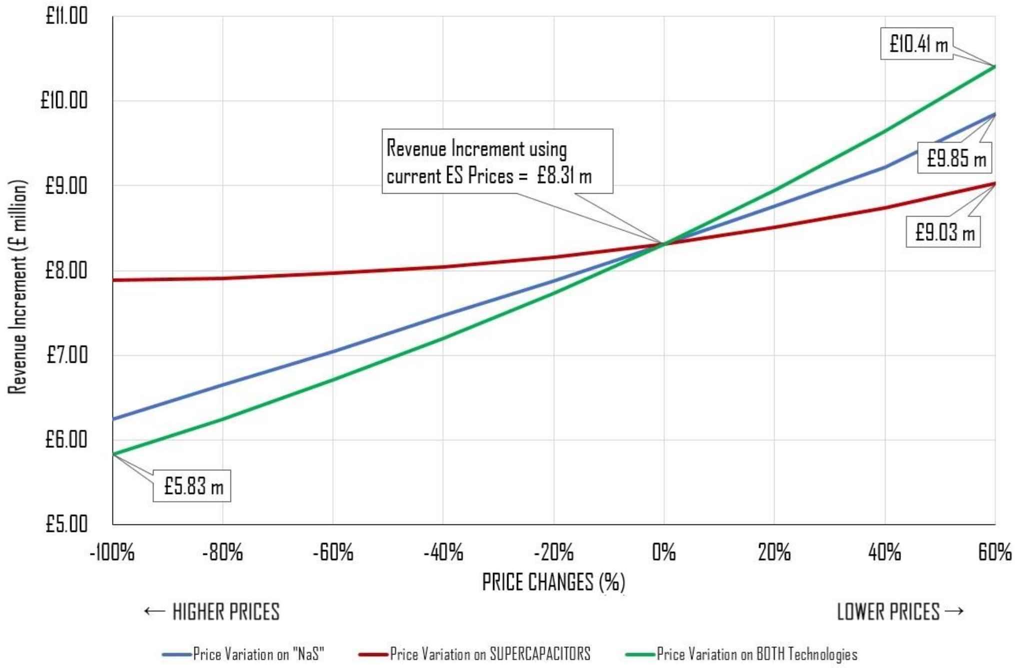

Figure 5.12. Sensitivity Analysis in Three Players Model – ES Components Price

From Figure 5.12 to Figure 5.16, it can be seen that this work presents higher prices as negative values since this represents a negative improvement (depreciation) of the prices that were considered to be current conditions. In this context, lower prices from current conditions are assumed to be positive as they represent future enhancements from current conditions allowing to analysed their influence in the value of ES devices.

As shown in Figure 5.12, the current components prices of ES devices (see Table 5.1 and Table 5.5) can achieve an increment in the TSR of REG providers of £8.31 million over the income obtained without ES technologies. When these ES Components Prices are assumed to be more expensive, however, investing in ES devices is still profitable for REG providers but at a lower degree. In particular, if the costs for energy and power components are twice the value of the current component prices for both

ES technologies, the revenue increment in the TSR of REG providers only reaches £5.83 million. If these ES component prices are, however, reduced, the revenue increments for REG providers could achieve £10.41 million over their TSR without using ES devices. This behaviour is of importance for generation providers and investors when performing investment studies and for ES technology developers and Manufacturers to support future reductions on these component prices.

This sensitivity analysis also shows that price reductions in the energy and power components of Supercapacitors have a lower revenue increment for REG providers than the same reductions in NaS batteries. This is caused by the energy reserve responsibilities of the latter when applying by REG providers in MFR services. As examined before, although REG providers could receive support from both ES devices to deliver mandatory frequency response, the renewable generators are still in charge of the majority proportion of the response. This is represented by the small-size of supercapacitors required by REG providers. NaS batteries, however, also provide assistance with energy reserves and, thus, they require a larger size for this purpose. This creates, in turn, greater revenue impacts for REG providers when varying the components price of this NaS technology. This can be visualized in Figure 5.13 where the Energy Ratings for NaS batteries and Supercapacitors are presented taking into account a price change in the NaS components.

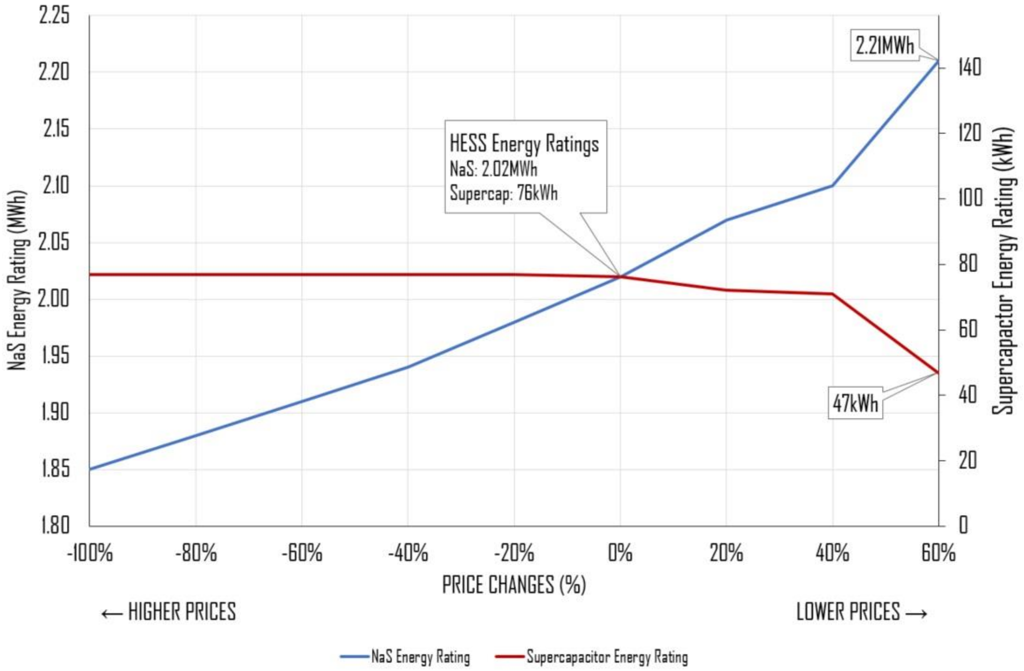

Figure 5.13. Cost Changes in NaS components of Three Players Model – ES Energy Ratings

Based on the simulation results, presented in Figure 5.13, the Energy Ratings of NaS batteries are continuously increasing alongside enhancements on the components price of NaS batteries. This is not the case in the Energy Ratings of Supercapacitors as their energy ratings remain static during most of the price reductions of NaS. When these components cost are further enhanced for NaS, however, REG providers might income more with lower contribution from Supercapacitors and, consequently, the energy sizes of SC are reduced (reaching 47kWh for a 60% price change).

Regarding the power ratings of the ESS, every time NaS components cost is improved, it is expected to see a raise on the power ratings of NaS batteries to further support REG providers with frequency services while Supercapacitors face a similar behaviour as their energy ratings. This is presented in Figure 5.14.

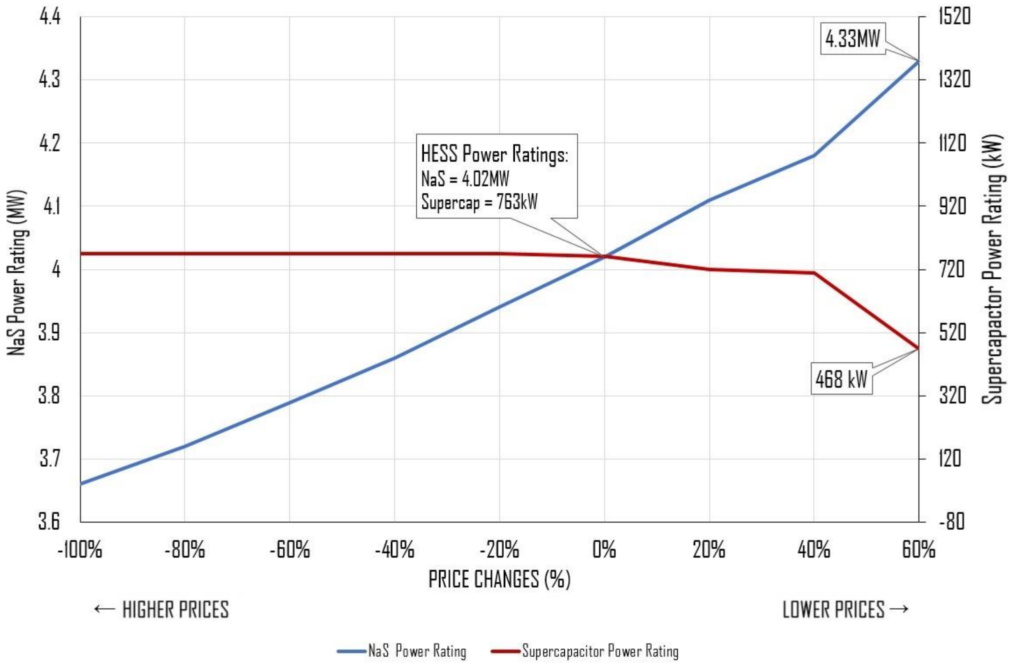

Figure 5.14. Cost Changes in NaS components of Three Players Model – ES Power Ratings

When the components cost enhancement is addressed to Supercapacitors, the power ratings of this technology will now be increased as greater support to REG providers for MFR service can be achieved. This increment, evidently, comes along with higher requirements in energy size for this device. In the case of NaS batteries, their energy rating will also be increased as additional energy reserves are always required when ES devices take a greater share in MFR service for supporting REG providers. In this case, SCs are increasing the provision of primary response and high frequency response and this causes more energy requirements for reserves from the NaS. This behaviour can be visualized in Figure 5.15.

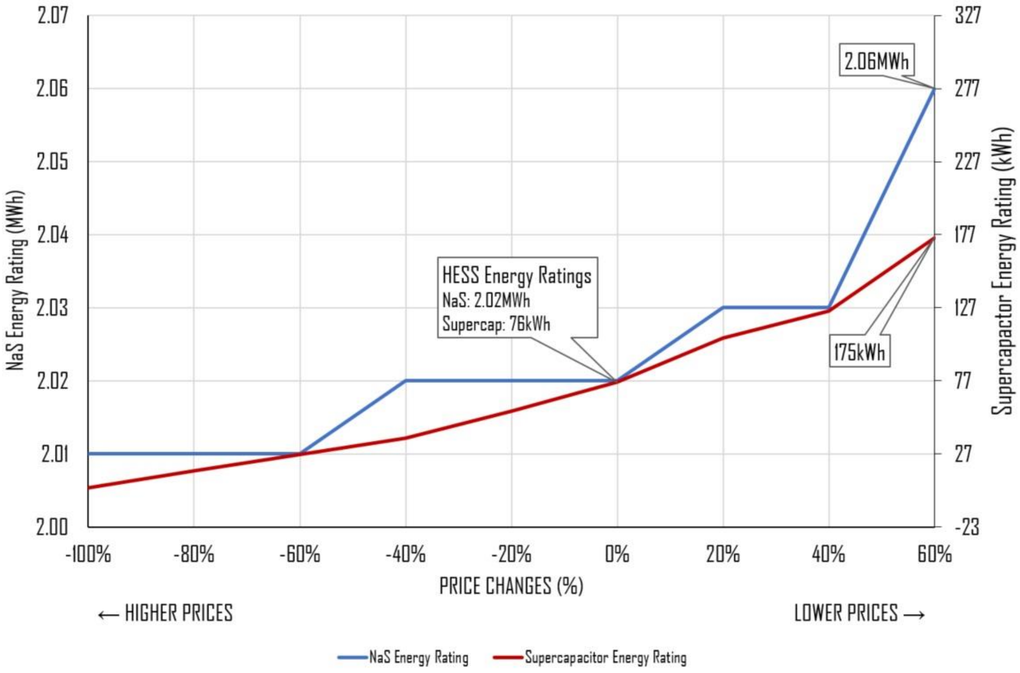

Figure 5.15. Cost Changes in SC components of Three Players Model – ES Energy Ratings

Regarding the NaS power ratings, when the components prices of Supercapacitors are enhanced, NaS batteries do not suffer an increment in their power ratings during part of the improvement. This is caused by the high-power ratings that NaS batteries must have in order to be able to deliver response for the worst cases of frequency deviation. However, while Supercapacitors keep increasing their support to frequency response through low-priced power components, the energy reserves of the ESS, required by regulation, can reach a point where NaS power ratings might need adjustments to maintain their capability of liberating the reserved energy whenever required. This can be seen in Figure 5.16 below.

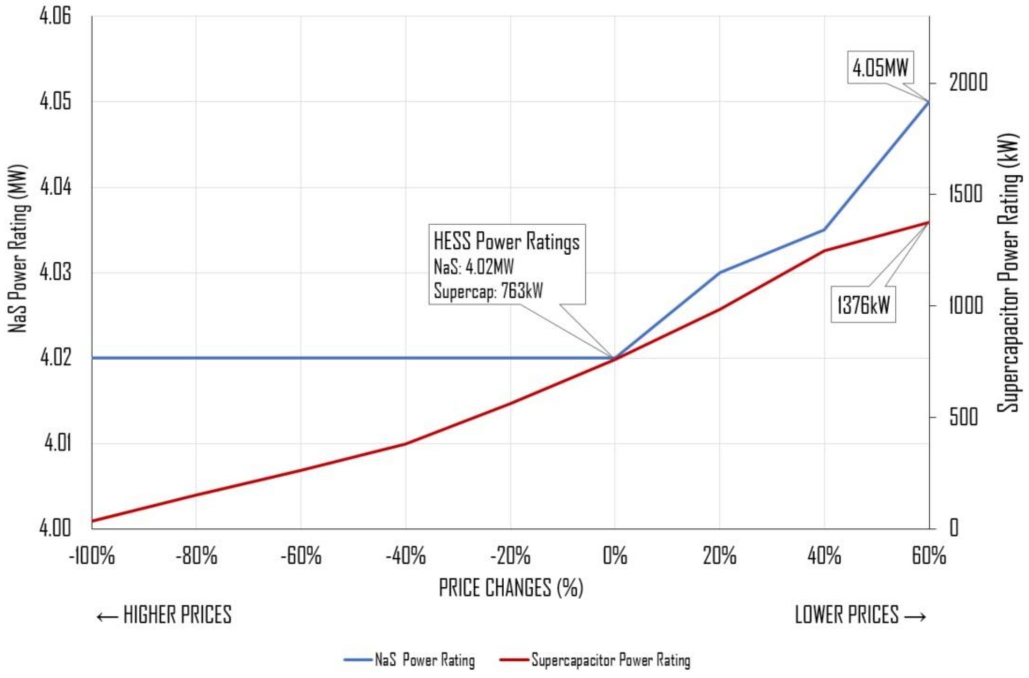

Figure 5.16. Cost Changes in SC components of Three Players Model – ES Power Ratings

Importantly, in all cases, the components price reductions over 60% were not included in the results as they create unbounded problems during simulation. This is caused by the wholesale market interaction capability of the system. At present conditions, wholesale market interaction is an operation that, on its own, does not justify an investment of REG providers in ES devices. The Three Players Model linked this wholesale market interaction opportunity as an additional strategy over MFR services. However, if ES technology component prices reach a non-realistic reduction, wholesale market interaction, alone, becomes a profitable application. This makes the solver try to design an unlimited ESS which can buy and sell unbounded amounts of energy in the energy markets. The solution of this type of problems could be addressed by limiting the ES capital cost of investment. This procedure is the one followed in the FFRA Model and, when required, in MFRA Model.

Further simulations carried out at high components price ranges of ES technologies showed that the HESS composed of NaS batteries and Supercapacitors could turn into a single ES device system (i.e. only NaS technology) when these prices are highly expensive. In particular, this breaking point was reached when Supercapacitors were 110% more expensive than the current component prices. Nevertheless, NaS batteries would remain a viable option for REG providers since energy reserves and active frequency response are still cost-effective for this technology. REG providers would not require any ES device when the component prices of NaS devices are, at least, six times higher than the current prices.

5.5.2. Impact of Interest Rates

The interest rate is an essential factor to consider by REG providers when analysing the investment in ES technologies. During previous sections, the interest rate utilized in the Three Players Model was defined as 3% (see Table 5.1). In reality, choosing the actual interest rate, for investment projects, depends on many economic factors out of the scope of this work. This section, however, studies the impact that different interest rates have on the revenues that REG providers can achieve when using ES devices for addressing MFR services and interacting with the wholesale market. The simulations of this model consider, in this section, interest rates ranging from 0% up to 8%. As in the previous section, the model outputs after simulation, presented in Figure 5.17, are presented in terms of revenue increments over the TSR that REG providers can achieve when non-using ES technologies.

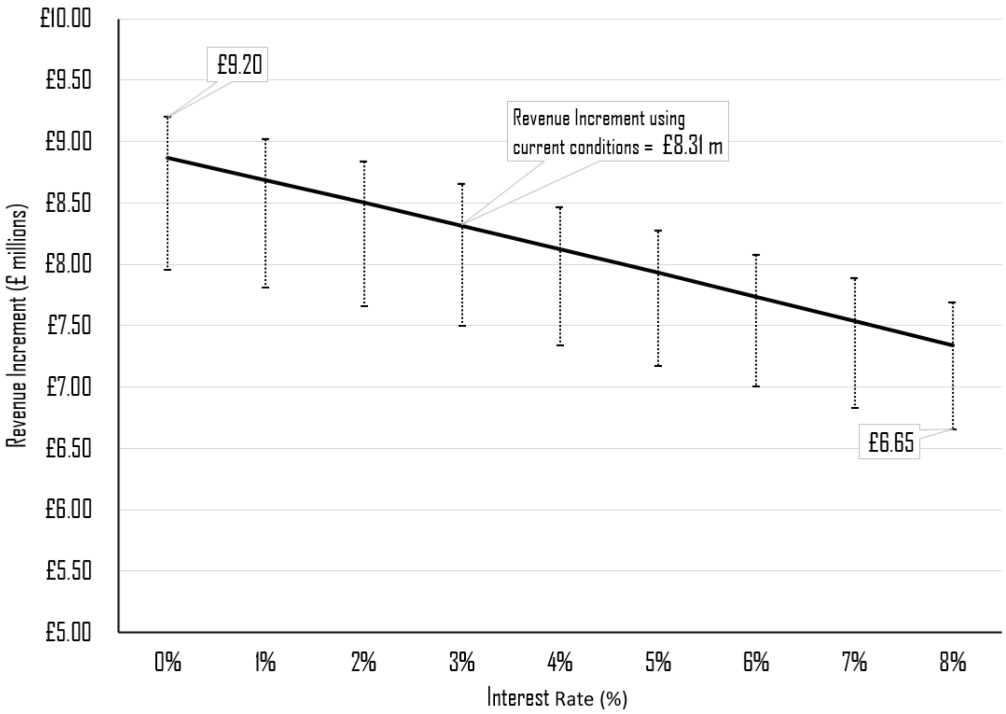

Figure 5.17. Sensitivity Analysis on the Interest Rates of Three Players Model

The upper and lower limits of each band in Figure 5.17 represent the sensitivity range in which each Interest Rate can achieve the highest and the lowest revenue for REG providers, respectively. The upper limits were obtained assuming the best ES technical characteristics while the lower limits applied the worst ES technical characteristics. The enhancements and detrimental in the features of ESS considered the following actions over the current conditions of NaS batteries and Supercapacitors:

- Cycling Lifetime: ±50% increment
- SOC Operational Window: from 20% gap to 100% gap
- Charging/Discharging Efficiency: ±5%
- Daily Self-discharge: ±50% increment

In the Three Players Model, the Interest Rate influences the TSR of REG providers through the Capital Recovery Factor applied to the ES investment cost. As this factor becomes a constant value in the model for each scenario, the revenue increment for REG providers presents a perfect linear slope inversely proportional to the Interest Rate (i.e. the higher the Interest Rates, the lower are the TSR of REG providers). For these reasons, it is expected from the power and energy ratings of each ES device to constantly reduce their values with higher Interest Rates. This is presented in Figure 5.18 and Figure 5.19 respectively.

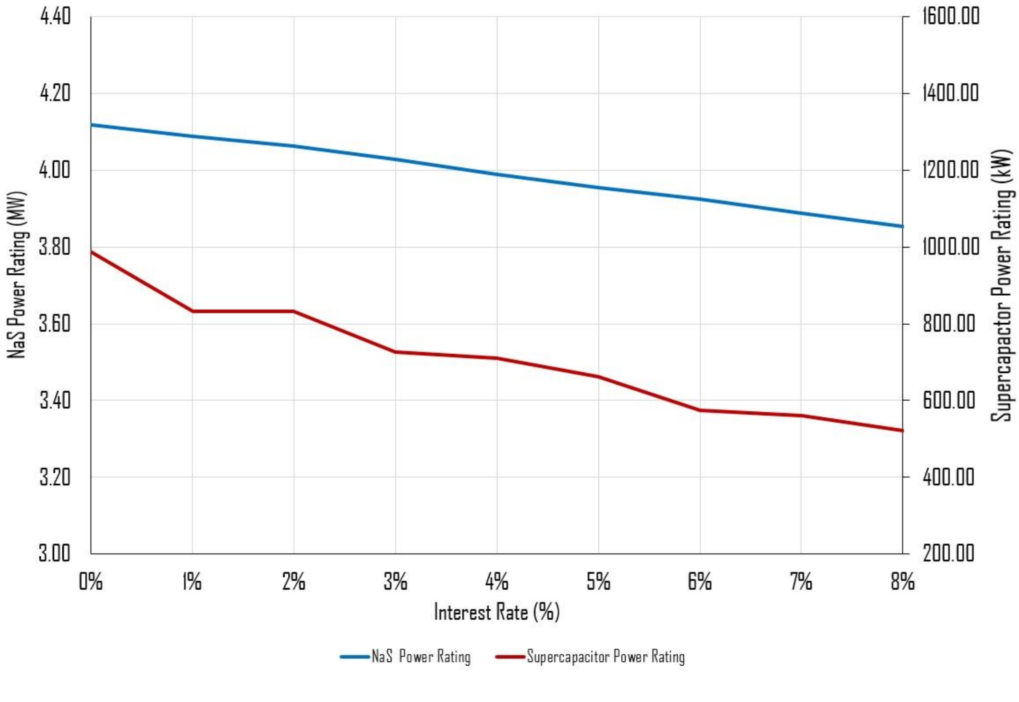

Figure 5.18. Interest Rates impact on ES Power Ratings of Three Players Model

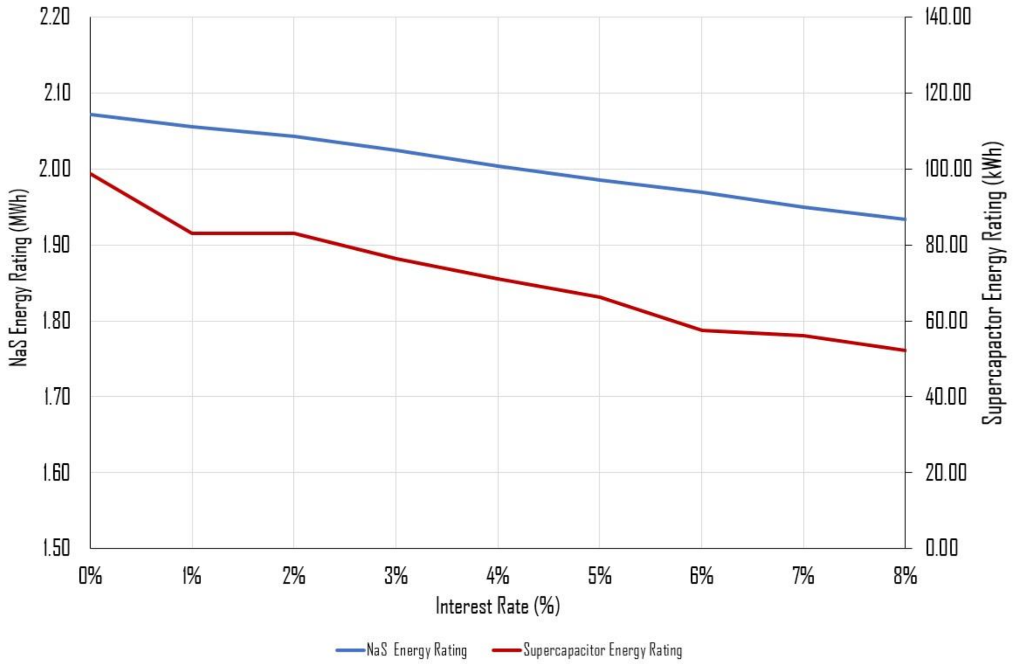

Figure 5.19. Interest Rates impact on ES Energy Ratings of Three Players Model

It should be noted that, at some point and depending on the system conditions, the HESS will turn into a single ES device system and, eventually, in a system with no ES technologies. It was found, for this case, that both events occur at 23% and 50% Interest Rates respectively. Since the Interest Rates is rarely that high in investment projects, it is difficult for this economic factor to interfere with REG providers decision of using ES technologies.

5.6. Sensitivity Analysis on ES Technical Parameters

In this work, the technical features of ES technologies refer to the model inputs required to shape each ES device in terms of Cycling Lifetime, Charging/Discharging Efficiency, Maximum and Minimum SOC limit, Daily Self-discharge and Manufacture Lifetime. The latter is used all framework models in conjunction with the Project Lifetime to determine the auxiliary factors of each ES technology as described in Section 4.2 (Equation 4.4 and Equation 4.5) and applied in Section 5.4. Without considering daily self-discharge, the rest of ES characteristics are matched with each other, in the following subsections, to examine their influence in the revenues of REG providers. The current ES conditions applied in the section for the Three Players Model are the same as in previous sections of this Chapter for Supercapacitors and NaS batteries and summarized below.

	Parameters	NaS	Supercapacitor
Technical	Charging/Discharging Efficiency (%)	87	90
	Maximum SOC (%)	100	100
	Minimum SOC (%)	0	0
	Cycling Lifetime (cycles)	4,500	500,000
	Daily self-discharge (%)	15	15
Economic	Cost of Energy (£/kWh)	400	5,000
	Cost of Power (£/kW)	200	120
	Interest Rate (%)	3	3

Table 5.7. Current ES characteristics of Supercapacitors and NaS batteries

5.6.1. Cycling Lifetime vs Efficiency

In this sensitivity analysis, the cycling lifetime and efficiency of ES technologies are addressed taking into account efficiency variations of up to ±5% and cycling lifetime increments of -50% to 50% from the current conditions of both ES technologies. The simulation outputs, expressed as revenue increments over the TSR of REG providers achieved when non-using ES technologies, are presented in Figure 5.20.

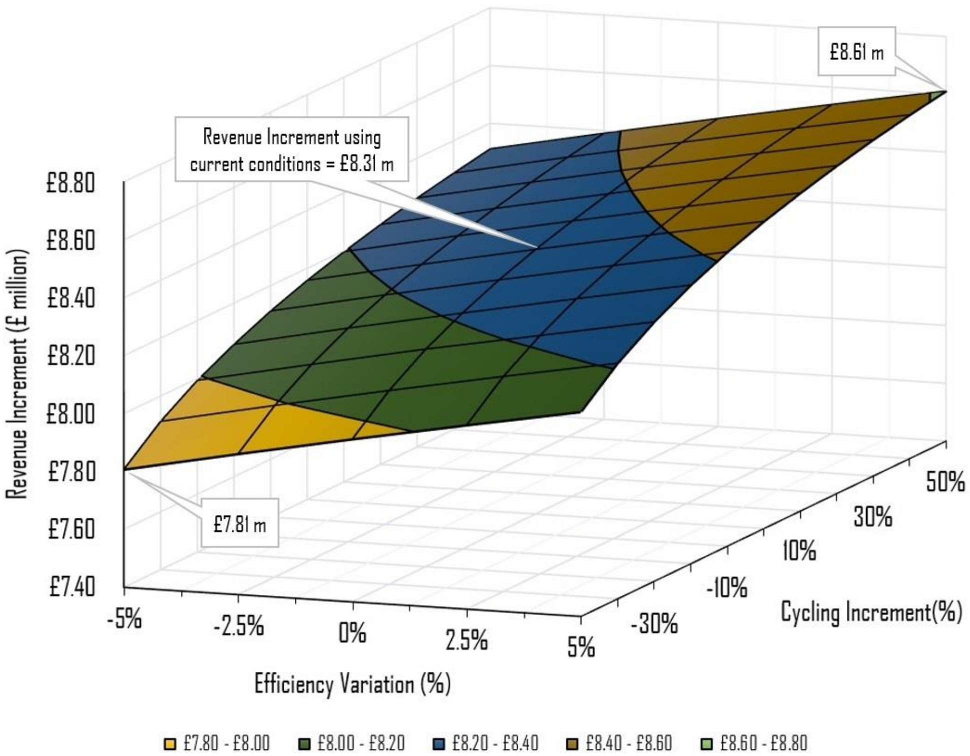

Figure 5.20. Sensitivity Analysis in Three Players Model - Cycling vs Efficiency

As shown in Figure 5.20, the TSR of REG providers can suffer variations from £7.81 million up to £8.61 million when cycling lifetime and charging/discharging efficiencies of its ES technologies are modified. The cycle lifetime of ES devices influences REG providers, in this model, by modifying the price of degradation of each ES device, as presented in Section 4.3 (Equation 4.25). Based on Figure 5.20, it is possible to see that improvements in this technical feature tends to reach a stabilization point in terms of revenues for REG providers. This point would represent an ideal maximum income of REG providers without incurring in any cost of ES degradation.

In the case of charging/discharging efficiencies, while this characteristic is enhanced in ES devices, the revenues of REG providers also follow a linear increment. Between both technical characteristics of ES technologies, the model results show that, under current conditions and assumptions, enhancements in cycling lifetime of ES devices have a greater impact on TSR of REG providers than the improvements in efficiencies of these technologies. This could be important for technology developers when prioritizing areas of improvement of ES devices.

Regarding power and energy ratings, Figure 5.21 presents the impact on NaS ratings of modifying cycling lifetime and efficiencies in the ESS.

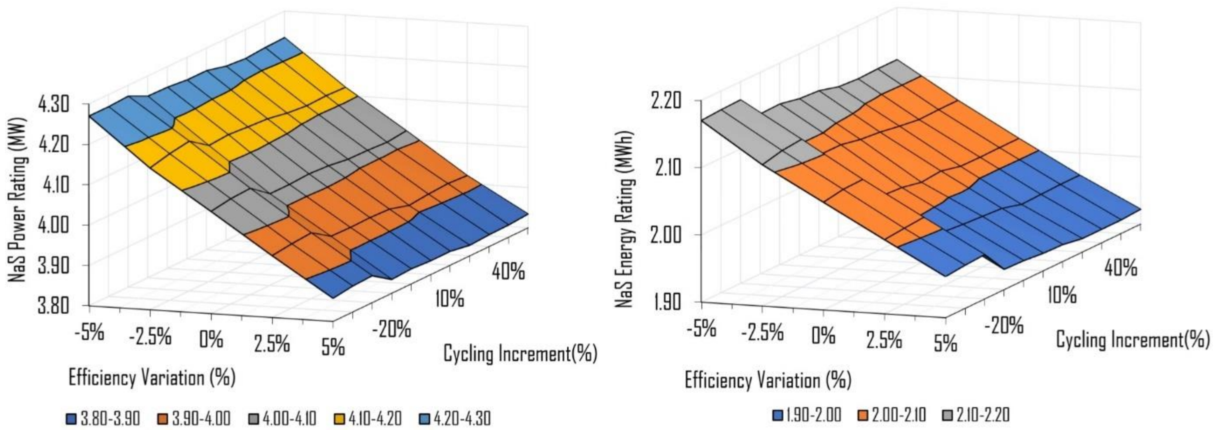

Figure 5.21. Cycling vs Efficiency in Three Players Model – NaS Power and Energy Ratings

For charging/discharging efficiency, when this technical factor increases, NaS batteries require a lower power capability and energy capacity to do the same tasks regarding frequency services, energy reserves and wholesale market interaction. This behaviour is represented as a linear fall in both curves of Figure 5.19. For cycling lifetime increments, NaS devices are almost entirely not affected as one of their main responsibilities is to support REG provider with energy reserves. Since these energy reserves must consider the most onerous cases of frequency deviations and large amounts of energy for secondary frequency response, increasing the cycling lifetime of NaS batteries will only produce reductions in their degradation costs but their ratings will still remain at maximum constant value in order to fulfil MFR regulations.

For Supercapacitors, the impact in their power and energy ratings when modifying the cycling lifetime and efficiencies in the ESS are presented in Figure 5.22.

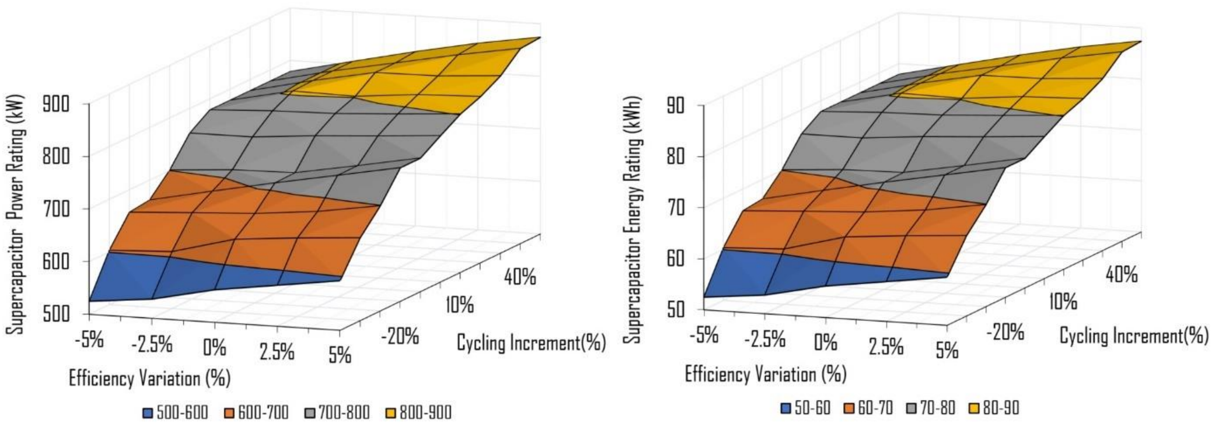

Figure 5.22. Cycling vs Efficiency in Three Players Model – SC Power and Energy Ratings

In this case, the enhancements in charging/discharging efficiency have a minimal but increasing impact on the power and energy ratings of Supercapacitors. This occurs since SC are able to enhance their active role in primary response, high frequency response and wholesale market interaction and because they are not regulated to maintain energy reserves, as in NaS batteries. The same logic applies to increments in cycling lifetime i.e. since Supercapacitors are mainly active elements in frequency support and wholesale market interaction, the higher are cycling enhancements, the larger becomes their power and energy rating.

It is important to mention that, although all the above results were obtained from a HESS applied by REG providers, this hybrid system can potentially become single ES technology when both features, efficiency and cycling lifetime, are characterized with very low values from current ES conditions. For instance, when the cycling lifetime drops below 70% while the efficiency worsens more than 10% of current conditions in both ES devices, the maximum revenues of REG providers can, instead, be achieved through NaS batteries exclusively. The latter technology will no longer be required by REG providers in cases in which maintain energy reserves with this device become less profitable than power curtailments of wind generators.

5.6.2. Cycling Lifetime vs SOC Window

The SOC window refers to storage space in which ES technologies can save energy. The limits of this operational window could proceed from the intrinsic characteristics of the devices or from control decisions of REG providers. In this section, SOC windows are the gaps between 100% and the minimum allowable SOC for each ES device. For instance, an SOC window of 60% represents an operational decision for ES devices to operate between 100% and 40% of their energy capacity. The simulation outputs in the Three Players Model from comparing cycling lifetime with SOC windows are shown in Figure 5.23 below for REG providers using NaS batteries and Supercapacitors.

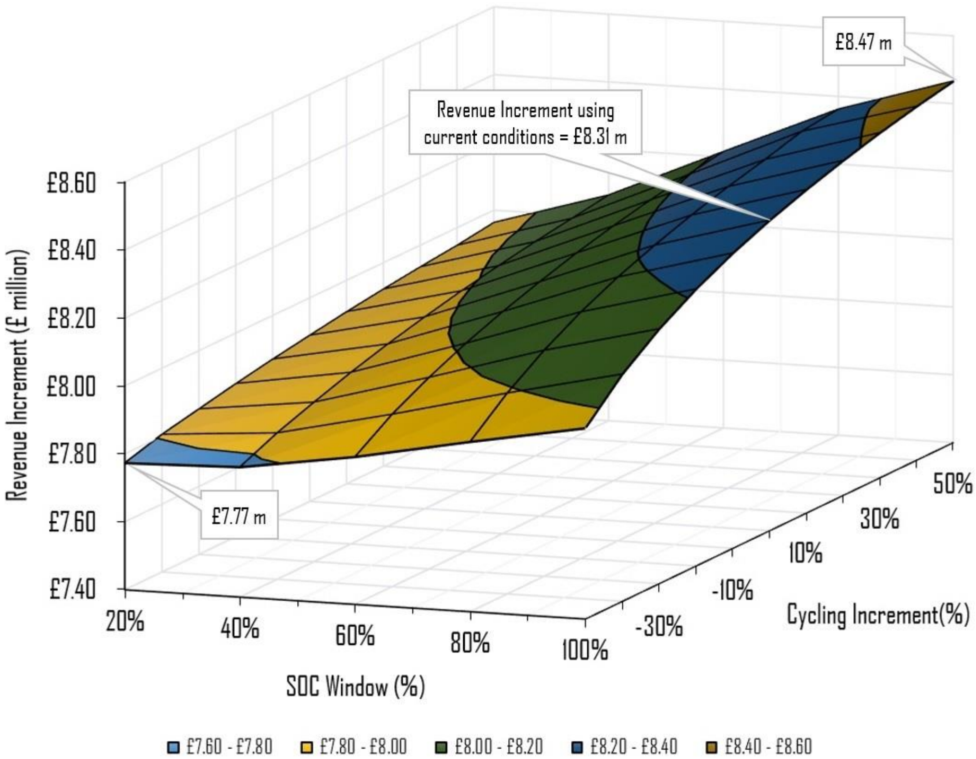

Figure 5.23. Sensitivity Analysis in Three Players Model - Cycling vs SOC Window

From the results presented in Figure 5.23, it is possible to visualize that increasing the operational window of NaS batteries and Supercapacitors creates greater impact on the revenues of REG providers than modifying their cycling lifetime. As discussed in Section 5.6.1, the cycling lifetime increments tend to reach an ideal stability point characterised by none degradation costs on the ES system. In the case of SOC window, the overall impact on the income of REG providers from varying this technical feature is based on having a bigger room to provide primary response, high frequency response and wholesale market interaction while minimizing the size of devices if possible. In Figure 5.23, there are two important stages to consider for operational windows of ES devices:

- Above 40% SOC window: REG provider revenues increase steadily being SOC window the major role player of these increments.
- Below 40% SOC window: in these scenarios, when cycling lifetime drops below -20%, REG provider obtains the lowest income. Here, the ESS goes from being a hybrid system to being based on a single ES device (i.e. NaS exclusively). This can be further visualized when analysing the effects of modifying the SOC window and cycling lifetime of ES devices on their power and energy ratings. These results are presented in Figure 5.24 for NaS batteries ratings and Figure 5.25 for Supercapacitors ratings.

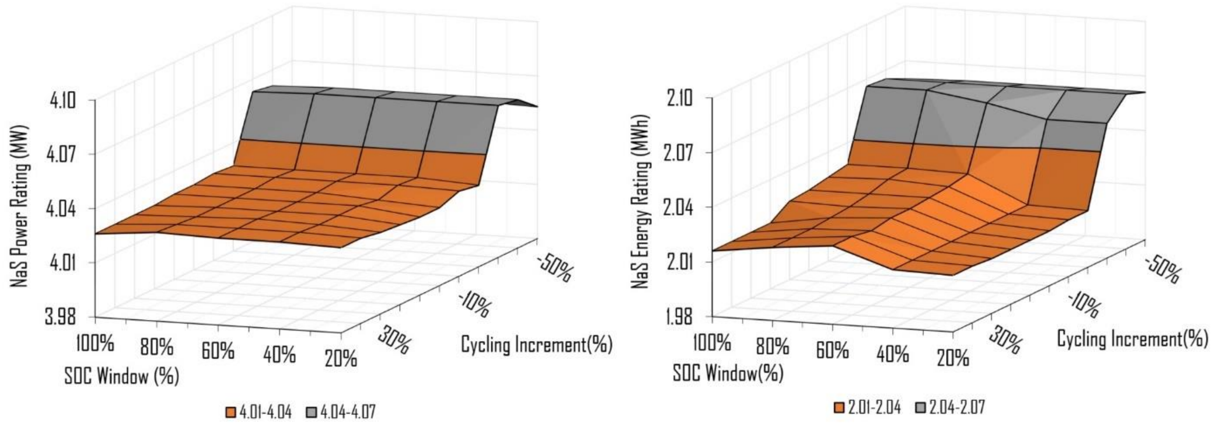

Figure 5.24. Cycling vs SOC Window in Three Players Model – NaS Power and Energy Ratings

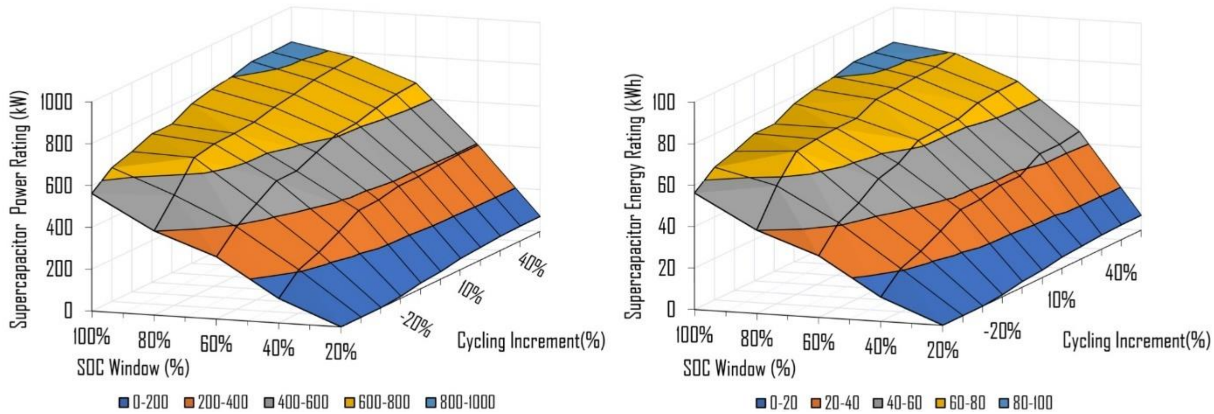

Figure 5.25. Cycling vs SOC Window in Three Players Model – SC Power and Energy Ratings

Although NaS batteries could provide immediate frequency response, they are also tied, by MFR regulation, to have energy reserve if supporting REG providers with this service. For that reason, improvements of the SOC window and Cycling lifetime in the ESS do not present changes in the ratings of NaS batteries throughout simulations as shown in Figure 5.24. Worsen both technical features, however, produce a rapid fall in the power and energy ratings of supercapacitors leading to eventual disappearance of these devices. This fall can be visualized in Figure 5.25 and is caused by the active role of Supercapacitors in the provision of primary response, high frequency response and wholesale market interaction. For both technical characteristics, the inferior the features, the smaller is the size requirement of Supercapacitors.

5.6.3. Efficiency vs SOC Window

Based on Section 5.6.1, modifying the efficiency of the ESS is expected to produce an increasing linear behaviour in the TSR of REG providers when its conditions are enhanced. For SOC window, higher income for REG providers are also expected when the operational window of the ES devices approaches to a full-opening. The simulation outputs when varying the Efficiency and SOC Window of ES devices in Three Players Model is presented in Figure 5.26 for REG providers using NaS batteries and SCs.

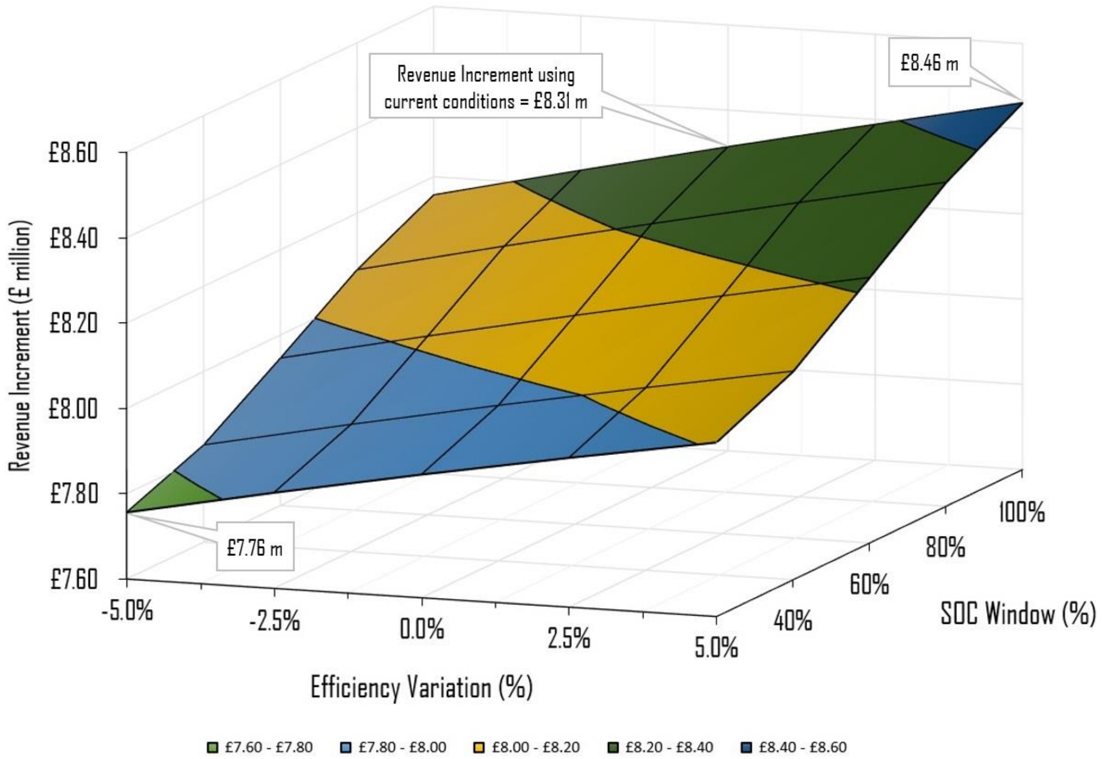

Figure 5.26. Sensitivity Analysis in Three Players Model - Efficiency vs SOC Window

As shown in Figure 5.26, REG providers achieve the lowest income increment of £7.76 million when Efficiency and SOC window are at their worst scenario in the ESS being the latter the technical characteristic with the highest impact on the overall income. Since NaS batteries support REG providers with energy reserves, this responsibility will produce a linear reduction in their power and energy ratings when improvements on charging/discharging efficiencies arise. For SOC window enhancements, however, the operational gaps will not affect the power and energy ratings of NaS as this device is rated to face the most onerous scenarios of frequency deviation and to have large amounts of energy for reserves. This means that providing primary response and high frequency response are never overpassing the maximum scenarios required by MFR regulation. These results are presented in Figure 5.27.

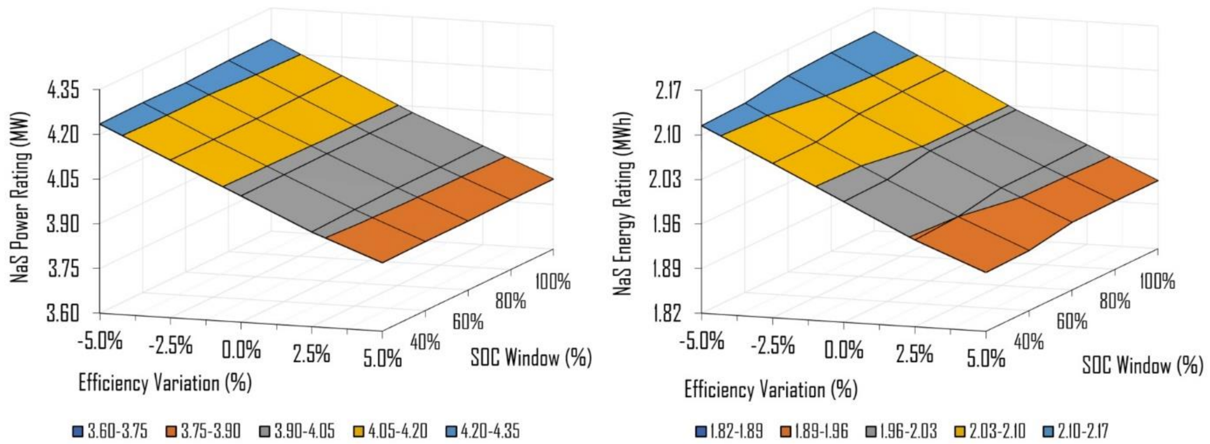

Figure 5.27. Efficiency vs SOC Window in Three Players Model – NaS Power and Energy Ratings

For Supercapacitors, improving the SOC window of the ESS play an important role in the power and energy ratings of SC as it represents the actual room of energy that can be delivered during active services of REG providers. The bigger is the SOC window, the more energy can be delivered during the operation of Supercapacitors to support REG providers. This, in turn, will increase the size of this technology. As the storage capacity is limited in all ES devices and can be achieved by allowing, in the Three Players Model, a complete SOC window in ESS, the power and energy ratings of SC tend to reach a stabilization point at 100% opening. This is presented in Figure 5.28.

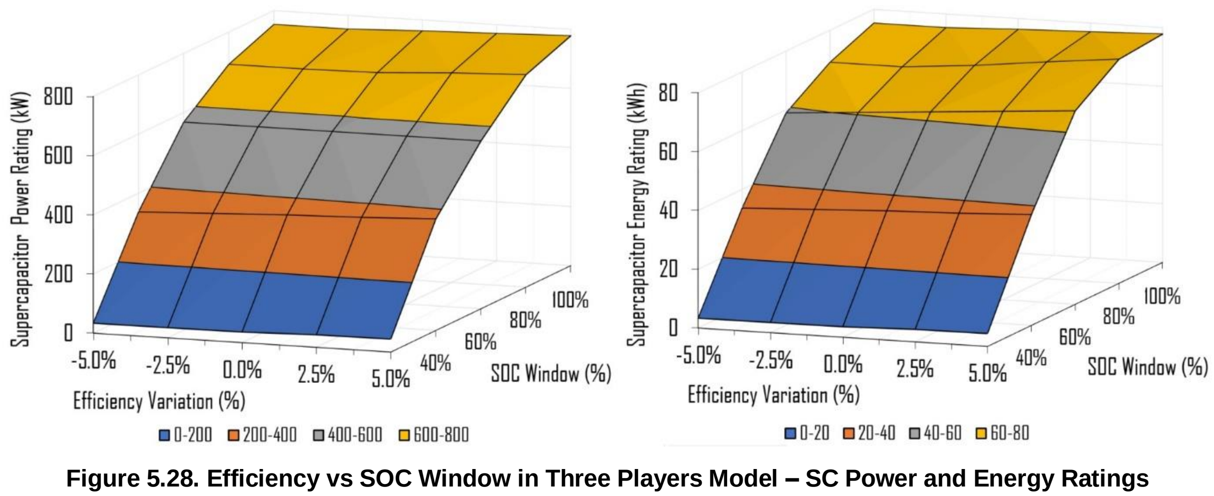

Figure 5.28. Efficiency vs SOC Window in Three Players Model – SC Power and Energy Ratings

It is noteworthy that, although all the cases in this subsection are HESS, the ESS can become single ES technology when the SOC window is modified in the ESS to be nearly closed and the efficiencies are at very low. In particular, when the operational gap is closed to 13% SOC window, or less, under current conditions, REG providers stop requiring Supercapacitors and applies only NaS batteries instead to achieve the best income possible.

5.7. Individual Contribution of ES Characteristics on Total Revenues

In Section 5.5 and Section 5.6, the sensitivity analyses on the technical and economic factors influencing the value of ES devices (using the Three Players Model) provided an insight on the actual contribution of these factors on the income of REG providers and in the ES sizing design. The present section complements these studies by ranking the individual influence of each technical and economic factor of ES technologies on the income of REG providers based on the current conditions of ES devices and a future scenario of them. The future scenario was designed based on the roadmaps of experts regarding the potential future situation of ES technologies in 2030 [73], [158], [159]. Table 5.8 summarizes the intrinsic characteristics of ES technologies that were applied under the future scenario. It is important to mention, however, that part of the data for future 2030 characteristics were not found in the literature. Therefore, for this data, the procedure was to enhance by 50% the values from current conditions since, in the majority of ES features, the projections from roadmaps have shown more than 50% improvement by 2030. For the SOC window, the current conditions of ES devices, presented in Table 5.7, considered a 100% depth of discharge (DoD) for all the cases. However, in order to also evaluate the effects of this factor in future scenarios, and based on the information provided by future ES roadmaps, the future scenario of this thesis is considering 100% DoD while the present ES situation is now assumed to have a 60% operation window. The interest rate is also an economic factor that plays a role in the value of ES technologies. In order to examine its influence, the best scenario possible, which is considered within the future scenario simulations, is assumed to be enhanced to 0% interest rate that could represent a direct investment without debt compromises.

	Parameters	NaS	Supercapacitor
Technical	Charging/Discharging Efficiency (%)	92 [158]	96 [159]
	Maximum SOC (%)	100 [158]	100 [160]
	Minimum SOC (%)	0 [158]	0 [160]
	Cycling Lifetime (cycles)	7,500 [158]	750,000
	ES Lifetime (years)	24 [158]	15 [159]
	Daily self-discharge (%)	1 [158]	5
Economic	Cost of Energy (£/kWh)	162 [158]	3,000 [73]
	Cost of Power (£/kW)	100	60
	Interest Rate (%)	0	0

Table 5.8. Enhanced Characteristics of Supercapacitors and NaS batteries

In the Three Players Model, Supercapacitors are ES devices that address the provision of primary response, high frequency response and wholesale market interaction to support REG providers with MFR service. NaS batteries, on the other hand, are technologies able to participate in the same response as Supercapacitors but they are also in charge of supporting REG providers with energy reserves for facing the worst cases of frequency deviation and for addressing secondary frequency response. This makes the ranking of the individual contributions of intrinsic ES factors to differ when enhancements are made in the NaS characteristics than when achieved in the features of SC.

Figure 5.29 presents, after simulation and categorization, the ranking of the individual contribution of intrinsic NaS technical and economic characteristics on the TSR of REG providers when NaS batteries are solely enhanced.

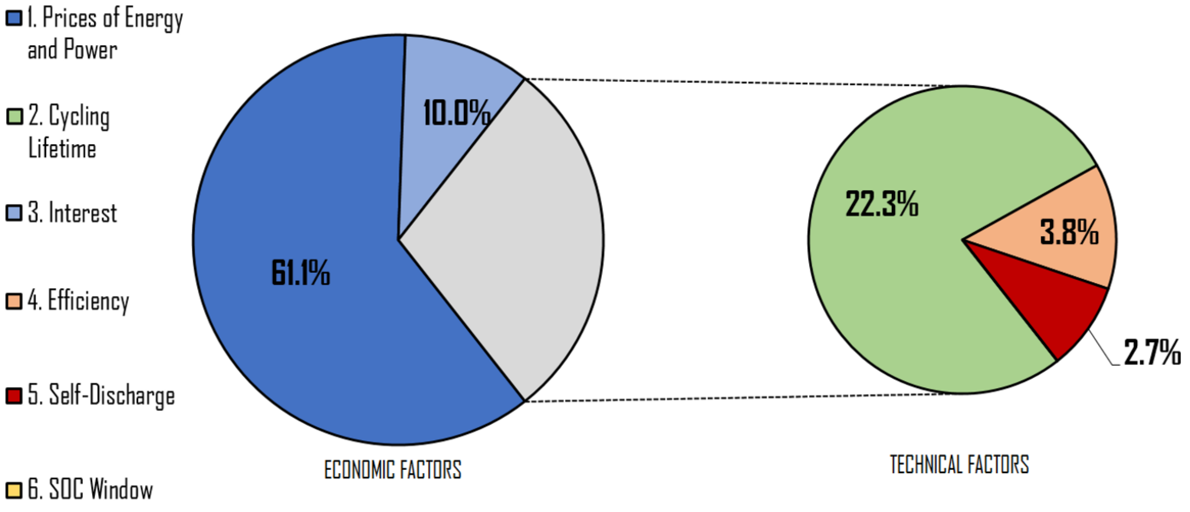

Figure 5.29. Three Players Model – Ranking of the Individual Contribution on TSR of NaS Characteristics

In Figure 5.29, the economic features of NaS batteries produce the highest impacts on REG provider revenues as 71.10% of potential increments on income are triggered by enhancements on the price of NaS components and the ES Project Interest Rate. This signifies that the technical characteristics of NaS batteries only influence 28.9% on the income increments of REG providers. A large proportion of the contribution from NaS technical features is achieved by increasing the Cycling Lifetime of NaS batteries (i.e. 22.30% increment in REG provider income). As mentioned in Section 6.6, a higher Cycling Lifetime in NaS batteries help to increase TSR of REG providers by reducing the costs of degradation for energy utilization. Another interesting outcome of this ranking of individual contribution of NaS features is that the operational window allowed to NaS has almost no contribution on TSR increments of REG providers. Since NaS devices also support REG providers with energy reserves by MFR regulation and since their actual response to primary frequency and high frequency events are small, the sizing of these batteries will mainly consider the worst scenarios of frequency deviation. This means that, although NaS batteries are able to present a wider SOC window, their capital costs of investment will remain at the same value, making SOC window factor has almost no-effect on TSR increments when improved.

Figure 5.30 presents, after simulation and categorization, the ranking of the individual contribution of intrinsic Supercapacitors technical and economic characteristics on the TSR of REG providers when Supercapacitors are solely enhanced.

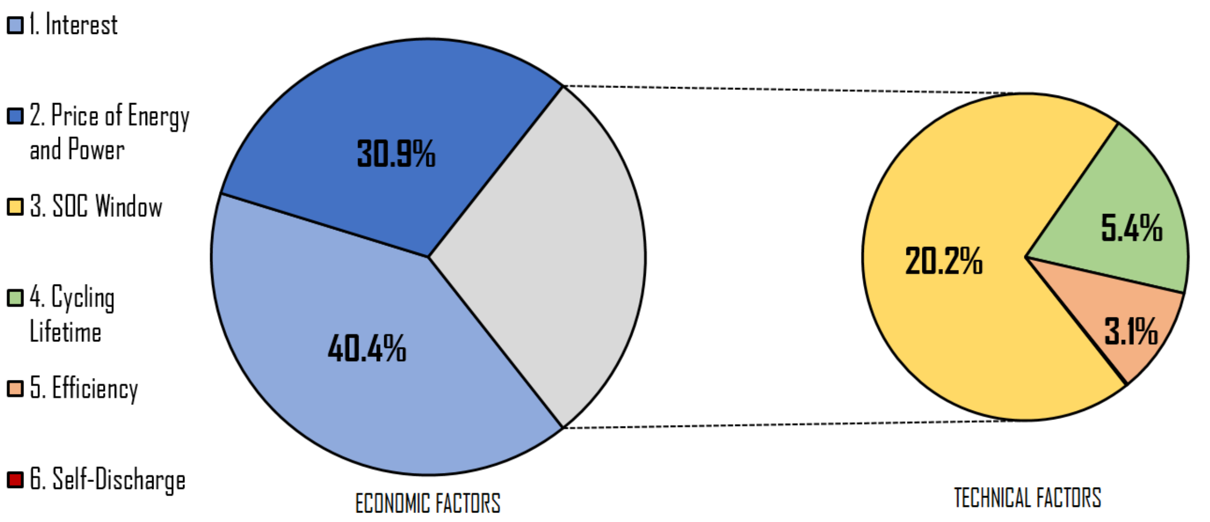

Figure 5.30. Three Players Model – Ranking of the Individual Contribution on TSR of SC features

In this case, since Supercapacitors do not support REG provider with energy reserves, enhancements in the operational window of these devices create direct impact on their ability to deliver responses, such as primary response, high frequency response and wholesale market interaction, and, thus, on their sizing design. For this reason, SOC window is now occupying the first position in the Supercapacitors contribution ranking among all technical features and third position overall.

Another interesting result of the SC Contribution Ranking on TSR Increments for REG providers is that improving self-discharge rates on these devices generates almost no contribution on the TSR increments for REG providers. This is caused by the instant response that Supercapacitors deliver to support REG providers with MFR service and wholesale market interaction. Since Supercapacitors are not in charge of storing large amounts of energy for long-periods, there is no time for self-discharge events to create a representative loss of energy on these devices.

Figure 5.31 presents, after simulation and categorization, the ranking of the individual contribution of ESS intrinsic technical and economic characteristics on the TSR of REG providers when Supercapacitors and NaS batteries are both enhanced.

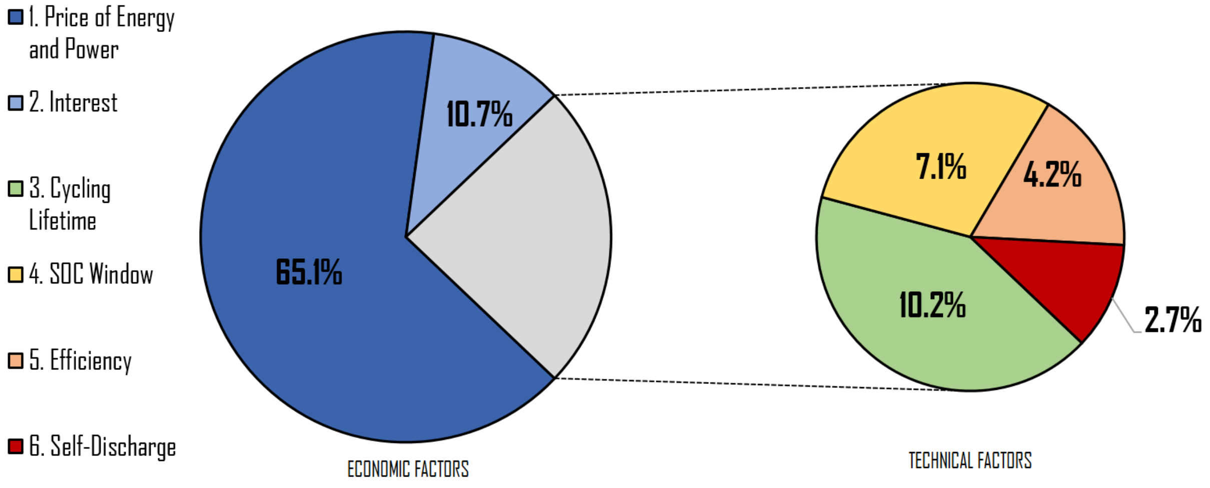

Figure 5.31. Three Players Model – Ranking of the Individual Contribution on TSR of NaS and SC features

As in all previous rankings on this section, the highest contribution on TSR increments of REG providers are produced by the enhancements on the economic features of NaS batteries and Supercapacitors. This means, for REG providers and investors, that reducing the Interest Rate of their ES investment project will play a significant role on potential income they can achieved with the use of these devices. For technology developers, they could, instead, address efforts on reducing the costs of power and energy components of these technologies. Enhancing the minimum SOC allowable on Supercapacitors, in the control operation, could also increase the value of using these devices for REG providers to deliver MFR services and wholesale market interaction as this will allow more energy to be used in actual responses by SC devices at a smaller ES design. Since NaS technologies, instead, present a relatively low cycling lifetime than SC, the impact on TSR increments of this technical feature will be higher in this ES technology and, therefore, could also be considered a priority feature to be enhanced by technology developers.

5.8. Discussion and Conclusion

In this Chapter, the techno-economic factors that influence the value of ES devices were assessed and quantified using the Three Players Model. This framework model permits to study ES technologies when supporting REG providers, in conjunction with Renewable Generators, to provide MFR service and interact with wholesale market. The outputs of this model provide the maximum revenue that REG providers can reach from these market applications alongside with the optimal sizing design of ES devices.

The initial case study, in which Three Players Model was applied, considered the use of ES devices in conjunction with Solar Farms and together with Wind Farms. The simulation outputs demonstrated that, under certain conditions, investing in an ESS might not be profitable for Solar Farms when participating in MFR service since their response and payments were conditioned, by regulation, to high-levels of generation. The results showed that marginal revenues arise from mandatory frequency response only during summer periods for Solar Farms, and this was not sufficient to justify the capital expense associated with the investment in ES technologies. This is not the case of medium-scale Wind Farms which were able to participate in MFR service all year round based on their generation levels. This allowed REG providers not only to income from using ES devices to support with the provision of frequency response and the wholesale market interaction but also to take advantage of the extra generation that Wind Generators were able to inject in the Wholesale Market.

The ES Technology Selection addressed the simulation of diverse ES combinations towards determining the single ES device or hybrid ES technologies that achieves the highest revenues for REG providers using the Three Players Model. Among all 31 ES combinations, the highest income for REG providers was achieved, for 15-year project, by combining NaS batteries with Supercapacitors. These results demonstrated that Supercapacitors were able to face part of the actual provision of primary response and high frequency response while also exploiting their interaction with the wholesale market when possible. On the other hand, NaS batteries made a slightly lower role on these active response but, instead, they also helped the REG providers with energy reserves. Although important by regulation, the benefits of the latter do not represent direct payments for REG providers, but they rather appear as extra renewable generation injected into the Wholesale Market.

The sections addressing the Sensitivity Analysis on the economic and technical factors influencing the value of ES devices ratified that hybridizing a single ES device could provide, under current certain assumptions, higher revenues to REG providers when supporting with MFR service and interacting with the wholesale market. The results showed a number of scenarios in which using a HESS were the best option for REG providers regardless of its high capital cost of investment, high component prices, interest rate, cycling lifetime, charging/discharging efficiency and operation window.

However, the results also demonstrated that enhancing prices the power and energy components of ES devices were pivotal to achieve greater income for REG providers. For instance, when these components prices were too expensive, Wind Farms were not able to income from using HESS or, even, from using a single ES technology. In theory, this de-hybridization of the ESS could also occur with very high interest rates but, in reality, the interest rates must reach unlikely high values for any investment project. Regarding intrinsic technical factors of ES devices, the simulation outcomes showed that these features produce lower contribution in TSR increments of REG providers than the economic factors of ES devices, such as Interest Rates, and they affect each device in a different way. This was further visualized with the individual ranking of ES features contribution on TSR increments for REG providers.

The ranking of the individual contributions of intrinsic technical and economic features of ES devices on the TSR of REG providers showed that the economic parameters influence a major proportion on income increments that the rest of factors. The prices of ES components, in particular, were a key area of improvement that influence to a large extent the revenues of REG providers and that requires the attention of technology developers. Lower Interest Rates must also be a priority for REG providers and Project investors to achieve significant increments in their benefits while reducing their risk in the ES investment. For technical parameters, the operation window represented the main factor to be enhanced in power-dense ES technologies to reach higher income for REG providers since this would allow greater responses at a lower manufacturing cost. For energy-dense technologies, however, the key improvement was, instead, appointed to their cycling lifetime since operational windows did not caused significant impact on the revenue potential for energy reserve-oriented devices.

Chapter 6. Framework Assessment of Mandatory and Non-Mandatory Schemes

6.1. Introduction

In Chapter 5, the techno-economic factors influencing the value of ES devices were assessed using the Three Players Framework Model. While this model facilitated the assessment to be performed considering a mutual operation, for REG providers, of ES devices and RGs, MFRA and FFRA are models that not only allows the study of ES devices applied, in exclusivity, to address frequency response and wholesale market interaction but also to investigate the effects that different regulatory schemes might have on the income of REG providers and, thus, on the value of ES technologies. In this chapter, it is presented the results from investigating and quantifying techno-economic factors influencing the present and future value of ES technologies using the MFRA and FFRA Models. The former model takes into account REG providers participating, with ES devices, in the mandatory frequency response service and interacting in the wholesale market. FFRA Model, on the other hand, considers REG providers aiming to offer services, using ES technologies, to contribute with firm frequency response service while also interacting with the wholesale market. Both models are technology agnostic allowing their use for assessing diverse ES technologies. Their simulation outcomes deliver, in all models, maximum TSR that REG provider can obtain using ES technologies and the optimal sizing design of such a system. The potential of hybridizing an ESS is also implicitly considered when solving these models and explicitly provided in their results based on the ES design.

The chapter is organised with a similar structure of Chapter 5. First, an initial case study is introduced to assess the value for Solar Farms and Wind Farms of applying, in exclusivity, ES devices to address frequency services, under mandatory and non-mandatory schemes, while also interacting with the wholesale market. A technology selection process for ES is then presented considering diverse ES combinations and based on seeking the most profitable ES solution for REG providers MFRA and FFRA Models. Following this, multiple sensitivity analysis on intrinsic technical and economic features of ES devices are examined for present and future conditions. This chapter concludes presenting a ranking of the individual contributions on the income of REG providers from each feature of ES devices based on current conditions and future improvements.

6.2. Case Study Description

As in Chapter 5, all studies developed in this chapter consider a medium-scale REG provider aiming to incorporate single or multiple ES technologies to avoid the curtailment of power from its RGs and, thus, exploit their power production. Unlike the Three Players Model, the renewable generators are now passive players on both MFRA and FFRA Models. This means that frequency responsibilities are fully covered by REG providers only through ES devices. The main target of these REG providers, ultimately, is to achieve the highest income while meeting regulations.

The initial case study applies the same inputs described in Section 5.2 (Chapter 5) regarding power generation profiles, grid-frequency data and energy markets prices. In this initial case study, the goal is to analyse the value of ES devices on Solar Farms and Wind Power Stations when participating in mandatory and non-mandatory frequency schemes. Both REG providers are 50MW grid-connected power stations. For the wind farm, it was utilized a half-hourly data of wind generation acquired from the North East of England and scaled for the purpose of this work. The solar generation profile, instead, was achieved through the solar irradiance data of [154] in Lincolnshire, UK, over a 12-years period (2005 – 2016). The hybrid ES combination selected for this case is composed of VRFB as the energy-dense technology and Supercapacitors as the power-dense technology. All the intrinsic technical and economic features of these ES devices are presented in Table 6.1.

	Parameters	VRFB	Supercapacitor
Technical	Charging/Discharging Efficiency (%)	92	90
	Maximum SOC (%)	100	100
	Minimum SOC (%)	0	0
	Cycling Lifetime (cycles)	15,000	500,000
	ES Lifetime (years)	15	15
	Daily self-discharge (%)	0.25	10
Economic	Cost of Energy (£/kWh)	280	5,000
	Cost of Power (£/kW)	700	120
	Interest Rate (%)	3	3
	Project Lifetime (years)	15	15

Table 6.1. ES Technical and Economic Parameters for the Initial Case Study

Based on Table 6.1, since VRFB technologies present a relatively low cost of energy components and low self-discharge, these devices could be considered a suitable candidate for energy-dense tasks. Supercapacitors, on the other hand, possess high cycling lifetime and low cost of power components, making them a power-dense candidate in this study.

6.3. Case Study Simulation

As MFRA Model was designed with a linear objective function and linear constraints, the simulation results for this model can be achieved using linear programming. In the case of FFRA Model, however, the model outcomes can be calculated with a mixed-integer linear programming solver since a conditional constraint were present during the modelling stage. In this work, both models, MFRA and FFRA, are developed and solved using GAMS software, equipped with IBM CPLEX solver.

For the initial case study, in which two different REG providers are considered when applying ES technologies, the simulation results are presented in Table 6.2. It is important to mention that, in order to compare the MFRA Model with the FFRA Model, the same investment costs for purchasing ES devices, in both models, were utilized. These investment costs proceed from the results obtained, first, by the MFRA Model and replicated, then, in the FFRA Model within each renewable generation case.

Farm	Model	Total Project Revenue (millions)	ES Ratings
WIND FARM	MFRA Model	£181.21	VRFB: 4.33MW/3.10MWh Supercapacitor: -
	FFRA Model	£193.78	VRFB: 4.48MW/2.74MWh Supercapacitor: -
SOLAR FARM	MFRA Model	£43.38	VRFB: 4.34MW/2.56MWh Supercapacitor: -
	FFRA Model	£55.96	VRFB: 4.31MW/2.64MWh Supercapacitor: -

Table 6.2. Initial Case Study of MFRA and FFRA Models – Solar and Wind farm Income and ES ratings

In Table 6.2, the results show that Wind Farms achieved higher TSR, throughout the 15-year project, than Solar Farms in all cases. This is caused by the nature source of solar generation which is limited to specific moments of sunlight during the day and season based. It is important to mention that, since the highest revenue in Table 6.2 was achieved by Wind Farms using a 4.48MW/2.74MWh VRFB technologies (reaching £193.78 million in TSR), hybridizing the ESS, in this case, is not the best option to invest for REG providers. Instead, it is a more profitable option for REG providers to address frequency services and interacting with the wholesale market using a single VRFB technology.

A more interesting outcome of these results is that, for REG providers, participating in the non-mandatory frequency scheme FFR provided greater TSR than being engaged in the mandatory frequency scheme MFR. This is represented by higher revenues of £12.57 million and £12.58 million reached by both REG providers (i.e. Wind Farms and Solar Farms respectively) when delivering FFRA service and interacting with the wholesale market over the income obtained by them when participating in the MFR service and interacting with the wholesale market. These superior returns from REG providers in the FFRA Model occur during every month throughout the year as shown in Figure 6.1 for Wind Farms and Figure 6.2 for Solar Farms.

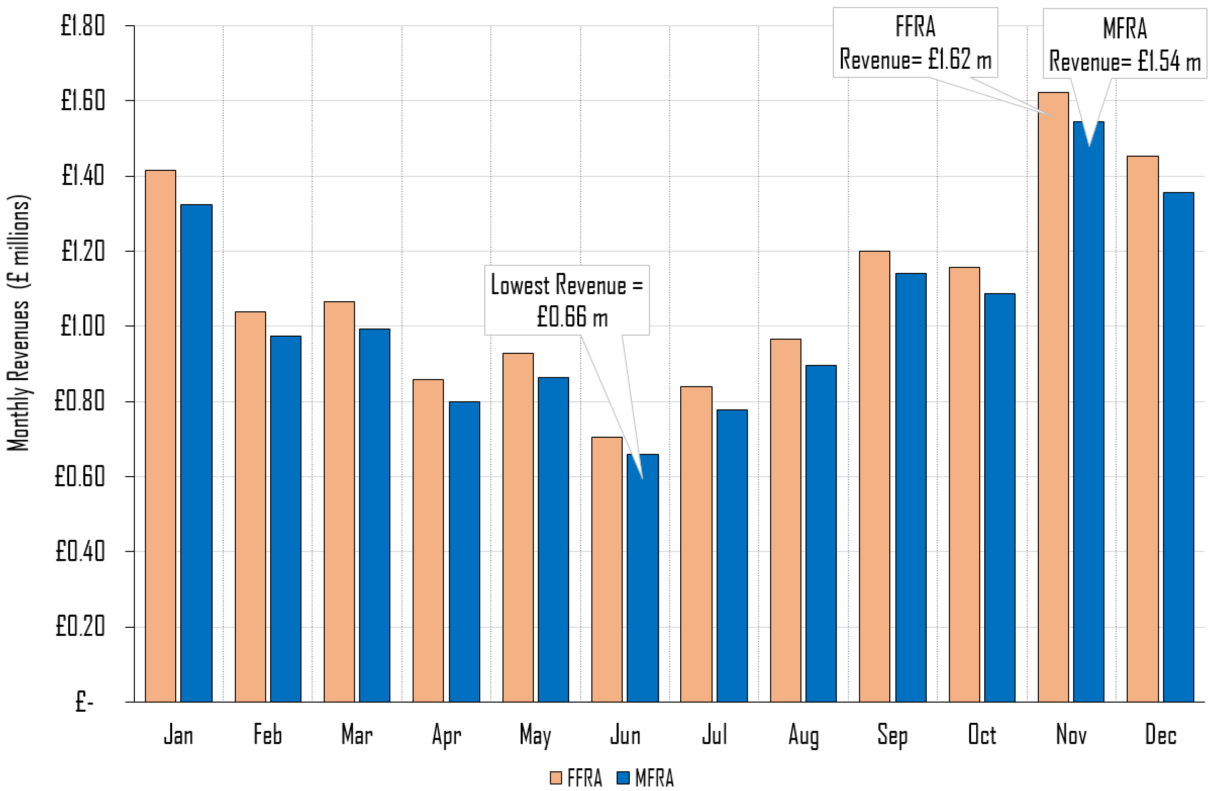

Figure 6.1. Monthly Revenues per year achieved by the Wind Farm in MFRA and FFRA Models

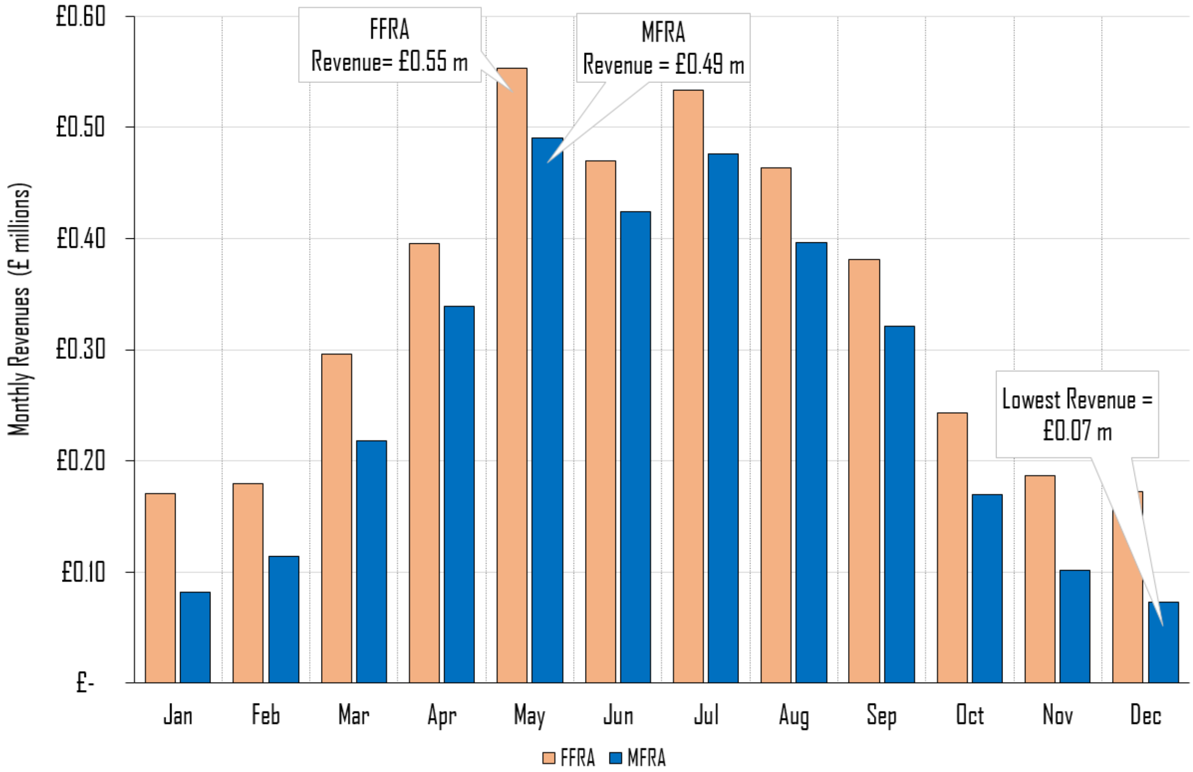

Figure 6.2. Monthly Revenues per year achieved by the Solar Farm in MFRA and FFRA Models

It is important to mention that wind generation and solar generation are not a constant value (i.e. constant 50MW rated capacity) and the market prices are also fluctuating. Therefore, the revenues presented in Table 6.2 and Figure 6.2 cannot be calculated by the simple multiplication of static market price with energy delivered. It is rather obtained by having into account frequency requirements, market prices, and the ES operation as developed in Chapter 4. Therefore, the load factors, for this study, are not directly considered within this study models since power generation profiles are inputs of the models and loading factors can be applied from the raw data stage rather than during model development and optimization process.

In MFRA Model, REG providers are forced to provide mandatory frequency response according to GB regulations and to maintain a proportion of energy reserves for dealing with the worst cases of frequency-change and for delivering secondary frequency response, if required. These energy reserves play an important in increasing the size of ES devices and, thus, in raising the investment cost as ES technologies must be oversized to cover extra energy reserves without being able to fully exploit these ES power and energy ratings in actual responses. Moreover, the MFR regulations also limit the ability of REG providers to deliver frequency response based on generation levels. For instance, ES devices collocated in Solar Farms are not allowed to provide MFR service during winter season since the generation levels of the Power Station are mostly below the grid-code requirements. For the FFRA Model, however, although the sizes of ES devices could be similar to the ones in MFRA Model, the ESS will have the ability to deliver higher power responses as the reserve levels in FFR service are not obligated to consider the worst cases of frequency-change. Additionally, in FFR services, the actual frequency response from ES devices are not linked with generation level of the Power Station but rather are free to be offered depending on the grid-frequency conditions. This can be better visualized through the monthly revenues of REG providers achieved from Frequency Services in both models (Figure 6.3 for Wind Farm revenues and Figure 6.4 for Solar Farm revenues).

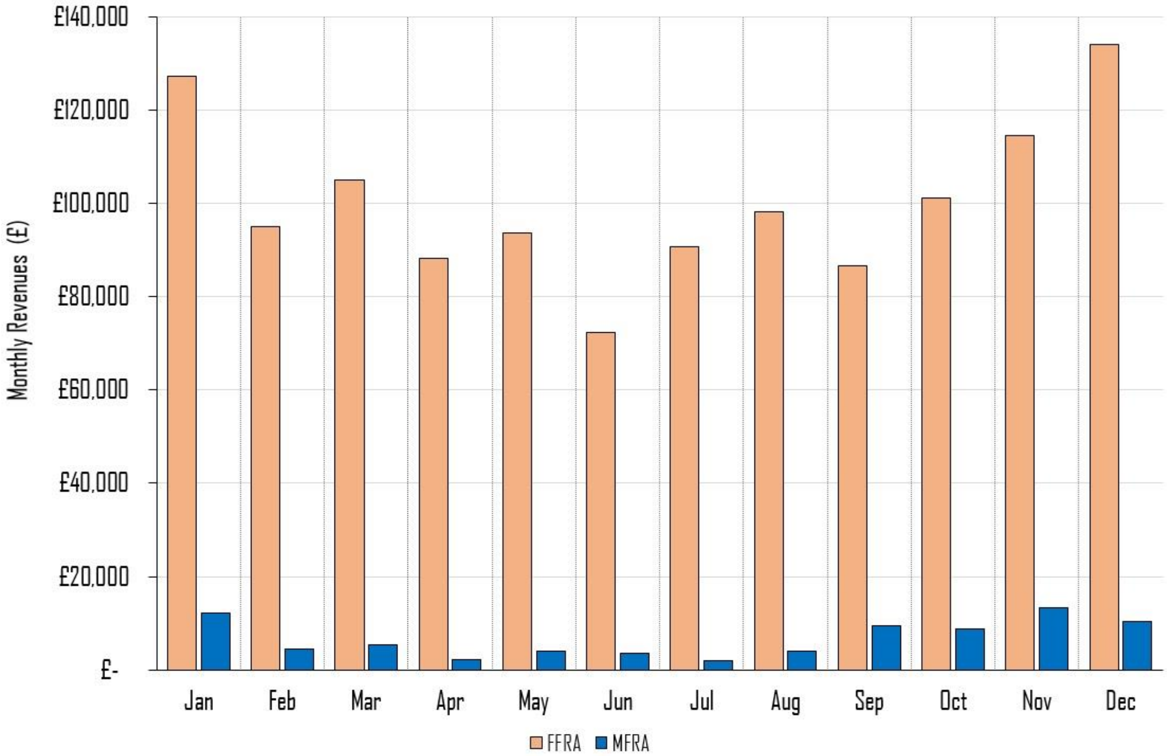

Figure 6.3. Monthly Frequency Revenues per year achieved by the Wind Farm in MFRA and FFRA Models

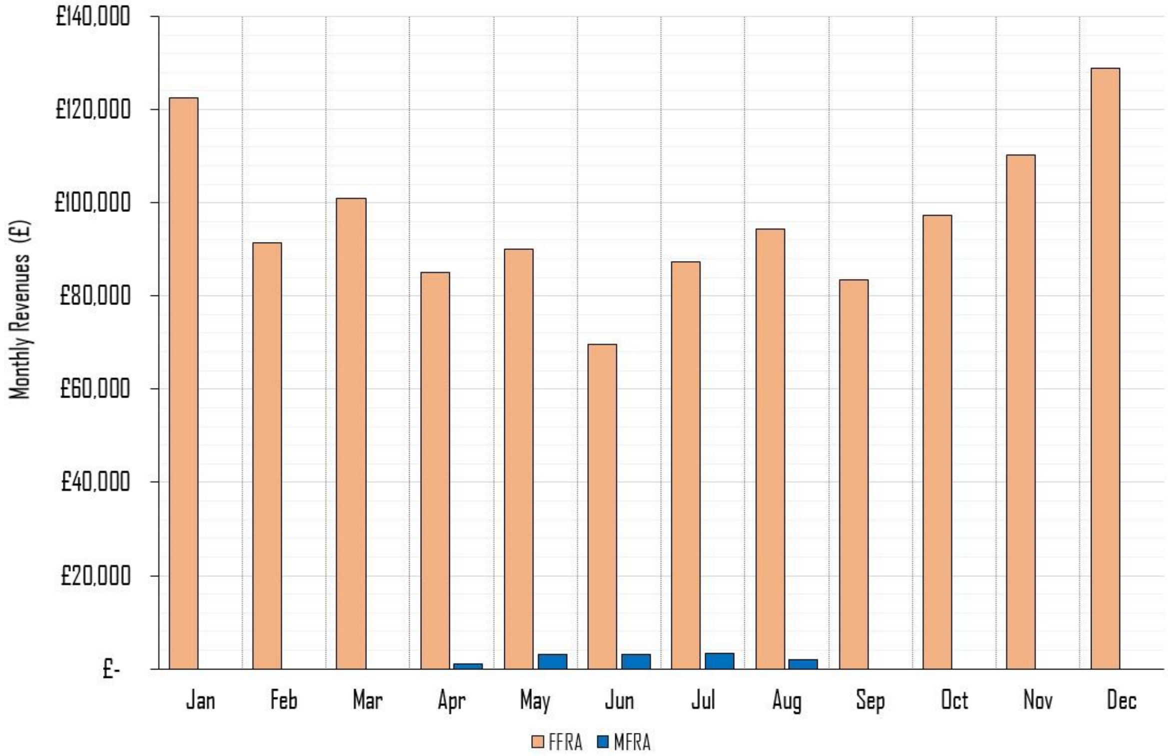

Figure 6.4. Monthly Frequency Revenues per year achieved by the Solar Farm in MFRA and FFRA Models

In Figure 6.3, it is possible to see that the monthly income of Wind Farm from providing frequency services, using VRFB devices, occurred every month in mandatory-scheme. This was not the case of Solar Farm that only reached the required generation levels for MFR service during summer periods based on its monthly income shown in Figure 6.4. Nevertheless, none of revenues were able to exceed, in any month, the revenue of these REG providers achieved from delivering firm frequency services (i.e. using the FFRA Model). It is important to mention that, the monthly income of REG providers acquired from the FFR service and wholesale market interaction presents the same shape for both REG provider cases (Figure 6.3 and Figure 6.4) since, in the FFRA Model, the service provision of ES devices is not linked by FFR regulation to the generation levels of the Wind Farm or Solar but rather related to the grid-frequency and the tendered bids.

As Wind Farms produced the highest revenue between MFRA and FFRA Models, the rest of this chapter is developed considering only this renewable source. The rationale behind this assumption is that the rest of the sections aims to present the results from investigating other techno-economic factors influencing the value of ES technologies rather than the ones influencing the value of renewable generators. In order to study these factors of ES devices under the same conditions for each model, FFRA and

MFRA, wind generation was the chosen profile although the methodology allows to apply solar generation if this is required. Moreover, in both models, MFRA and FFRA, the generation from renewable generators does not play an active role when interacting with the wholesale market other than a constant power input into the grid and to determine the MFR response profile. Therefore, for FFR, this service is exclusively addressed by the ES system rather than from renewable generators as described in Section 3.4.3 (see Table 3.4). It is also important to mention that, both models, MFRA and FFRA, are always addressed in each section regardless of which one is more profitable.

6.4. Technology Selection

The main goal of this section is to examine the impact that different technologies have on the income of REG providers when providing, in exclusivity, Frequency Services, both MFR and FFR, while also interacting with the wholesale market. The selection criterion is based on using different ES combinations in the MFRA and FFRA Models to, ultimately, choose the most profitable option for REG providers in each regulatory frequency scheme.

Table 5.5 summarizes the main characteristics of each ES candidate used in both models when combining technologies. Except for VRFB and Supercapacitors, the rest of these ES devices are applied in the MFRA and FFRA Models as both, energy-dense and power-dense technologies, during simulations. This made a total of 31 hybrid ES combinations that were examined under each model. It is important to acknowledge, however, that further ES combinations can be studied with these framework models as they are technology agnostic.

Parameters	NaS	Li-ion	Lead-Acid	Sodium–Nickel Chloride	NiCd
Charge/Discharge Efficiency (%)	87	95	75	85	65
Maximum SOC (%)	100	100	100	100	100
Minimum SOC (%)	0	0	0	0	0
Cycling Lifetime (cycles)	4500	6000	1500	2500	3500
ES Lifetime (years)	15	8	8	15	15
Daily self-discharge (%)	10	0.3	0.2	15	0.4
Cost of Energy (£/kWh)	400	280	180	250	1500
Cost of Power (£/kW)	200	190	180	650	1000

Table 6.3. Technology Selection in MFRA and FFRA Models – ES Characteristics

For FFRA and MFRA Models, the simulation results for all possible ES combinations are shown in Figure 6.5 and Figure 6.6 respectively. The outcomes present scenarios in which only using one ES device could be more profitable for REG providers and cases in which hybridizing ESS could produce the best outcome. All ES combinations that are not included in these figures were either not profitable for REG providers or the highest revenue of REG providers was achieved through a single ES technology.

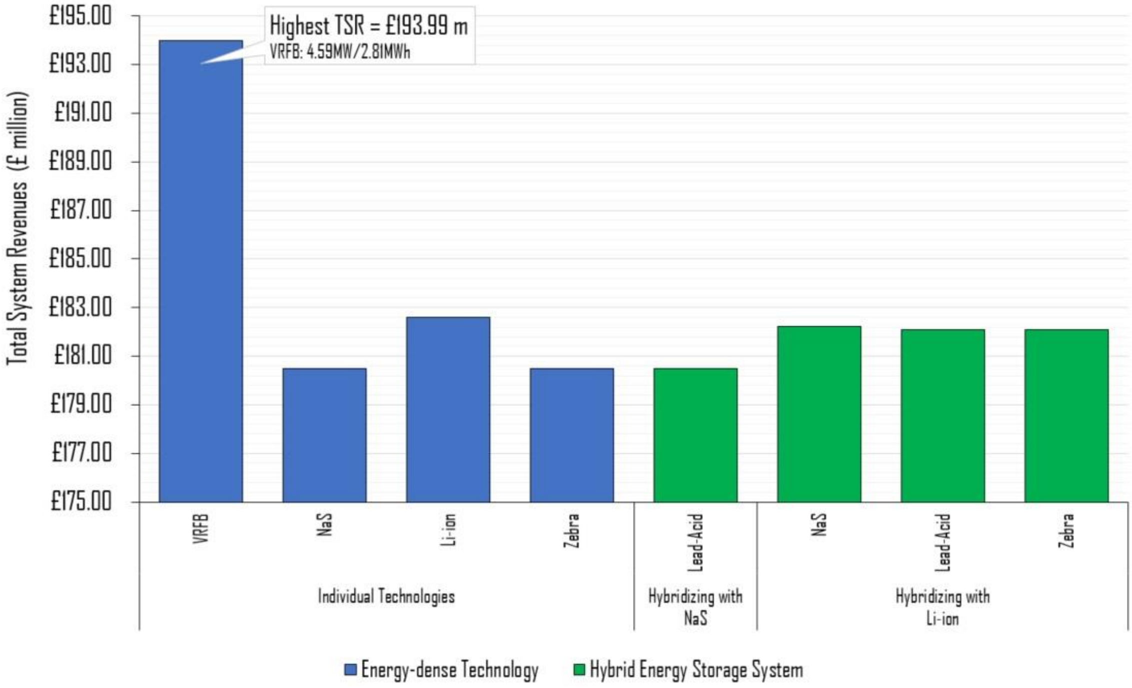

Figure 6.5. Technology Selection – ES Combination Outputs for FFRA Model

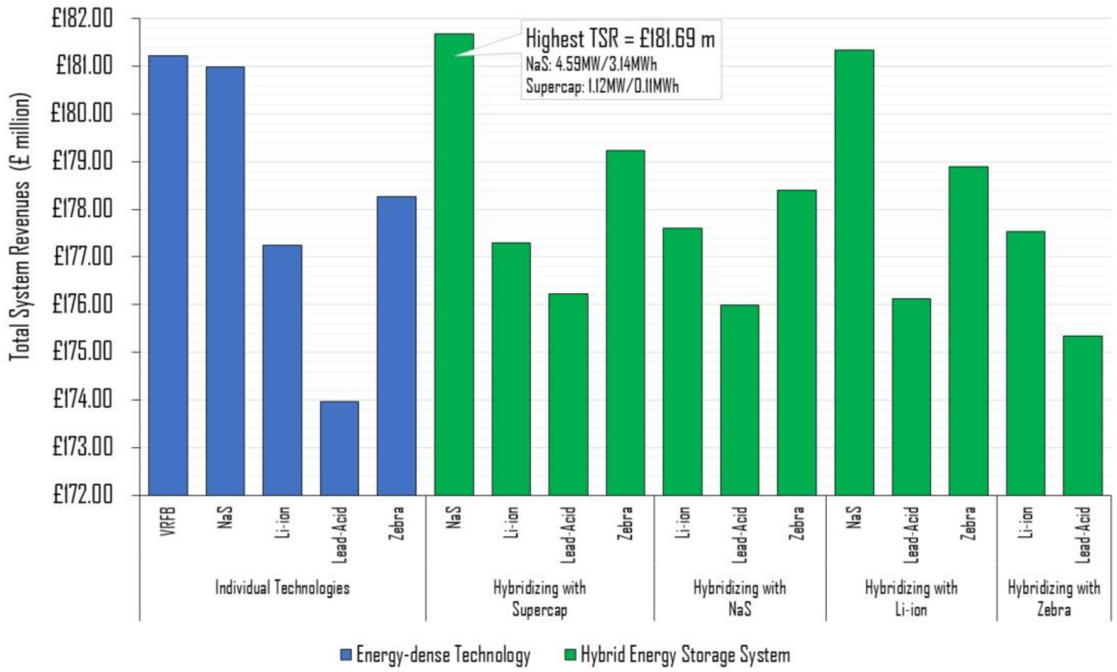

Figure 6.6. Technology Selection – ES Combination Outputs for MFRA Model

The main goal, here, was to find the best ES device or ES combination that can provide the highest revenue for REG providers rather than comparing MFRA and FFRA Models. For this reason, each model was analysed and presented independently, and it also implied the use of the same investment cap in each ES combination of the FFRA Model, established in £4 million. For the MFRA cases, it was not required to set this limit in order to assess all ES combinations.

Although the simulation results, presented in Figure 6.5, for the FFRA Model show scenarios in which hybridizing an ESS is profitable, the best return for REG providers was achieved using a single 4.59MW/2.81MWh VRFB technology with a TSR of £193.33 million. In the ES combinations applied into the MFRA Model, the highest TSR for REG providers, presented in Figure 6.6, was, in turn, reached using a HESS composed of 4.59MW/3.14MWh NaS and 1.12MW/0.11MWh Supercapacitors. These results not only show the economic potential of applying single ES device and HESSs, depending on the circumstances, for REG providers but also the importance, for them, of selecting an appropriate set of ES when delivering multiple market applications.

A mentioned before, an important characteristic of the results presented in Figure 6.5 and Figure 6.6 is that, although they present the value that different ES technologies might have for REG providers under mandatory and non-mandatory schemes, they do not allow the assessment of the value of ES devices when comparing both frequency regulatory schemes. The constraint involved in this comparison limitation is the investment cap required in the FFRA Model. For that reason, the best ES technology combination for REG provider in the FFRA Model was again simulated using different ES investment limits and the simulation results, presented in Figure 6.7, are now compared with their counterpart from the MFRA Model.

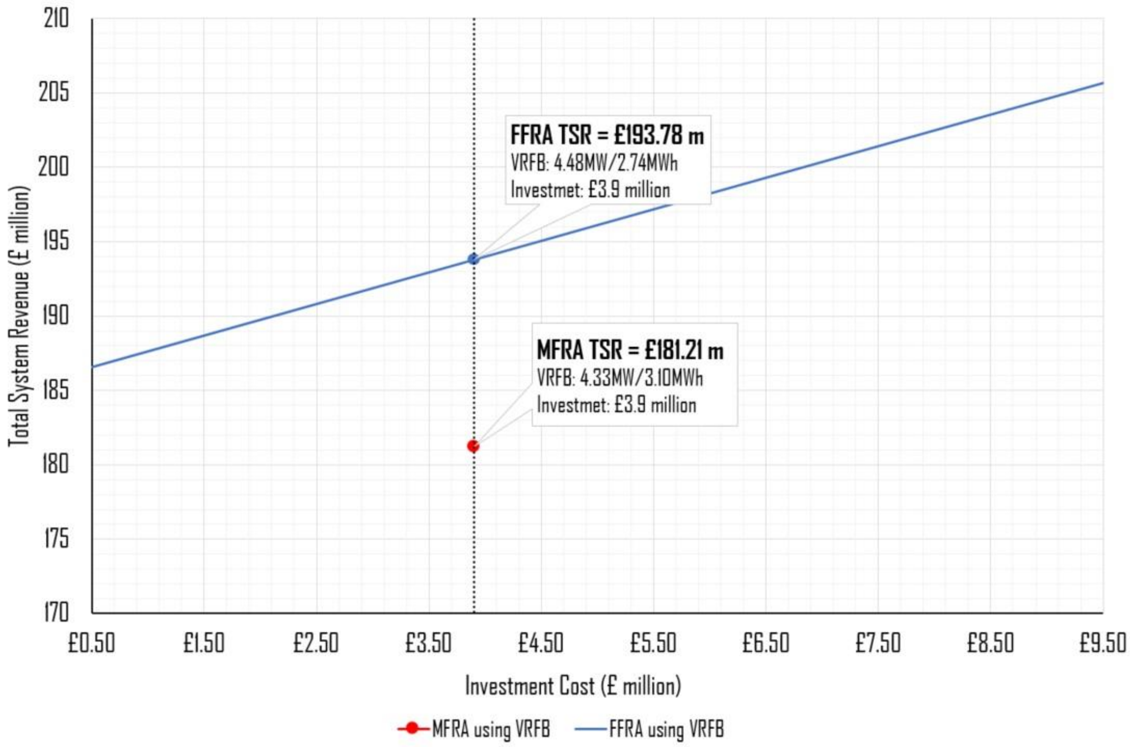

Figure 6.7. Technology Selection - MFRA and FFRA Models comparison under different Investment Caps

In Figure 6.7, the simulation results of MFRA Model produced a single solution since this model does not require different investment cap to reach the highest income. For FFRA Model, however, the investment limits are essential and, based on simulation results, it influences the TSR of REG providers in a linear proportion as shown in Figure 6.7. In the FFRA Model, the higher is the investment cap, the greater are the revenues of REG providers. This condition not only allows independent studies to be carried out on ES devices by applying one specific investment cap but also to compare the results under a different market scheme as in the MFRA Model.

Both models presented, in Figure 6.7, the same investment cap of £3.9 million. At this level, the most profitable scenario for REG providers was achieved by using a VRFB in the FFRA Model with £12.57 million more revenues than in the MFRA Model. Based on these simulation outcomes, it is also expected for REG provider to receive a greater contribution in TSR from ES devices applied to FFR service and wholesale market interaction than used in MFR service and wholesale market interaction. The contributions on TSR of REG providers, over a 15-year project period, from different Frequency Schemes are presented in Figure 6.8.

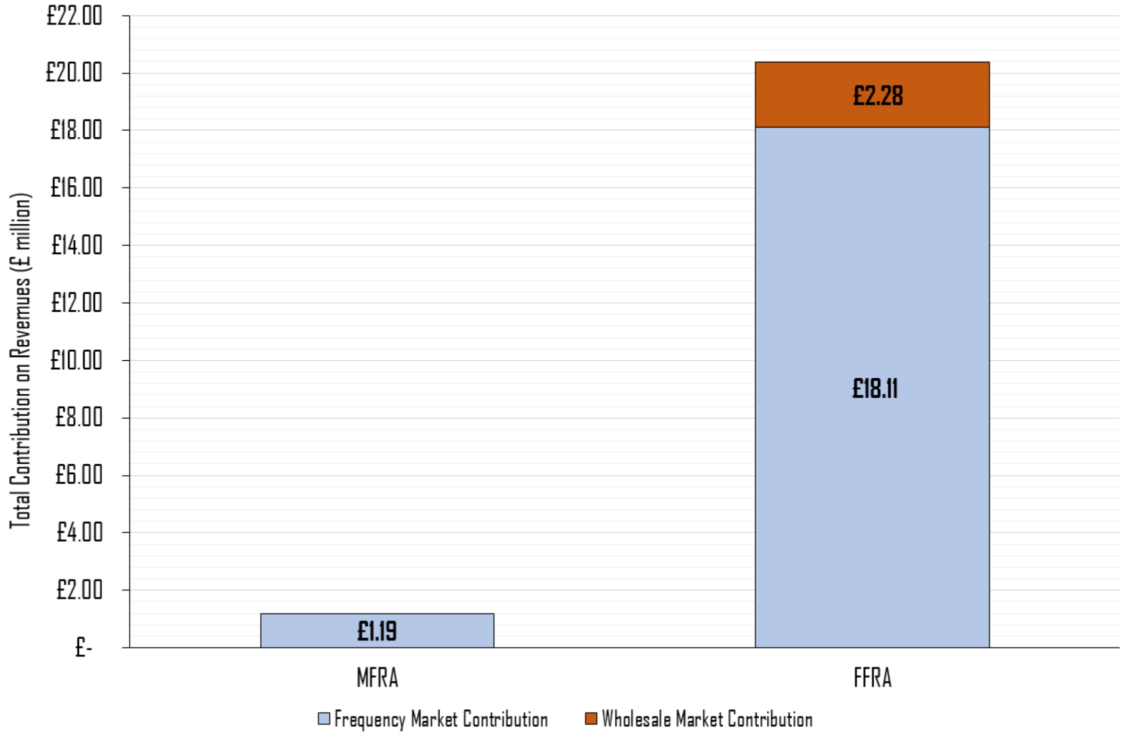

Figure 6.8. Technology Selection - Individual Contributions to TSR in MFRA and FFRA Models

The individual contributions on TSR in MFRA and FFRA Models were divided in two revenue streams, the income from delivering frequency services with ES devices and the income from interaction in the wholesale market with ES technologies. In total, the contributions to the income of REG providers were £20.39 million in the FFRA Model where 11.2% came exclusively from interacting with the wholesale market and the remaining were from FFR. This can be seen in more detail in Figure 6.9. In the MFRA Model, the complete contribution on the TSR of REG providers was almost entirely achieved only from delivering mandatory frequency response. However, this contribution only reached 6.6% of the income reached by firm frequency response in the FFRA Model (see Figure 6.9). This shows the relevance that this regulatory scheme factor might play on the income of REG providers when using ES technologies and, thus, in facilitating the deployment of these devices.

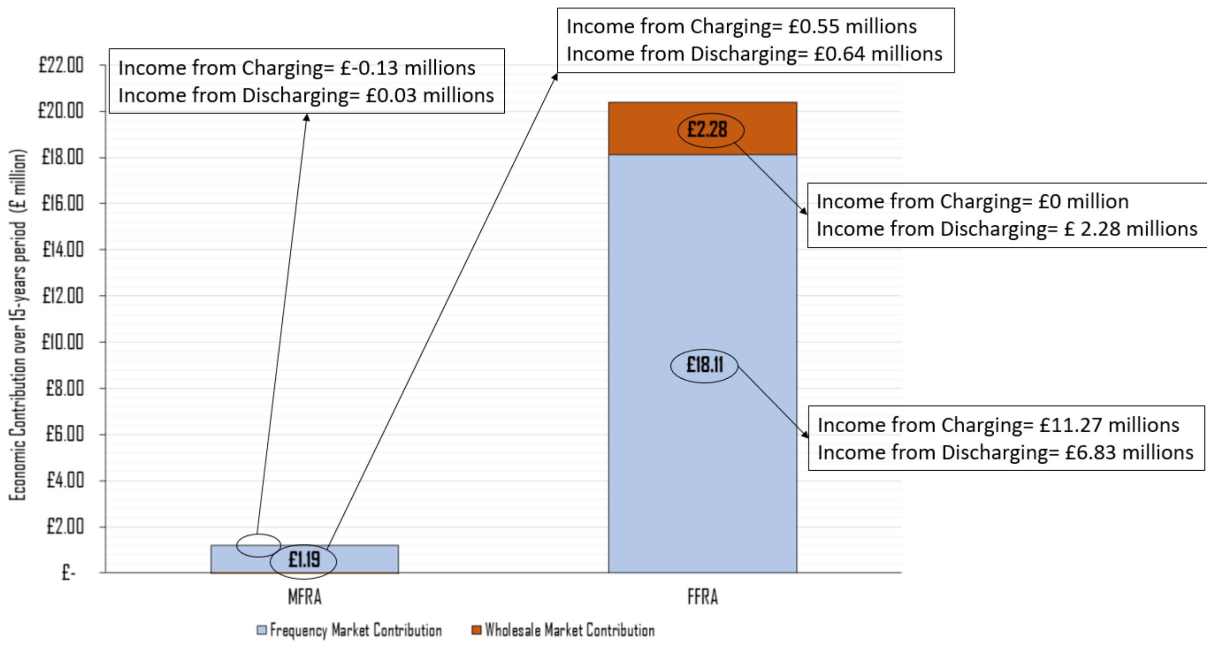

Figure 6.9. Explanation of the Individual Contributions to TSR in MFRA and FFRA Models

The remaining sections in Chapter 6 are addressed considering the best ES device, from all models, determined in this section for REG providers: VRFB as energy-dense ES technology. Supercapacitors are also applied as the power-dense technology in order to address potential scenarios in which hybridization of ES devices could achieve greater income for REG providers.

6.5. Sensitivity Analysis on ES Economic Parameters

Investigating techno-economic factors of ES technologies involve analysing each key element, described in Section 1.3, that influence the present and future value of energy storage. In this research, the approach followed in Chapter 6 was first to investigate the value of using ES technologies in conjunction with different renewable generators (i.e. Solar Farms and Wind Farms) for REG providers under different frequency schemes while also interacting in the wholesale market. This approach is of importance to understand the value of ES technologies when supporting REG integration from different sources under mandatory and non-mandatory frequency market schemes. Moreover, the value of ES technologies was also examined in this work by taking into account technology selection processes for both frequency market schemes. The results of these factors could help different energy actors to visualize how selecting a specific ES device or a hybrid combination of them is key for decision-making processes that could increase revenues while complying with grid-commitments.

Additionally, a direct comparison between ES technologies participating in MFR and FFR services, under same conditions and investment targets, were also addressed to examine the influence of mandatory and non-mandatory factors in the value of ES.

In Section 6.5 and Section 6.6, it is analysed the value of ES technologies from the economic factors and inner technology features point of view that directly influence the value of ES devices and, thus, the systems in which these devices are applied taking into account FFR and MFR services. For these sections, the approach followed to examine the present and future value of ES devices is to perform sensitivity analyses to represent current conditions and potential future changes that could occur for these influencing factors.

6.5.1. Impact of ES Prices of Energy and Power components

The prices of the power and energy components of ES technologies are a significant factor that not only affect the sizing of ES devices but also the profitability potential of REG providers when using these technologies, as shown in Chapter 5 when applying the Three Players Model, for the MFR service and wholesale market interaction. This section carries out a sensitivity analysis on the components prices of ES devices using the MFRA and FFRA Models. The case study takes into account the best ES option for REG providers, in terms of revenues, determined in the previous section (i.e. VRFB technology) and complement the ESS with Supercapacitors for including the potential of hybridization. The technical and economic characteristics considered for each ES device in both models are the same as the ones presented in Table 6.1. Also, the simulations of MFRA and FFRA Models are performed utilizing data inputs from November, as shown in Section 5.2, as this represents the most profitable month for REG providers and for simulation simplicity. Since the aim of the sensitivity analysis is to analyse patterns in the simulation outputs from both models, the assumption does not disturb the findings.

Figure 6.10 presents the simulation results of the MFRA Model when the components prices of ES technologies are modified both independently and simultaneously. These results are all expressed as additional income for REG providers over the income that can be achieved when they are not using ES devices.

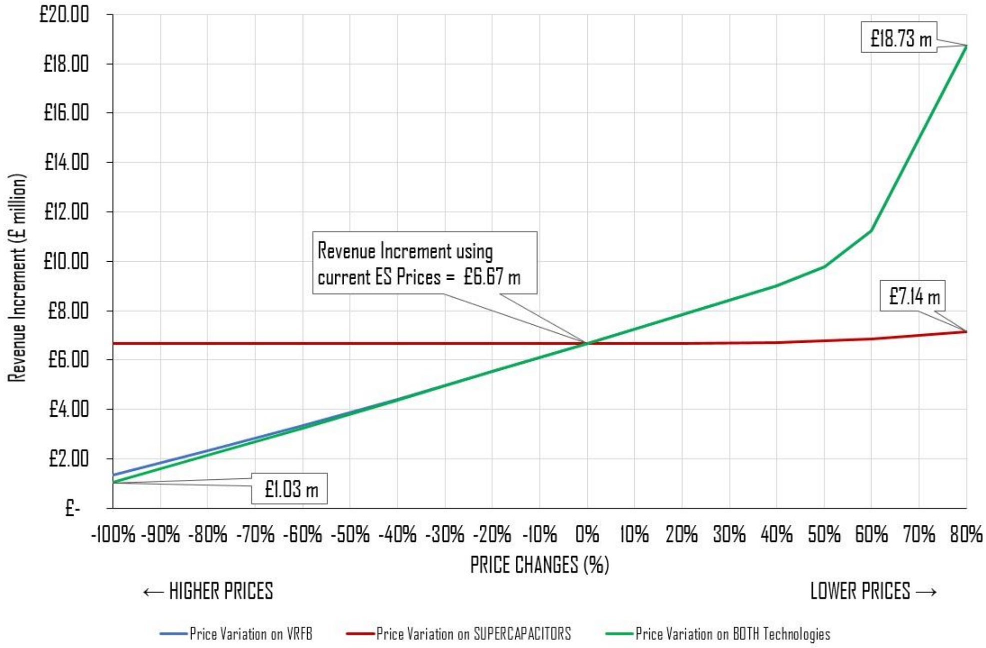

Figure 6.10. Sensitivity Analysis in the MFRA Model – ES Components Price

From Figure 6.10 to Figure 6.19, it can be seen that this work presents higher prices as negative values since this represents a negative improvement (depreciation) of the prices that were considered to be current conditions. In this context, lower prices from current conditions are assumed to be positive as they represent future enhancements from current conditions allowing to analyse their influence in the value of ES devices.

The MFRA Model outcomes, when applying the current conditions of ES devices (see Table 6.1), show that REG providers achieve the highest income increment when using an ESS composed of a single 4.24MW/3.42MWh VRFB technology. The results, depicted in Figure 6.10, also show that future enhancements on the prices of the power and energy components of Supercapacitors only create marginal TSR increments for REG providers. This is not the case of price variations in the components of VRFB technologies which produce significant increments on the income of REG providers when enhanced. The continuous rise in the income of REG providers when modifying the components prices of VRFB is almost linear until 40% of enhancement. After this point, the TSR increment becomes sharp as interacting with the wholesale market becomes a profitable application on its own. This creates an unbounded problem in the simulations of MFRA Model since it has not been established a limit for ES investment cost. For that reason, the last segment of Figure 6.10 (i.e. >40% of enhancement) was achieved by applying an investment cap of £4 million to be calculated. Regarding the modifications on components prices of both ES devices, the simulation results, after the 20% price detriment point, show that Supercapacitors are no longer necessary for REG providers since using exclusively VRFB devices can produce the highest income for them. This caused an overlap in Figure 6.10 between the curve of VRFB price variation and the price variation of both technologies.

Figure 6.12 and Figure 6.12, below, present the effect that varying the components prices of VRFB has in the ES sizing design of both VRFB and Supercapacitors.

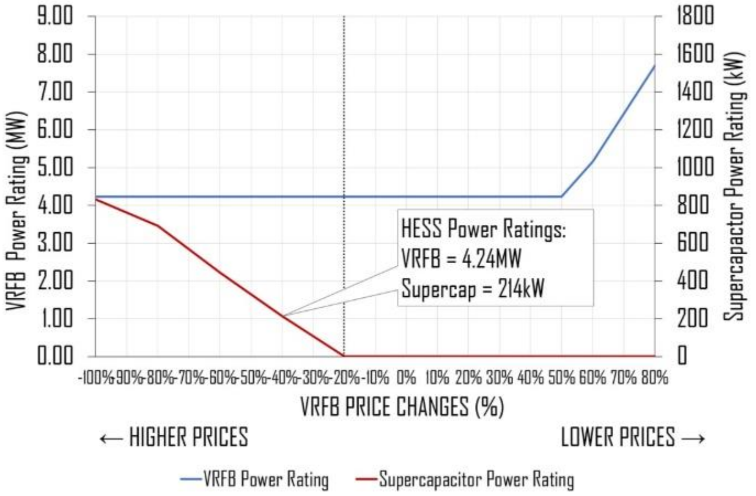

Figure 6.11. Cost Changes in VRFB power components of MFRA Model – ES Power Ratings

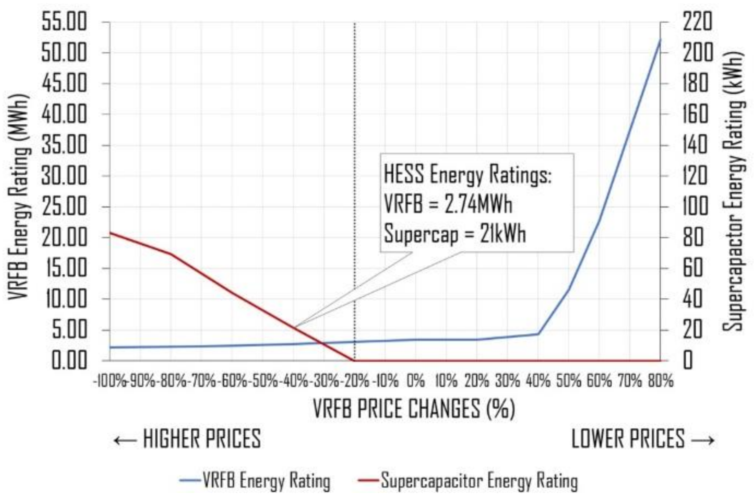

Figure 6.12. Cost Changes in VRFB components of MFRA Model – ES Energy Ratings

As shown in Figure 6.12 and Figure 6.12, when the components prices of VRFB are improved, the highest income for REG providers is reached using a hybrid combination of VRFB and Supercapacitors. This occurs from 100% price detriment until 20% price detriment. After this percentage, the ESS of REG providers only requires a single VRFB device to be profitable. This makes Supercapacitors not to be required and, thus, the graph shows flat power and energy ratings in zero value. In the case of VRFB ratings, the sizing remains stable during most of the improvements since its power and energy ratings must be oversized to cover the most onerous cases of frequency deviation and to cover energy reserves by MFR regulation. In particular, VRFB power rating remains in the same size value while the energy rating presents a smooth increment which is produced in order to address the responsibilities taken from the disappearance of Supercapacitors and to increase wholesale market interactions. However, after 40% of price enhancement, both VRFB ratings start to continuously rise as interacting with the wholesale market becomes a profitable application and the system requires extra power and energy capabilities to address these new actions.

Regarding the components prices of Supercapacitors, Figure 6.13 and Figure 6.14 show the effect of changing these prices on the ES sizing design of both VRFB and Supercapacitors.

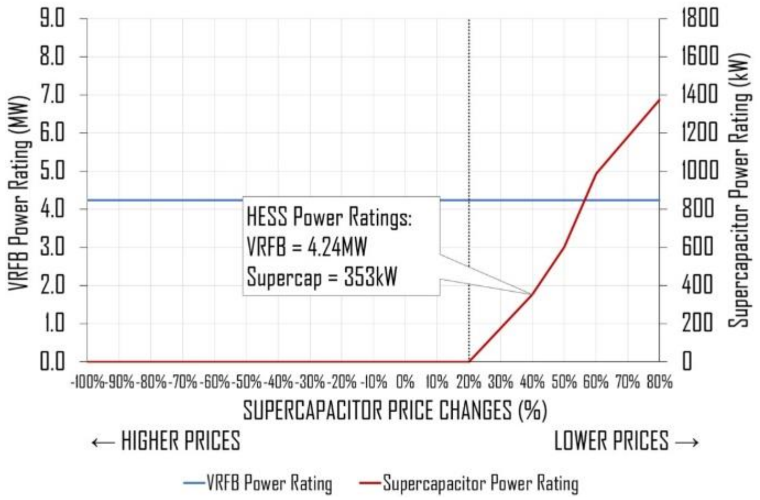

Figure 6.13 Cost Changes in Supercapacitor power components of MFRA Model – ES Power Ratings

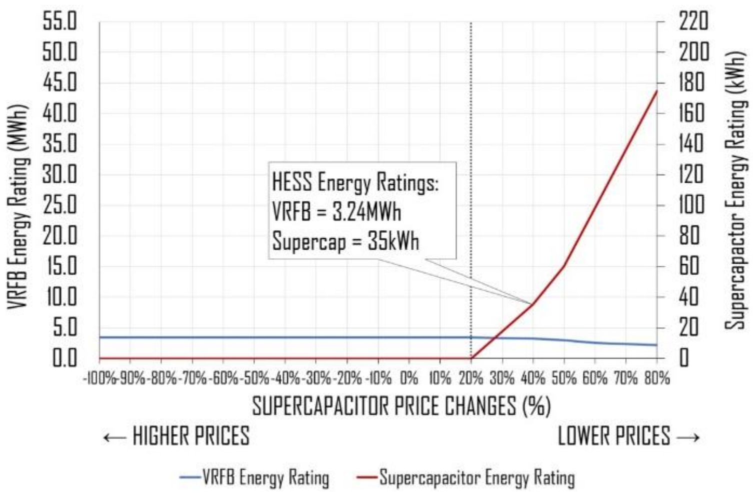

Figure 6.14. Cost Changes in Supercapacitor components of MFRA Model – ES Energy Ratings

As shown in Figure 6.13, the power rating of the VRFB remains at the same size value during the complete variations of the components prices of SCs since VRFB must be able to cover the most onerous cases of frequency deviation when providing MFR support for REG providers. The energy rating of VRFB, in Figure 6.14, is also stable until 20% price enhancement as varying the prices of the components of SCs do not influence the paraments of VRFB when REG providers only use a single VRFB device. After 20% price improvement on the components of Supercapacitors, combining VRFB with SCs can achieve the highest income for REG providers. This creates a continuous raise on the power and energy ratings of SCs, as seen in Figure 6.13 and Figure 6.14, to face the additional tasks of primary response, high frequency response and wholesale market interaction. Although this SC ratings behaviour does not affect the VRFB power rating, the VRFB energy rating is, to a small extent, reduced for allowing an increasing participation of SCs in primary response and the wholesale market.

For the FFRA Model, Figure 6.15 presents the simulation results when the components prices of ES technologies are modified both individually and simultaneously within this model. All the simulations were performed assuming an investment cap of £4 million.

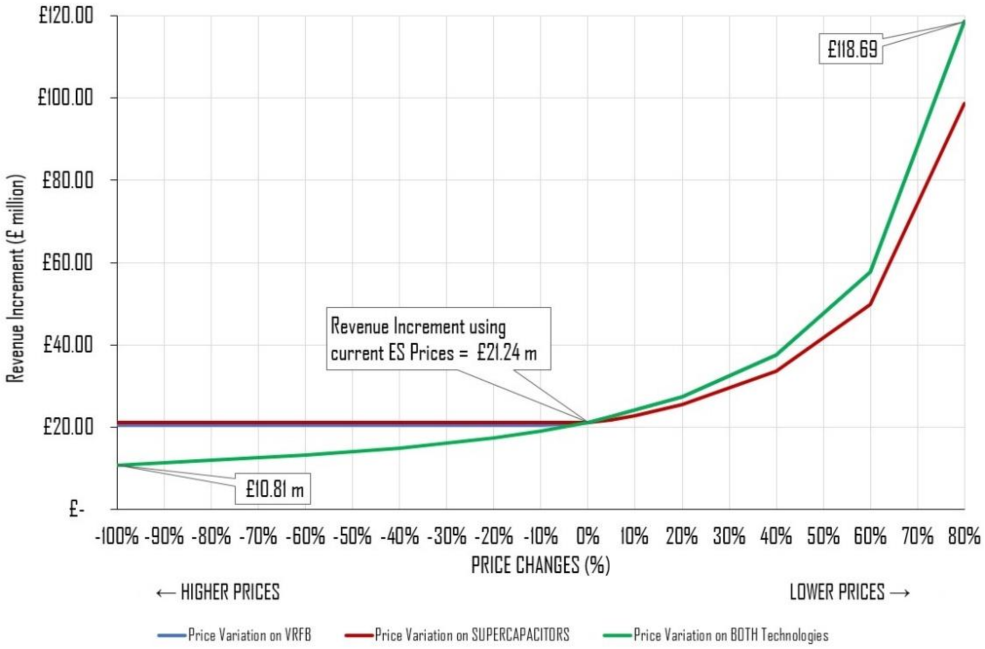

Figure 6.15. Sensitivity Analysis in the FFRA Model – ES Components Price

The simulation results of the FFRA model, under current condition of ES devices (see Table 6.1), showed that REG providers can achieve the highest income by using a HESS composed of 3.61MW/1.91MWh VRFB and 1.52MW/0.15MWh SCs. Unlike the results from the MFRA Model, in this case the components prices variation, for both devices, presents continuous exponential increments in TSR as REG providers are not limited, by regulation, to have power reserves and energy capabilities for the most onerous cases of frequency-deviations. This allowed REG providers to obtain a greater income from frequency response and wholesale market interaction while also enhancing the ES sizing design for the same investment cost. The double economic advantage is not completely present in the MFR scheme where frequency response and the improvements of ES sizing are, to some extent, regulated by the MFR requirements.

When the prices variation only occurs for the power and energy components of SCs, the simulation results show that the income of REG providers remains stable until 5% price detriment since using VRFB is the most profitable option. Here, the revenue of REG providers is not affected by the price improvements of SC. After this 5% detriment point, however, SCs contribute to the TSR of REG providers in two stages:

- Supercapacitors hybridize the ESS when the components prices are between 5% prices detriment and 10% prices enhancement for achieving the highest TSR of REG providers.
- Supercapacitors are the most profitable option for REG providers individually after 10% components prices enhancement.

The aforementioned patterns in the income of REG providers are also followed by the power and energy ratings of both technologies as depicted in Figure 6.17 and Figure 6.17. In these figures, the VRFB power and energy ratings remains stable while the components prices of SC are increased until reaching a hybridization point at 5% prices detriment. In this hybridization stage, the ratings of VRFB technologies start to decrease until achieving a zero value at 10% SC price enhancement. For the ratings of Supercapacitors, the size of this device is increased according to the ratings of VRFB during hybridization stage but rises independently after 10% SC prices enhancement. The stage in which Supercapacitors are used by REG providers independently is characterized by only focusing on high frequency response and wholesale market interaction while leaving aside primary frequency response and, thus, energy reserves. Depending on the regulation and contractual agreements, the latter scenario might not be possible since providing primary frequency response could also be asked as participation requirement.

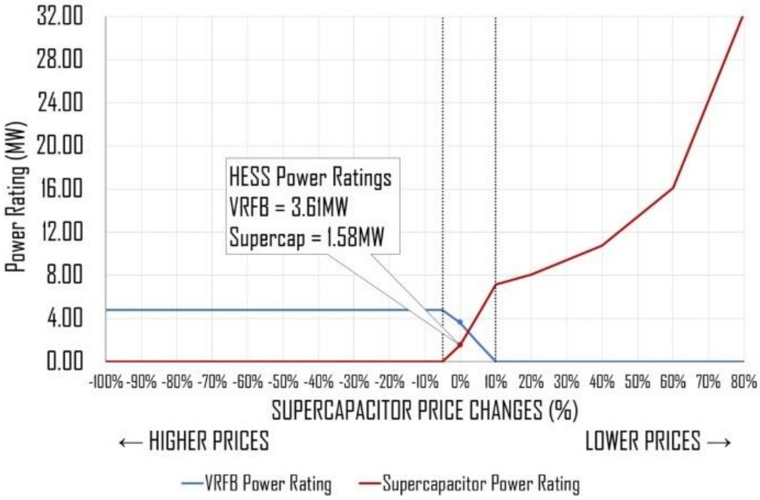

Figure 6.16. Cost Changes in Supercapacitor components of FFRA Model – ES Power Ratings

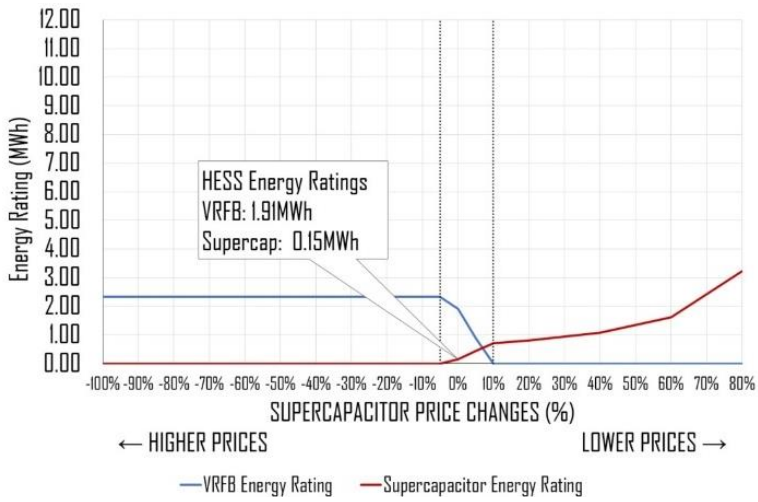

Figure 6.17. Cost Changes in Supercapacitor components of FFRA Model – ES Energy Ratings

Regarding the price variation of the power and energy components of VRFB, the TSR of REG providers remain steady when prices are modified until 10% detriment since using Supercapacitors is the most profitable option during that period. For that reason, TSR of REG providers is not influenced by any improvement in VRFB technology. When the components prices of VRFB device are enhanced over 10% price detriment, however, the use of VRFB also contributes to reach the highest TSR of REG providers in two stages:

- VRFB technology hybridizes the ESS between 10% VRFB price detriment and 5% VRFB price enhancement for reaching the highest TSR of REG providers.
- VRFBs produce the highest TSR for REG providers individually after 5% prices enhancement.

The aforementioned patterns in the TSR of REG providers are also followed by the power and energy ratings of both ES technologies as depicted in Figure 6.19 and Figure 6.19. The ratings of SCs present the same value during the prices variation of VRFB below 10% prices detriment. After this point, both SC ratings start to continuously decrease until disappearing at 5% prices enhancement point. In the case of the sizing design of VRFB devices, the power and energy ratings begin to increase according to the SC ratings during the hybridization stage and independently after 5% price enhancement. The latter stage is characterized by REG providers carrying out all the tasks, primary response, high-frequency response, energy reserves, and wholesale market interaction, by only using VRFB technologies.

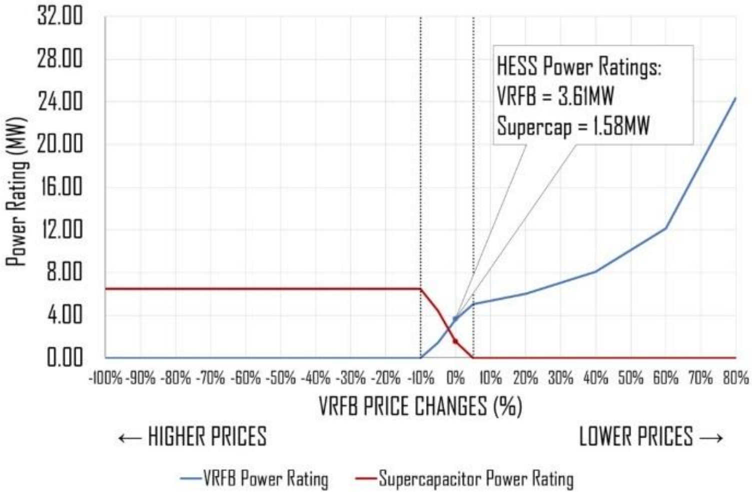

Figure 6.18. Cost Changes in VRFB components of FFRA Model – ES Power Ratings

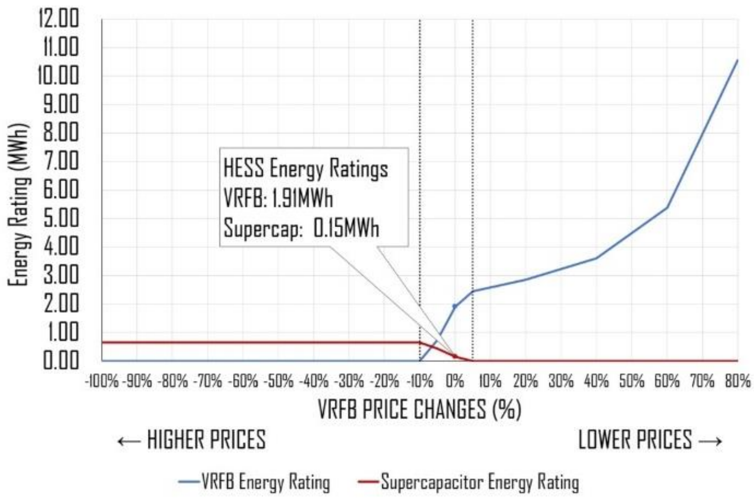

Figure 6.19. Cost Changes in VRFB components of FFRA Model – ES Energy Ratings

6.5.2. Impact of Interest Rates

The Interest Rate is an important economic parameter that could influence the decision of developing a project. When carrying out any investment, such as acquiring an energy storage system, the feasibility analysis of the project should include an Interest Rate that not only fits with the expectations and goals of the company, investors, and any involved stakeholder but also with the real conditions of the market which, in turn, depends on many factors that are out of the scope of this thesis. This section, however, performs a sensitivity analysis with a range of Interest Rates for the MFRA and FFRA Models. The aim is to assess and quantify the effect of this economic parameter on the value of ES technologies when applied by REG providers.

By utilizing the same system conditions as in the previous section, Figure 6.20 and Figure 6.21 present the simulation results of the MFRA Model and FFRA Model, respectively, when considering multiple Interest Rates, ranging from 0% to 8%. Both figures also include the maximum and minimum TSR increments that can be achieved by REG providers when improving or worsen the characteristics of the ES devices until the following limits:

- Cycling lifetime: ±50% increment
- SOC window: from 20% operation gap to 100% operation gap
- Charging/discharging efficiency: ±5%
- Daily self-discharge: ±50% increment

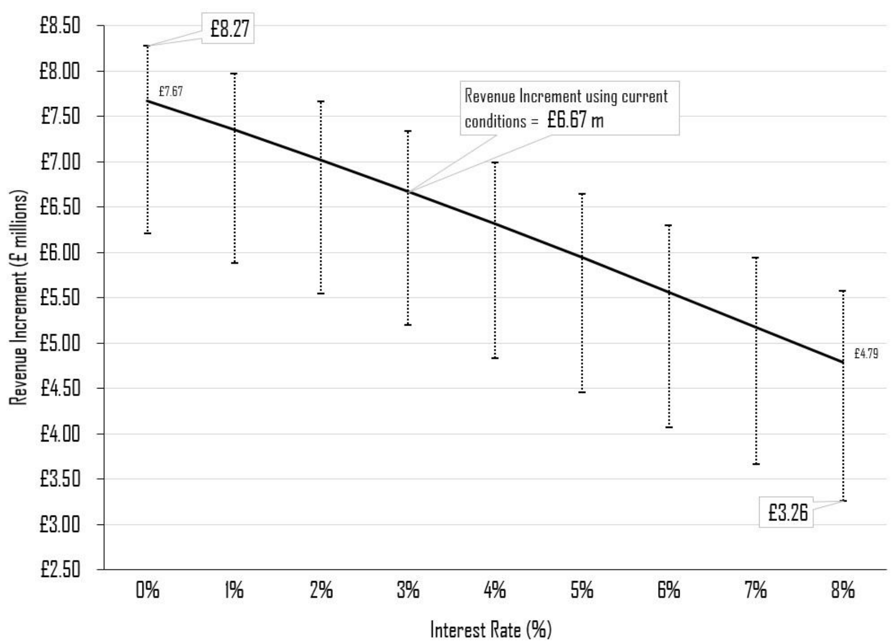

Figure 6.20. Sensitivity Analysis on the Interest Rates of MFRA Model

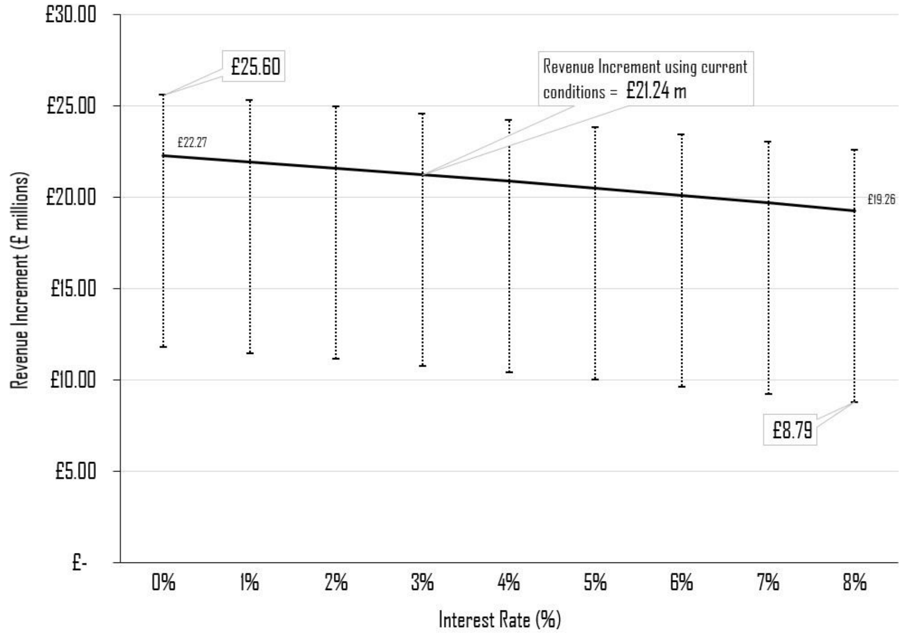

Figure 6.21. Sensitivity Analysis on the Interest Rates of FFRA Model

Based on the simulation results, presented in Figure 6.20 and Figure 6.21, the most important characteristic of varying the Interest Rates, in both models, is that the TSR increments of REG providers are affected with an inversely proportional relationship. The degree in which the income vary from 0% to 8% interest, for a 15-year project period, is similar in both models i.e. 2.88 million variation in the MFRA Model and up to £3.01 million in the FFRA Model. This is caused by the way in which the Interest Rate is considered within the MFRA and FFRA Models. In both models, the Interest Rate is fixed and established as input of the models. Since this economic parameter is a constant that, ultimately, is multiplied with the capital cost of investment through the capital recovery factor, the simulation results for different interest rates are simply escalated depending on the proportion of change among these rates.

Figure 6.22 and Figure 6.23 present the effects of different Interest Rates in power and energy ratings of the ESS for the MFRA Model. Since the highest income of REG providers is reached in this model utilizing a single ES technology throughout all interest rates, Figure 6.22 and Figure 6.23 only include the behaviour of the power and energy ratings of VRFB devices. In the case of power ratings of VRFB, in Figure 6.22, the sizing value remains constant in all the cases as, by regulation, it must consider the most onerous cases of frequency deviation. Regarding the energy rating of VRFB, however, the sizing value must not only consider energy reserves to meet regulation but also, on the top of that, extra energy for interacting with the wholesale market. With higher Interest Rates, these extra levels of energy are no longer affordable for the ES device producing reductions on the energy ratings of VRFB.

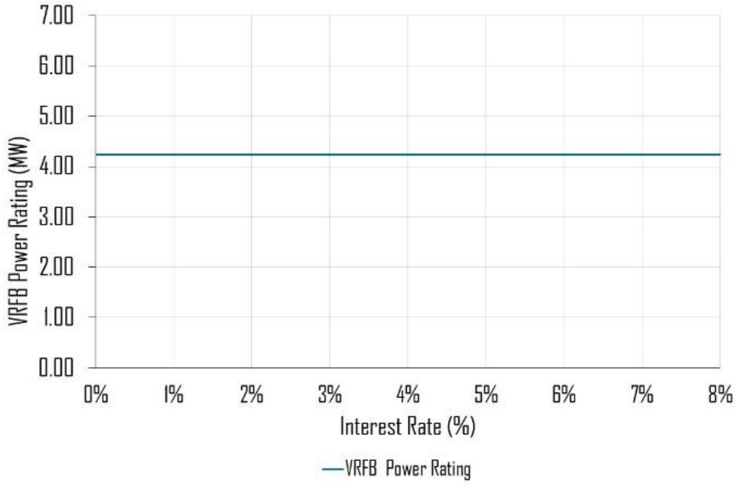

Figure 6.22. Interest Rates impact on ESS Power Rating of MFRA Model

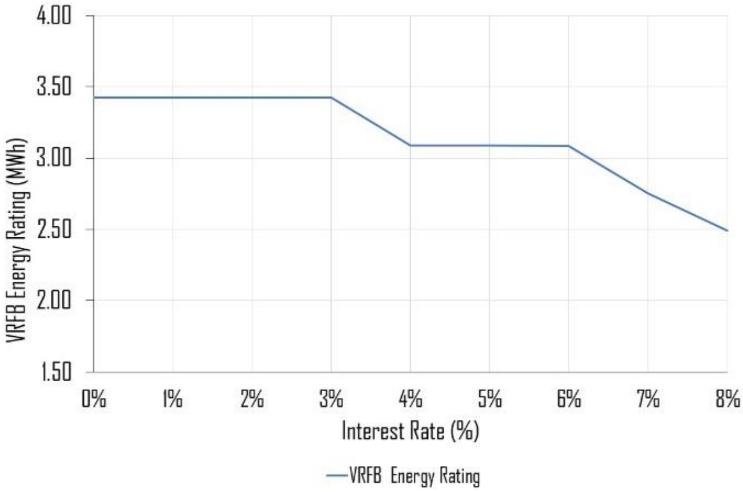

Figure 6.23. Interest Rates impact on ESS Energy Rating of MFRA Model

With regards to the effects of different Interest Rates in the power and energy ratings of the ES devices when applying the FFRA Model and as the investment cap is fixed in this model, the variation of the Interest Rate does not produce any change in the sizing ratings of the HESS. This is caused as this economic parameter only influence the investment cost of ES technologies, through the capital recovery factor, which in the FFRA Model is fixed. For this case study, the HESS was determined to be combination of 3.61MW/1.91MWh VFRB and 1.52MW/0.15MWh SCs.

To finalize this section, it is important to mention that the technical characteristics of ES technologies can create a different revenue band for each Interest Rate between MFRA and FFRA Models, as shown in Figure 6.20 and Figure 6.21. Based on these figures, the income for REG providers in the FFRA Model is more susceptible to change because of the ES technical features than in the MFRA Model. The effects on the income of REG providers and ratings of ES technologies produced by the modifications of the technical characteristics of ES devices are further explored in the next section.

6.6. Sensitivity Analysis on ES Technical Parameters

The technical characteristics of ES technologies are an important factor that influence the income that can be acquired by REG providers when applying these devices to deliver multiple market applications. In this section, the influence that Cycling Lifetime, Charging/Discharging Efficiency and Operation Window could have on the value of ES technologies is assessed and quantified for the MFRA and FFRA Models based on a number of sensitivity analyses of each characteristic. The approach is to apply realistic ranges of improvements and detriments in each ES technical feature and to make comparisons among them in terms of TSR and ES sizing ratings. In this analysis, the current technical characteristics of VRFB and SCs are the same as in the previous section and summarized in Table 6.4.

	Parameters	VRFB	Supercapacitor
Technical	Charging/Discharging Efficiency (%)	92	90
	Maximum SOC (%)	100	100
	Minimum SOC (%)	0	0
	Cycling Lifetime (cycles)	15,000	500,000
	Daily self-discharge (%)	0.25	15

Table 6.4. Current Technical Characteristics of VRFB and Supercapacitors

6.6.1. Cycling Lifetime vs Efficiency

The cycling lifetime and charging/discharging efficiency are addressed in this section taking into account efficiency variations of up to ±5% and cycling lifetime increments of -50% to 50% from the current conditions of ES technologies. The simulation outputs, expressed as revenue increments from the TSR achieved by REG providers when non-using ES devices, are presented in Figure 6.24 for the MFRA Model.

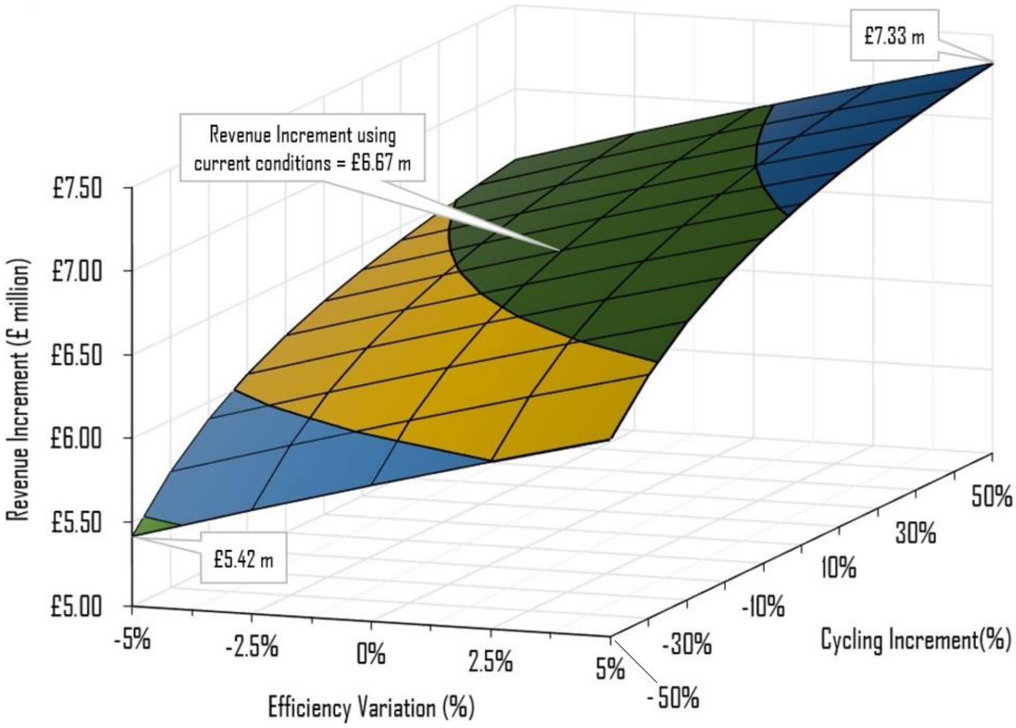

Figure 6.24. Sensitivity Analysis in MFRA Model - Cycling vs Efficiency

Since the cycle lifetime influences the MFRA model by affecting the cost of degradation of each ES device, the effects of modifying this technical feature, shown in Figure 6.24, produce the income of REG providers to be increased and tending to be stabilized with higher enhancements in the cycle lifetime. The stabilization point of TSR increments represents the application of an ideal ESS with zero costs of degradation. In the case of efficiency variations, the TSR of REG providers are affected with linear increments in relation to the enhanced values of efficiency. The best scenario for both ES technical characteristics reaches a TSR increment of £7.33 million from the scenario in which REG providers are not using ES devices. This represents a further £666,000 of more revenues for REG providers than the income obtained with the current ES conditions.

The same behaviour of TSR increments is also followed by the revenues acquired by REG providers when modifying the technical characteristics of ES devices in the FFRA Model, as shown in Figure 6.25. In this case, however, REG providers can reach a maximum revenue increment of £24.58 million which represents a further £3.34 million over the income achieved under the current ES conditions.

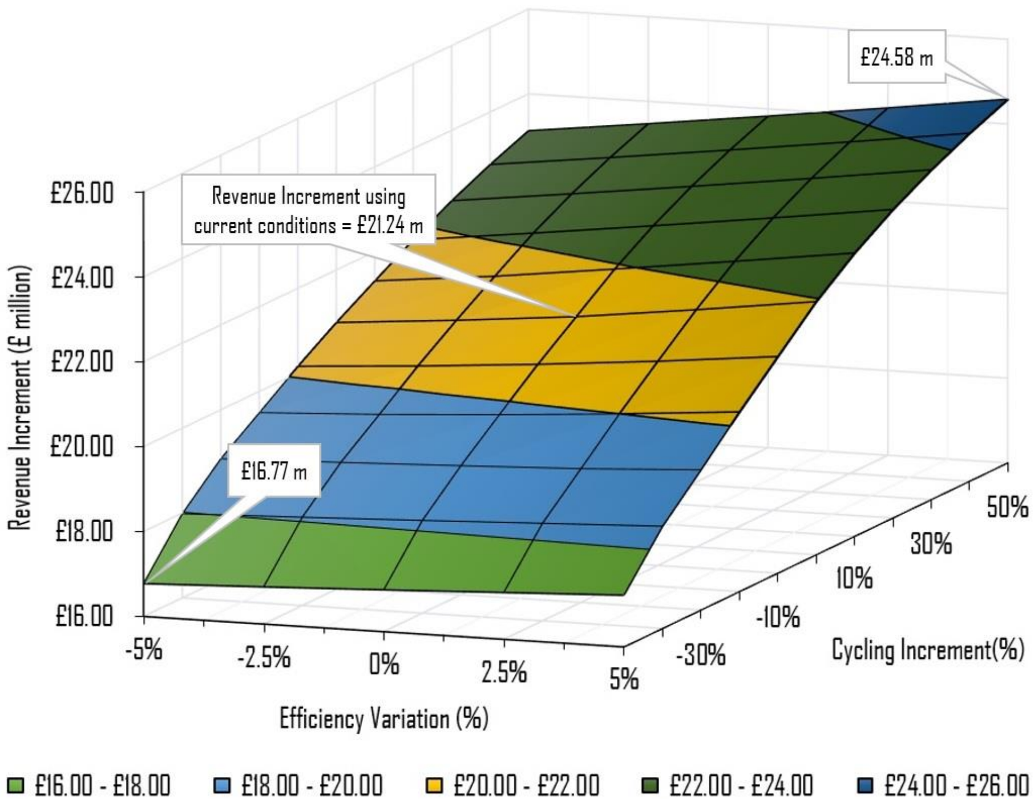

Figure 6.25. Sensitivity Analysis in FFRA Model - Cycling vs Efficiency

When varying the efficiency and cycling lifetime of ES devices under the MFRA Model, the power and energy ratings of each ES technology also suffer changes. The effects of modifying these technical features in the sizing ratings are presented in Figure 6.26 for VRFB technologies and Figure 6.27 for Supercapacitors. For the power rating of VRFB devices, in Figure 6.26, the improvements of cycling lifetime do not change this rating since, by regulation, the power rating has been oversized to consider the most onerous cases of frequency deviation. This is not the case when the ES efficiencies are enhanced. In this scenario, the power ratings of VRFB can be decreased as power losses produced during the charging and discharging processes of ESS are minimized for the same onerous requirements. The power ratings of SCs are, instead, non-existent when the cycling lifetime is over 30% detriment (see Figure 6.27). Below this point, however, the use of supercapacitors to hybridize the ESS of REG providers becomes profitable and, thus, the power ratings of SCs face increments.

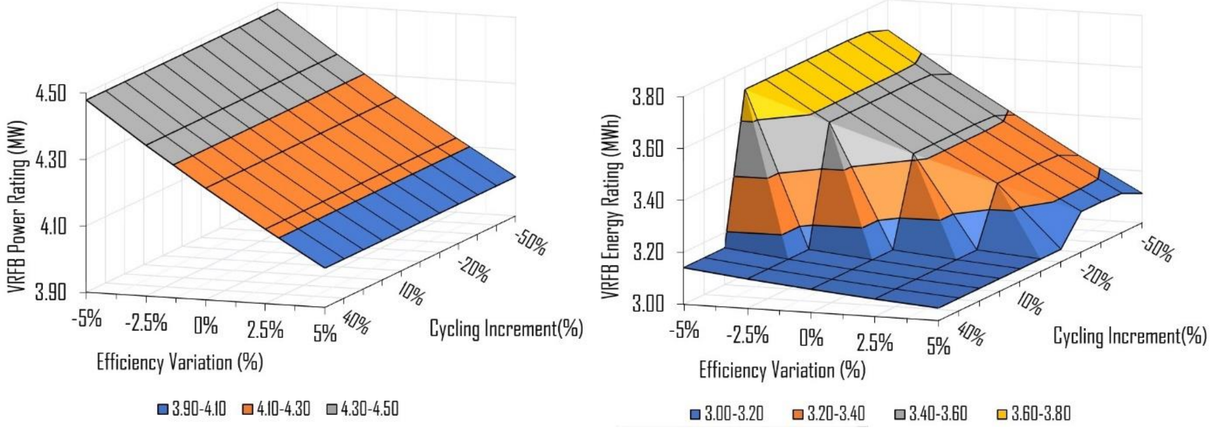

Figure 6.26. Cycling vs Efficiency in MFRA Model – VRFB Power and Energy Ratings

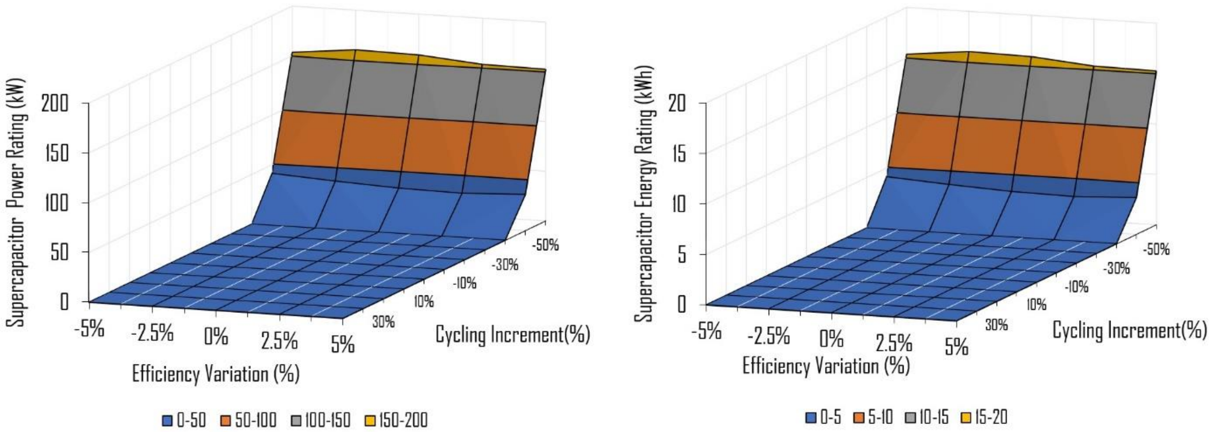

Figure 6.27. Cycling vs Efficiency in MFRA Model – Supercapacitor Power and Energy Ratings

Since SCs are not in charge of energy reserves as VRFB technologies, the energy ratings of Supercapacitors also follow the same pattern of SC power ratings in Figure 6.27. For VRFB energy ratings in Figure 6.26, however, enhanced efficiencies produce reductions in the sizing requirements of these ratings. Nevertheless, these reductions in VRFB energy ratings are even larger when both, enhanced efficiency and enhanced cycling lifetime, occur together in VRFB. This is caused by the improved efficiency effect on diminishing energy losses of ES device and the reduced costs of degradation of VRFB technologies that are produced with enhanced cycling lifetime. The latter means that REG providers are able to obtain a greater income when cycling lifetime of VRFB is enhanced than when expanding the energy ratings of VRFB to perform more actions.

For the FFRA Model, the impact of modifying the efficiency and cycling lifetime on the sizing ratings is presented in Figure 6.28 for VRFB technologies and Figure 6.29 for Supercapacitors. Based on the simulation results, the most important characteristic for all cases is that both, power and energy ratings, present three stages of behaviour based on the variations of efficiency and cycling lifetime in the ESS. The first stage is produced when cycling lifetime increments are highly enhanced. Here, REG providers benefit from utilizing VRFB, in exclusivity, to achieve the highest TSR. On the contrary, when the cycling lifetime is reduced, REG providers only requires Supercapacitors to reach the highest income. In these two stages, both ES technologies show the highest power and energy ratings with a minimal effect from varying the efficiency and cycling lifetime. However, the scenario in which REG providers can reach the highest TSR using a hybrid ESS is visualized as continuous increments in the VRFB ratings when improving the cycling lifetime while facing progressive reductions in SC ratings.

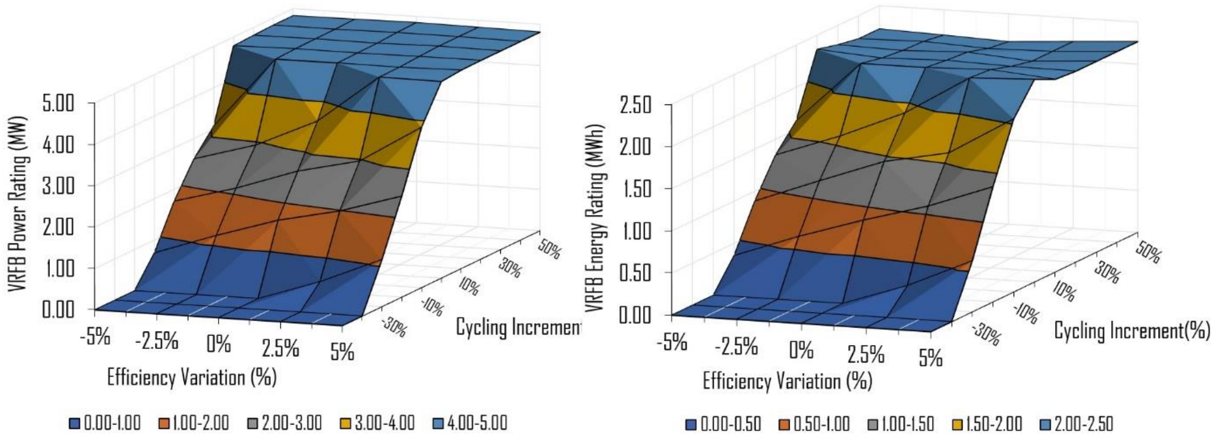

Figure 6.28. Cycling vs Efficiency in FFRA Model – VRFB Power and Energy Ratings

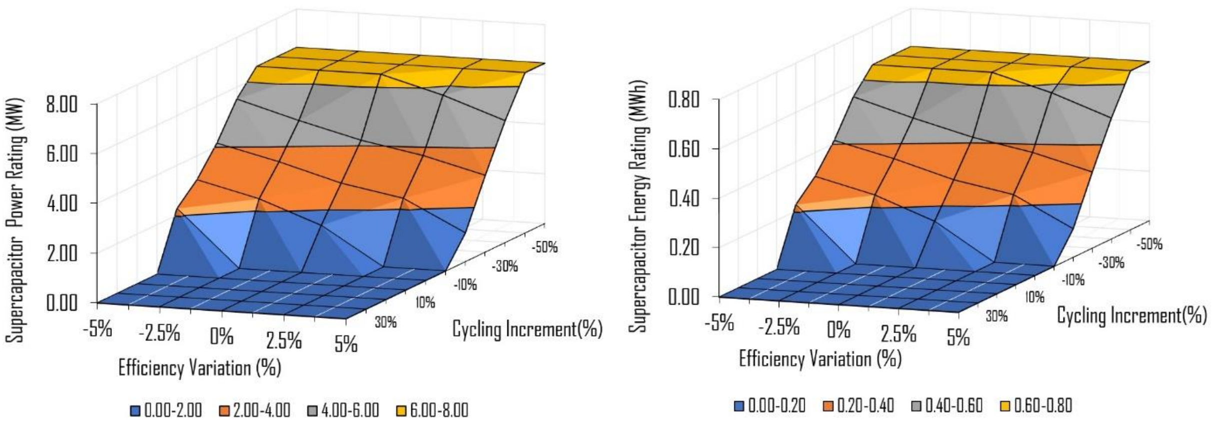

Figure 6.29. Cycling vs Efficiency in FFRA Model – Supercapacitor Power and Energy Ratings

6.6.2. Cycling Lifetime vs SOC Window

As mentioned in Section 5.6.2, the SOC window refers to the actual storage space in which ES technologies can operate. The limits that defines this window could proceed from the intrinsic characteristics of ES devices or from operational decisions. An 80% SOC window, for instance, means that ES technology is able to utilize energy in the range between a maximum of 100% SOC and a minimum of 20% SOC. The effects of modifying the Operational Window and Cycling Lifetime on the TSR of REG providers is presented in Figure 6.30 for the MFRA Model when applying VRFB and SCs.

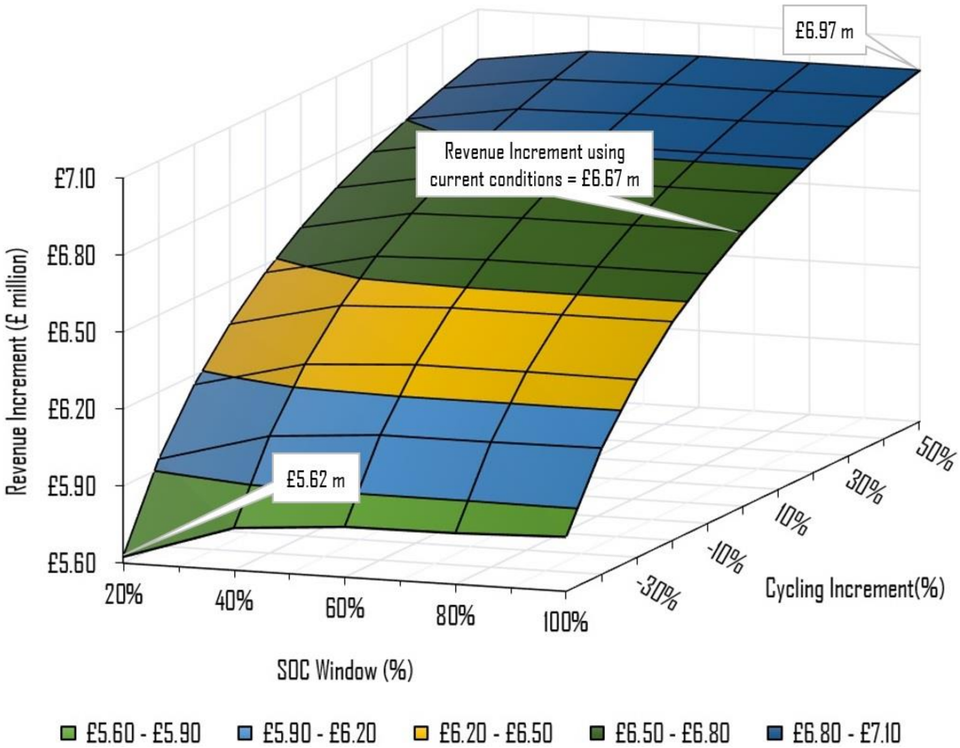

Figure 6.30. Sensitivity Analysis in MFRA Model - Cycling vs SOC Window

Based on the results after simulations, presented in Figure 6.30, REG providers can reach a maximum TSR of £6.97 million when the cycling lifetime is enhanced in each ES device and the SOC window is at maximum opening in both ES technologies. This only represents £300,000 more revenues in total from the income that can be obtained by REG providers when using ES technologies with current conditions. The outcomes of MFRA Model also show that enhancing cycle lifetime in ES devices produce, in the entire range, a continuous TSR increment for REG providers which tend to reach a stabilization point. Since this technical feature directly affects the cost of degradation of ES devices, the highest income of REG providers with respect to cycling lifetime is achieved when there are no costs of degradation in the ES technologies.

In the case of SOC Window, when the operational gap of ES devices is narrowed below 40%, the TSR of REG providers face a marginal reduction. Since REG providers are forced, by regulation, to meet all MFR requirements in the MFRA Model, this TSR behaviour is almost entirely a product of income decrements from wholesale market interaction. On the contrary, when the SOC window of ES technologies is wider than 40%, the TSR of REG providers is almost static since the investment costs for purchasing ES devices are not reduced and interacting with the wholesale market is only feasible to a certain extent. This is a result of the oversizing of VRFB power rating to meet the most onerous cases of frequency deviation and of VRFB energy rating to store energy reserves for the same requirement and for secondary frequency response. This can be visualized in Figure 6.31, below, when analysing the effect of changing the Cycling Lifetime and SOC Window of ES devices in the power and energy ratings of VRFB.

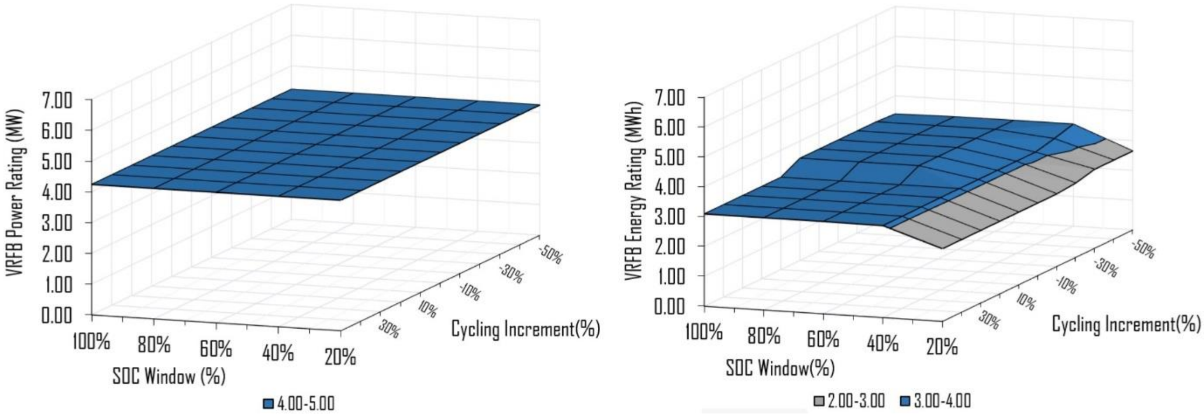

Figure 6.31. Cycling vs SOC Window in MFRA Model – VRFB Power and Energy Ratings

As presented in Figure 6.31 and similar to previous section, the VRFB energy ratings are smaller when enhancing cycling lifetime since REG providers are able to obtain greater TSR with higher cycling lifetimes than expanding the ES ratings. Regarding the SC ratings, these only appear when hybridizing the ESS achieves the highest TSR for REG providers as presented in Figure 6.32. This only occurs when the variations in cycling lifetime faces a 40% detriment or less in both ES devices, but the SOC Window is widely opened (i.e. above 60% opening). In such a case, SCs are capable of supporting VRFB with MFR service and wholesale market interaction while marginally reducing the costs of degradation of the ESS.

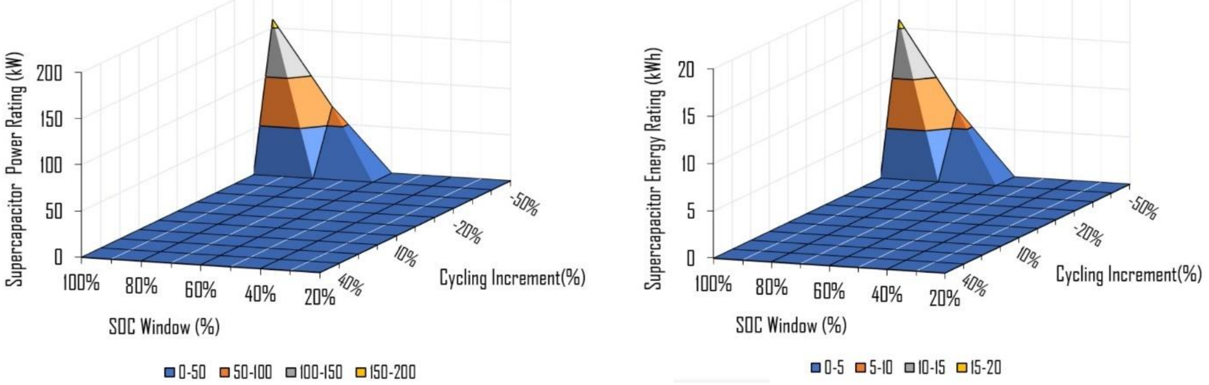

Figure 6.32. Cycling vs SOC Window in MFRA Model – Supercapacitor Power and Energy Ratings

The influence of modifying the SOC Window and Cycling Lifetime of ES devices in the TSR of REG providers is presented in Figure 6.33 for the FFRA Model. In this case, the highest TSR increment reaches £23.82 million which represents a £2.58 million of extra revenue from the income that REG providers can acquire when using ES devices under current conditions.

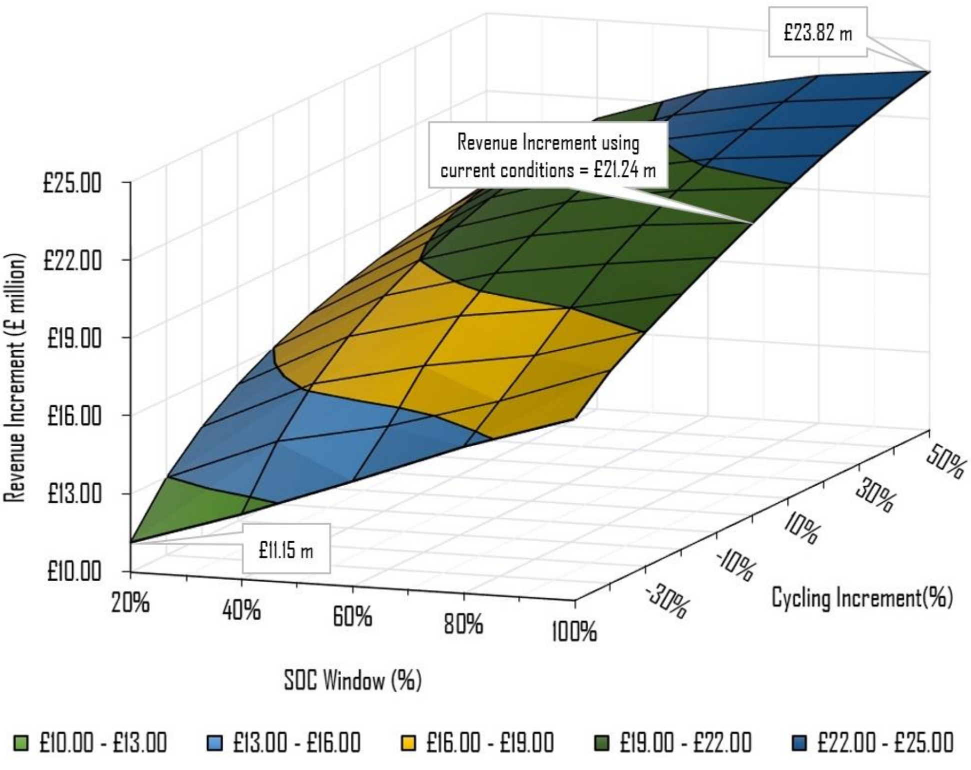

Figure 6.33. Sensitivity Analysis in FFRA Model - Cycling vs SOC Window

As in the cases for the MFRA Model, the simulation results show that cycling lifetime increments produce higher TSR for REG providers and these values tend to reach a stable maximum point characterized by zero ES costs of degradation. The difference occurs when analysing the modification in the SOC Windows. Here, since the response from REG providers is not limited in the FFRA Model by MFR regulations, allowing a wider operational window in the ES technologies can produce significant increments in revenues. This is caused by the ability of the ESS in providing a greater frequency response and wholesale market interaction. In particular, the VRFB power rating increases with wider SOC windows in order to face additional FFR and wholesale market interaction tasks. The VRFB energy rating, however, behaves in an opposite way as the VRFB power rating since, with wider operating windows, portions of energy reserves can now be used in interacting with the wholesale market rather than being stored to permit more FFR. The behaviour of the ratings of VRFB devices when varying the Cycling Lifetime and SOC Window of this technology is presented in Figure 6.34 below.

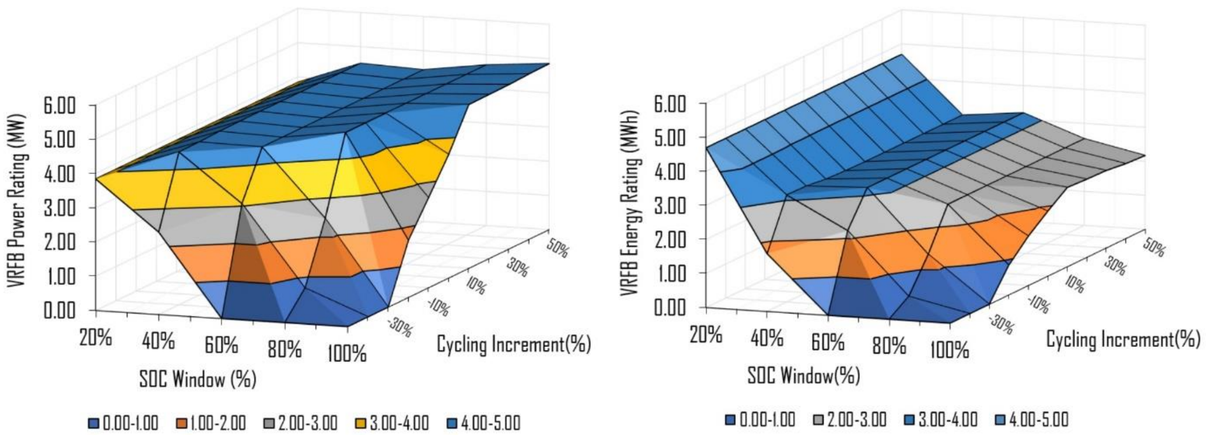

Figure 6.34. Cycling vs SOC Window in FFRA Model – VRFB Power and Energy Ratings

In Figure 6.34, the areas in which both, power and energy ratings of VRFB, decreases are caused by the hybridization of VRFB technologies with SCs, first, until the exclusive use of Supercapacitors is reached. For that reason, the power and energy ratings of Supercapacitors, in Figure 6.35, suffer increments in these areas. Ultimately, the VRFB ratings disappear when only using SCs is profitable. The exclusive use of SCs obeys the condition in which the cycling lifetime of VRFB and Supercapacitors is very low. In these cases, SCs are able to provide high frequency response and interacting with the wholesale market while marginally reducing the cost of degradation. This scenario is dependent, however, on the frequency response regulation allowing REG providers to only provide high frequency response.

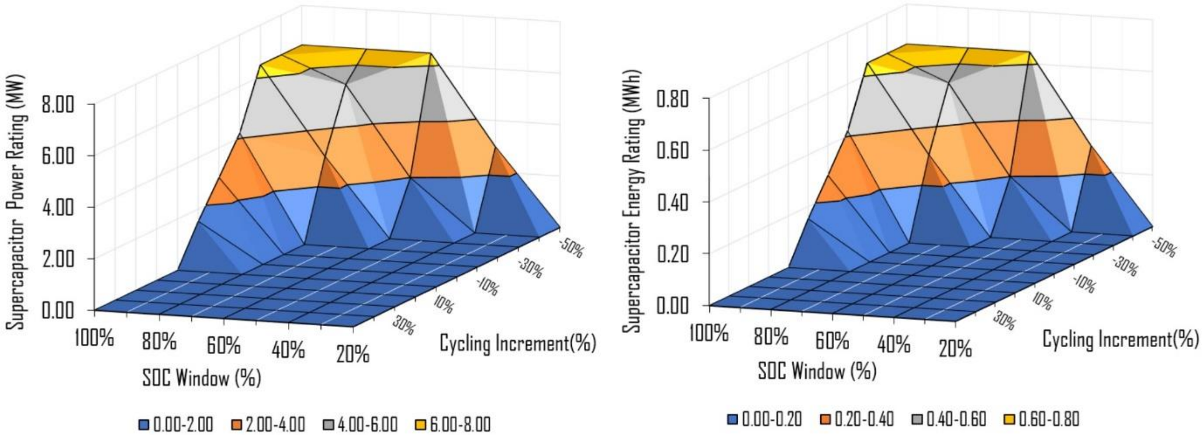

Figure 6.35. Cycling vs SOC Window in FFRA Model – Supercapacitor Power and Energy Ratings

6.6.3. Efficiency vs SOC Window

In Section 6.6.1, enhancements on the efficiency of ES devices in the MFRA Model produced higher TSR for REG providers while wider operational windows, in Section 6.6.2, did not increase the TSR. This behaviour is also expected in the present section when analysing the variation of both technical characteristics of ES technologies in the MFRA Model. The simulation results are presented in Figure 6.36 below.

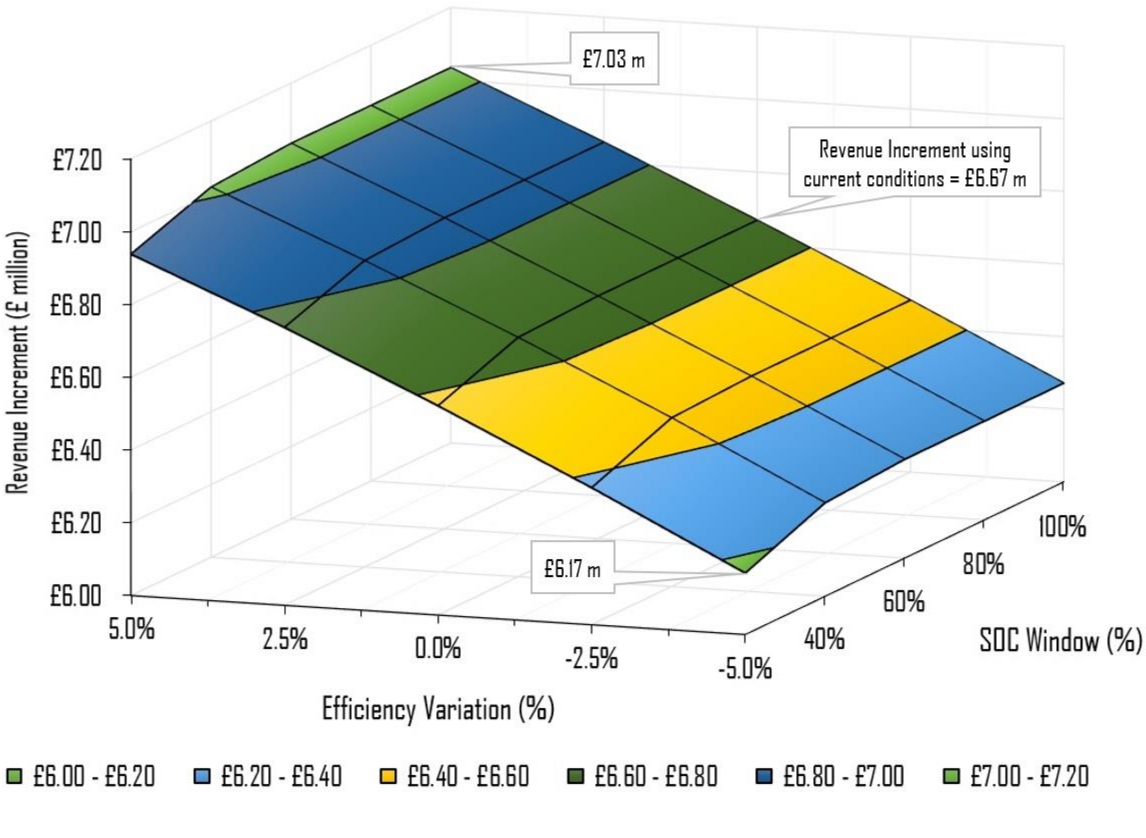

Figure 6.36. Sensitivity Analysis in MFRA Model - Efficiency vs SOC Window

The simulation results when the efficiency and the SOC window are enhanced in ES technologies show that the highest TSR of REG providers can reach an increment of £7.03 million over the income achieved by REG providers when not ES device is used. This represents an additional income of £336,000 from the TSR acquired by REG providers under the current conditions of ES technologies. Figure 6.36 also shows that improvements in the efficiency of ES devices rise the TSR in a linear proportion. This is caused by direct reductions in the VRFB power and energy ratings which, in turn, minimizes the ES investment costs. This can be visualized in Figure 6.37. Regarding changes in SOC windows of VRFB, wider operation windows, in Figure 6.36, do not create a significant impact on the TSR increments of REG providers, excepting when the operational gaps are restricted to very low levels. In such a cases, the revenues are decreased since wholesale market interaction must be reduced to prioritize the MFR service. The consequence of this behaviour is the minimization of VRFB energy ratings in order to reduce investment costs while meeting regulation as depicted in Figure 6.37. It is important to mention that:

- VRFB power ratings remain in the same value for different SOC Windows since they are sized for the most onerous cases of frequency deviation.
- When modifying the efficiency and SOC window, hybridizing the system is not as profitable as only using a single VRFB technology.

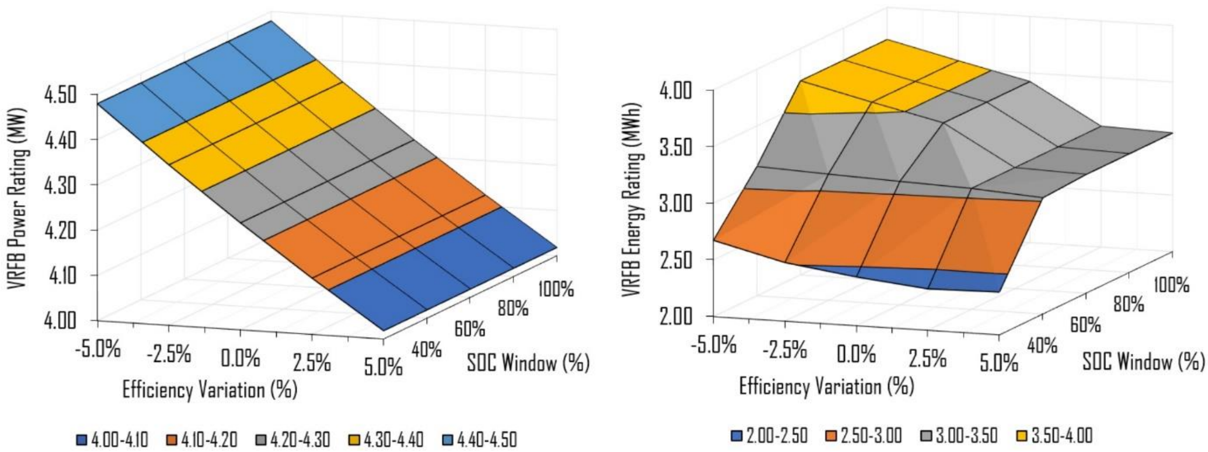

Figure 6.37. Efficiency vs SOC Window in MFRA Model – VRFB Power and Energy Ratings

The influence of the efficiency and SOC Window of ES technologies in the FFRA Model is presented in Figure 6.38 below in terms of TSR increments of REG providers.

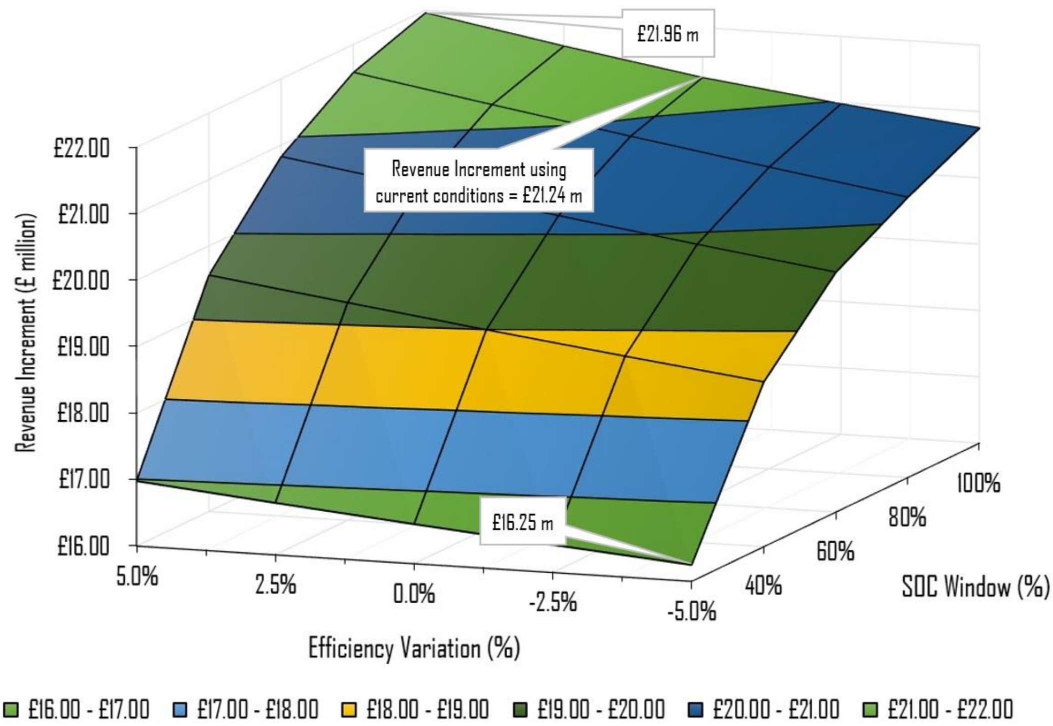

Figure 6.38. Sensitivity Analysis in FFRA Model - Efficiency vs SOC Window

In Figure 6.38, the maximum TSR of REG providers reaches £21.96 million of revenue increment when enhancing the efficiency and opening the SOC window of ES devices. This only represents £720,000 more income than the TSR acquired by REG provider when using the current ES conditions. For different SOC Windows, unlike the MFRA Model, here, the ES technologies actually benefits from wider operational gaps by being capable of providing greater frequency response and wholesale market interactions. Since wholesale market interaction tasks could be increased with wider windows of ES technologies, the energy reserves of VRFB for FFR can, to some extent, be reduced which, in turn, minimizes investment costs in the ESS. This is represented as smaller VRFB energy ratings in Figure 6.39. The VRFB power ratings, however, are required to be increased to exploit the additional tasks from frequency services and wholesale market interaction. This behaviour in the ratings of VRFB changes if the efficiency is at low values in VRFB and Supercapacitors as shown in Figure 6.39 and Figure 6.40. In such cases, hybridizing the ESS is the best option for REG providers to reach the highest TSR since Supercapacitors can further support with wholesale market interaction and high frequency response. In the remaining cases, when the SOC window is below 80% opening in both ES devices, REG providers only require a single VRFB technology to achieve the highest TSR with no significant impact on the power and energy ratings of VRFB from efficiency changes.

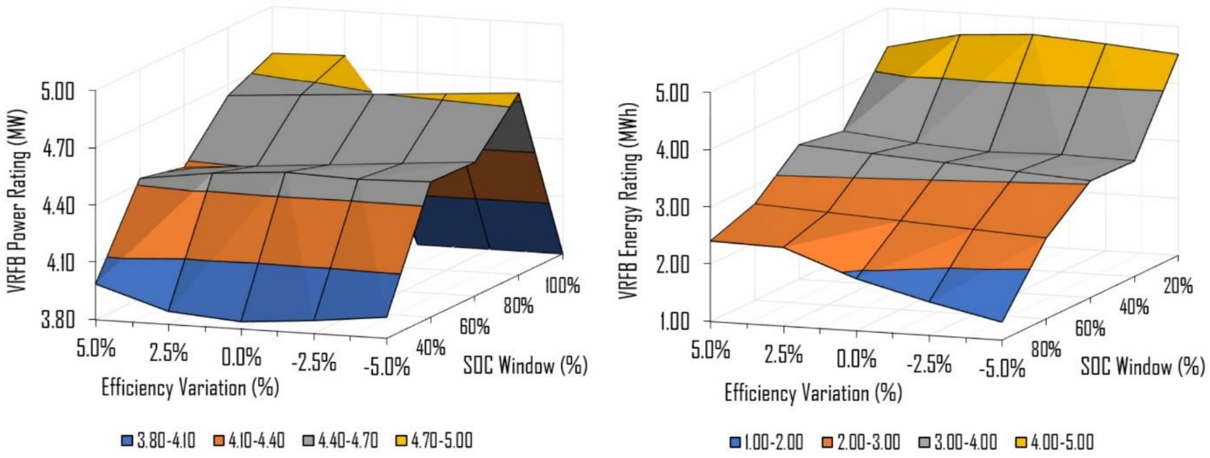

Figure 6.39. Efficiency vs SOC Window in FFRA Model – VRFB Power and Energy Ratings

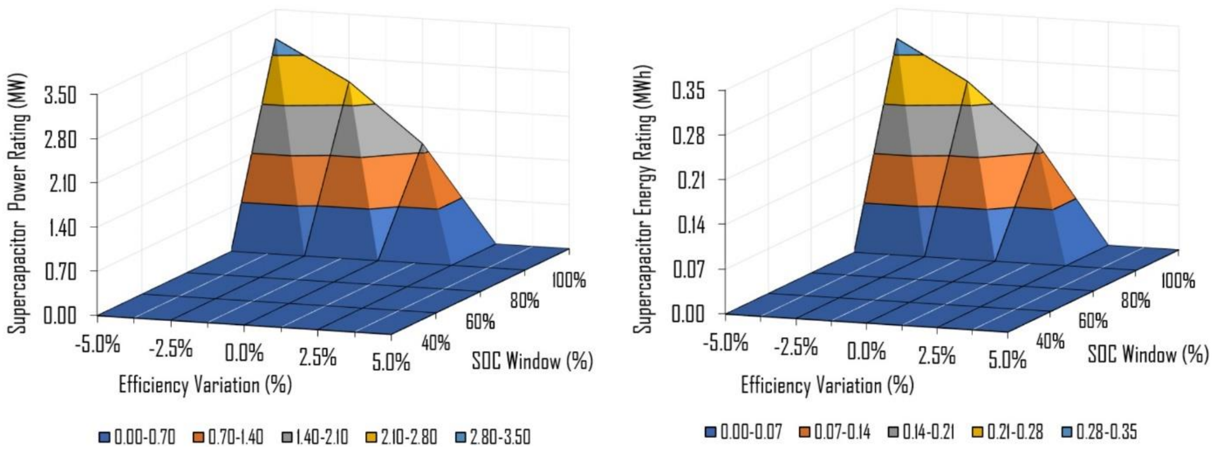

Figure 6.40. Efficiency vs SOC Window in FFRA Model – SC Power and Energy Ratings

6.7. Individual Contribution of ES Characteristics on Total Revenues

In Section 6.5 and Section 6.6, the sensitivity analyses on the technical and economic parameters of ES technologies using the MFRA and FFRA Models provided an insight of the actual contributions of these factors on the income of REG providers and in the ES sizing design under different regulatory schemes. This section complements these studies by ranking the individual influence of each intrinsic technical and economic characteristic of ES technologies on the TSR of REG providers based on the current conditions of ES devices and a future scenario in which these devices are enhanced. Table 6.5 presents the characteristics of the ES technologies applied under the future enhanced scenario. Regarding current conditions, the SOC window of VRFB and SCs was considered to be 60% open while the rest of technical and economic features of both technologies are presented in Table 6.4.

	Parameters	VRFB	Supercapacitor
Technical	Charging/Discharging Efficiency (%)	95 [158]	96 [159]
	Maximum SOC (%)	100 [158]	100 [160]
	Minimum SOC (%)	0 [158]	0 [160]
	Cycling Lifetime (cycles)	22,500	750,000
	ES Lifetime (years)	19 [158]	15 [159]
	Daily self-discharge (%)	0.125	5
Economic	Cost of Energy (£/kWh)	190 [158]	3,000 [73]
	Cost of Power (£/kW)	347 [158]	60
	Interest Rate (%)	0	0

Table 6.5. Enhanced Characteristics of VRFB and Supercapacitors

For the MFRA Model, Figure 6.41 presents the contribution ranking on TSR of REG providers from the technical and economic parameters of VRFB exclusively.

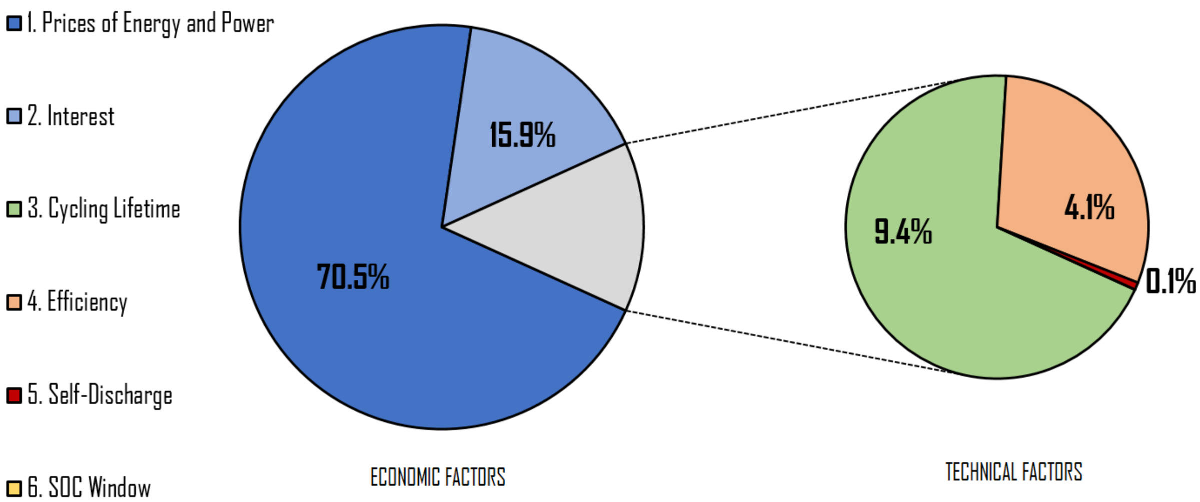

Figure 6.41. MFRA Model – Ranking of the Individual Contribution on TSR of VRFB features

In Figure 6.41, the highest impact on the TSR increment of REG providers is caused by the economic characteristics of VRFB technologies with a total contribution of 86.4% from which VRFB component prices represented over 70% of TSR increment. Regarding ES technical features, the highest contribution on TSR increments of REG providers was achieved by enhancing the VRFB cycling lifetime. The enhancement of this feature is translated into lower costs of degradation for REG provider as described Section 6.6. Charging/discharging efficiencies, assumed in this work to be constant throughout the project lifetime as mentioned before, are also an important feature that influenced the TSR increments of REG providers since, in mandatory schemes, they allow REG providers to minimize the ES investment costs by reducing the power and energy ratings of VRFB technologies. In the last positions, daily self-discharges and SOC windows are characteristics that almost entirely did not produce significant contributions on the TSR increments of REG providers.

Figure 6.42 presents the contribution ranking on TSR of REG providers from the technical and economic parameters of Supercapacitors exclusively.

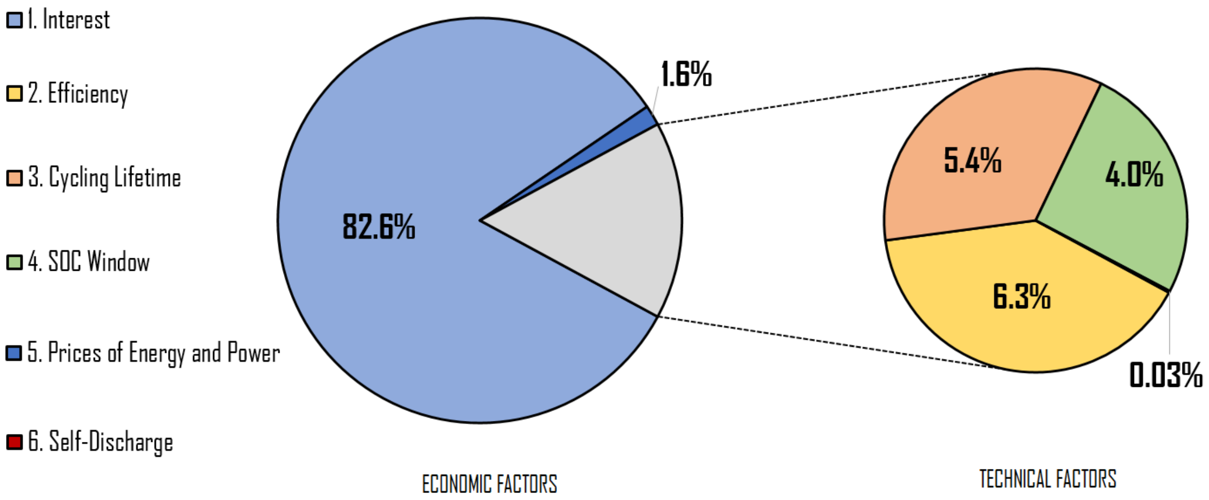

Figure 6.42. MFRA Model – Ranking of the Individual Contribution on TSR of SC features

In this case, the highest influence on REG provider income increment was also achieved by the economic characteristics of SCs. The difference with the results of MFRA Model for VRFB technologies, however, is in the first position which is now occupied by the Interest Rate of the ES Project. This occurs since the ESS has become a hybrid combination of VRFB and Supercapacitors. or this reason, the interest rate is not only affecting the investment costs of one technology occurred in the contribution ranking of VRFB technologies but also the purchasing costs of the additional ES device (i.e. Supercapacitors). This generated a sharpen effect of this feature in the income of REG providers. Regarding SC technical parameters, the highest contribution on TSR increments was caused by the charging/discharging efficiencies which permitted to reduce the costs of investing in SCs by minimizing their power and energy ratings. Other technical factor that influenced the value of SC was the operational window of

Supercapacitors. Although this technology is also restricted by regulation when supporting MFR services, the VRFB is the device in charge of maintaining energy reserves for the most onerous cases. For that reason, when Supercapacitors are present, they are able to have significant benefits from the additional storage capability provided by the SOC window to face primary response, high frequency response and for interacting with the wholesale market. Regarding the cycling lifetime of SCs, based on the assumption of this work described in Section 4.3.3, it is important to mention that this feature will appear with reduced contribution on the TSR increments of REG providers since SCs already presents high values of cycling lifetime at present conditions. This feature can be considered as one of the strengths of Supercapacitors over other ES technologies.

For the FFRA Model, Figure 6.43 presents the contribution ranking on revenues of technical and economic parameters from VRFB exclusively.

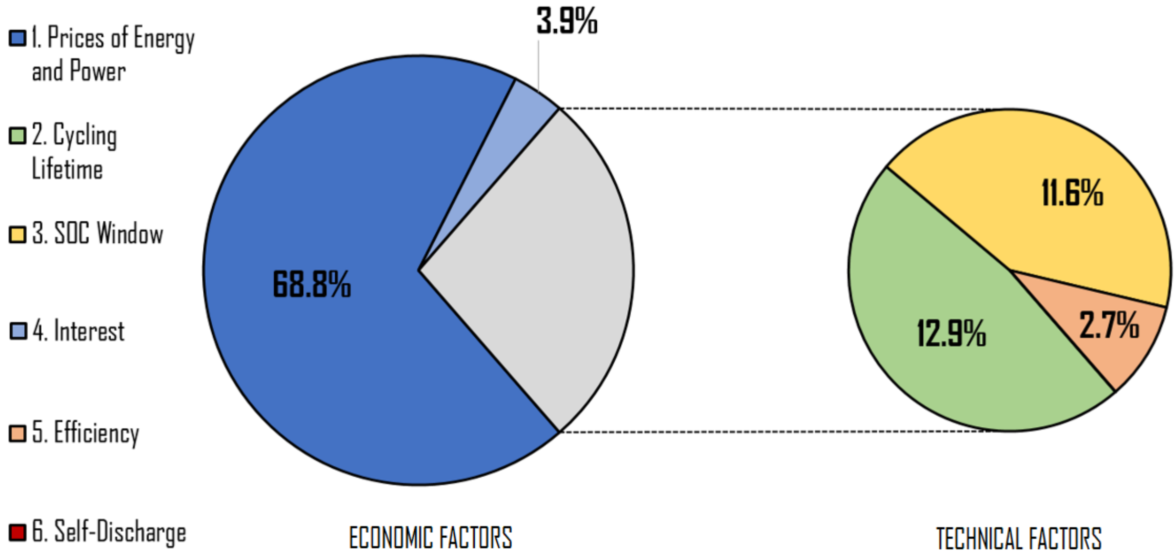

Figure 6.43. FFRA Model – Ranking of the Individual Contribution on TSR of VRFB features

Aside from daily self-discharges, here, the technical characteristics of this technology are able to influence system income in a greater or similar proportion than the interest rates. This occurs as the VRFB sizing ratings are not limited by regulation to the most onerous cases of frequency deviation. For that reason, improvements in each technical characteristic can also affect the dimensions of the system and be further reflected in the revenues. The cycling lifetime, in particular, effects the system in the costs of degradation. As VRFB device is largely used for frequency response and wholesale market interaction, enhanced degradation costs can create significant increments in total revenues. In this case, the SOC window also produces large impacts on the income as higher frequency response and, especially, wholesale market interactions can be achieved by the VRFB device.

Figure 6.44 presents the contribution ranking of technical and economic parameters from Supercapacitors in the FFRA Model.

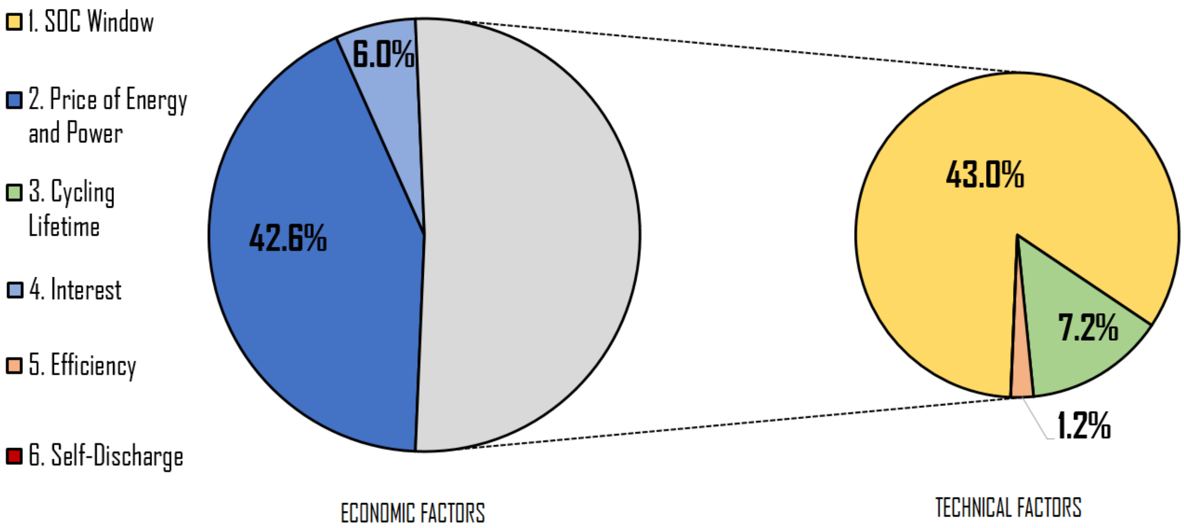

Figure 6.44. FFRA Model – Ranking of the Individual Contribution on TSR of SC features

Unlike all the other cases above, here, the highest contribution on revenues is achieved by a technical characteristic: SOC window. Although the component prices of Supercapacitor are an important characteristic to be reduced in order to enhance income, this technology is entirely free from frequency regulations and energy reserves and, therefore, it benefits in a larger extent from having a bigger room for responses. This will not only increase the participation in frequency services and the wholesale market but also enhance the ES ratings (i.e. investment costs). In this ranking, as in VRFB technologies, the interest rates are also relegated to the fourth position of the contribution ranking on revenues as the system is only based on one ES technology, being Supercapacitor. Regarding cycling lifetime, it already presents an enhanced characteristic in Supercapacitors than other ES technologies from current conditions. For that reason, the contribution in revenues, coming from reduced degradation costs, is not as significant as other characteristics in future scenarios.

6.8. Discussion and Conclusion

In this Chapter, the techno-economic factors that influence the value of ES devices were assessed and quantified using the MFRA and FFRA Models. These framework models permit the of study ES devices when supporting REG providers, in exclusivity, to provide frequency services and for interacting with the wholesale market. The outputs of both models provide the maximum income that REG providers can achieve from MFR service and wholesale market interaction, in the case of MFRA Model, and from FFR service and wholesale market interaction, in the case of FFRA Model. These TSR of REG providers come along with the optimal sizing design of ES technologies.

The first case study took into consideration, for MFRA and FFRA Models, REG providers with different renewable sources, being solar power and wind generation. The simulation results demonstrated that, for both Power Stations, the highest income was reached by making REG provider participate in FFR non-mandatory frequency scheme rather than making REG provider being engaged in MFR regulations. The superiority of FFRA Model, in terms of economic benefits for REG providers, was based on the moments and degrees in which frequency response can be delivered and the freedom not to consider the most onerous cases for power response and energy reserves as established by MFR regulation. The problem with the MFRA Model is that REG providers are forced to deliver specific mandatory response according to regulation and to maintain certain amount of reserves for the worst frequency-deviation scenarios and for secondary frequency response. These unexploited energy reserves expand the ES sizing design which, in turn, increases the ES investment costs.

In the ES technology selection study, multiple storage combinations were addressed with FFRA and MFRA Models. In the latter, the chosen ESS was a hybrid mixture of NaS batteries and Supercapacitors since they achieved the best income for REG providers from the rest of combinations. For the FFRA Model, however, the highest revenue of REG providers only involved the use of a single VRFB technology. Since the VRFB case produced the highest revenues from all the cases, this technology was further utilized to make a comparison between the mandatory and non-mandatory frequency schemes. The results not only showed that FFR service actually benefits in a larger degree to REG providers than MFR services, but also the amount of energy traded in the wholesale market is also significantly greater in FFRA Model. This revenue stream further enhanced the total income of REG providers when participating in FFR non-mandatory scheme.

This chapter also addresses a number of sensitivity analyses on the economic and technical factors of ES technologies and their effect in the total revenues of REG providers. In the case of MFRA Model, the system income are permanently influenced to a greater extent by the economic features. This is not always the case in the FFRA Model where the operational windows of Supercapacitors have the potential of playing a superior role in the revenues of REG providers when the system is single-ES based. This makes SOC window a key characteristic to be enhanced by technology developers when addressing Supercapacitors. For VRFB devices, however, improving cycling lifetime is the parameter that occupies this position in the contribution ranking on TSR increments since it creates, in all cases, the highest influence on income of REG providers in both models among all technical features.

Simulation results also showed MFRA cases in which the interest rates could be the leading parameter, from all, affecting the income of REG providers. These scenarios are linked to the hybridization of the system since this economic feature, ultimately, affects the purchasing cost of each ES technology. This condition is an important consideration by project investors and REG providers when developing ES investment cases. In the majority of cases, however, the predominant characteristic that drives the system to higher revenues is the components price of ES technologies. This is an essential characteristic that should be considered by technology developers when enhancing ES devices towards their introduction into power systems.

Chapter 7. Discussion

7.1. Introduction

The assessments and analyses performed throughout this work, utilizing the Three Player, MFRA and FFRA models, presented important findings about techno-economic factors that influence the present and future value of ES technologies. The discussion that follows describes the findings of this research and pave the way for conclusions to be formed.

7.2. The influence of Renewable Generators and Market Conditions

In Chapter 3 and Chapter 4, a techno-economic assessment framework model, known as Three Players Model, was described and developed. The results from this model delivered key information to REG providers about the maximum revenue that they can achieve from participating in wholesale market and MFR services with the support, or not, of ES devices.

The main finding of this factor is that an ES system can enhance its value, under certain present conditions, when supporting Wind Generators rather than when collocated with Solar Generators. This is because, in general, wind farms with the same capacity as solar farms can produce more power due to the nature of the resource. Moreover, solar farms are obtaining less incomes than wind farms from the frequency market under MFR regulation since they do not reach the required generation to participate for most part of the year. In this context, the advantage of using ES technologies to profit from multiple market interaction is reduced. This is not the case of Wind Farms, in which, ES device are interacting in both markets in the most profitable way possible.

A scenario in which ES technologies can fully participate in the frequency market and interact in the wholesale market without depending on the renewable generation is applied the FFRA model. Here, the results showed that the value of ES devices is not dependent of the renewable generator as the markets participation is not linked, by FFR regulation, to the generation levels but rather to the grid-frequency and the tendered bids. The future value of ES technologies when operating in conjunction with renewable generators, independently of the generation source, could be improved if these devices are able to obtain greater revenues from the wholesale market. At present, ES devices are not a viable option if they are only interacting in the wholesale market. However, if the investment cost for acquiring ES devices can be decreased by technology developers or if the wholesale market payment prices could be increased through special market pricing to ES devices, ES technologies could be able produce, on their own, greater revenues and become profitable. At present, CfD contracts aims to support the integration of low-carbon generators into the grid but, as the results have shown, this measure is convenient for REG providers but "fixed" prices are still below the required value that could make ES devices profitable on their own. Moreover, since the logic of CfDs is to pay the difference between actual market prices and the static agreed price, this levelized procedure could make the potential outcomes of ES to be similar to the revenues that common generation plants can obtain from the wholesale market. In future, CfD scheme should potentially analyse and consider further updates to incentivise additional economic benefits for REG providers so that a low-carbon grid can be achieved.

About MFR service, this frequency service is part of the actions, developed by the ESO, that compromises REG provider to support in the achievement of grid-balance. The MFR scheme, in general, limits the free operation of REG providers and, thus, the operation of the energy storage devices. Although, at present, it was demonstrated by this work that the value of ES devices could be increased when supporting REG providers in MFR while also interacting, when possible, in the wholesale market, the future value of ES technologies, in this context, is difficult to be enhanced if current rewarding scheme for MFR is not enhanced for renewable generators and, specially, ES devices. Greater payments for MFR, in future, not only could rise the value and future deployment of ES technologies for MFR purposes but also could increase the TSR of REG providers as ES technologies will be able to further their revenues by interacting in the wholesale market. Ultimately, the best future of ES technologies would represent lower investment costs for acquiring an ES system and greater or preferential payment schemes for ES devices that participates in frequency market and wholesale market. It is acknowledged that a limitation of the present research is that the future market price prognostics were not considered. The rationale behind this factor is that, for long-term project horizons, as it is the case when analysing ES sizing design and investments, predicting market price changes is a complex task which still will not be accurate in periods over many years. Nevertheless, by including potential future market prices through advanced forecasting methodologies, the results and conclusions of this work could further be enhanced, and it is recommended to pursue for next extensions of this work. These future studies have the potential of quantifying the influence of market prices in the TSR of REG providers and in the value of ES technologies, as discussed in this section, to be profitable under different energy markets. It must be mentioned, however, that increasing the number of participants in energy markets will also produce direct effects in the electricity prices. This assumption was mentioned in Section 3.5 for the present work, but it is recognized that comprehensive market studies would require to include the implications of increasing the number of market participants in the prices and behaviour of these markets.

7.3. The influence of Mandatory and Non-mandatory Regulations

As described in Chapter 2, grid-frequency support from REG providers could fall under mandatory and non-mandatory services depending on the characteristics of the grid and of the participants. A mandatory and a non-mandatory frequency schemes were addressed in this work based on GB regulations: MFR and FFR. MFR refers to the mandatory scheme of frequency provision for certain REG providers under specific conditions and procedures. FFR is a non-mandatory frequency scheme in which REG providers are able to bid their own contribution to primary response, secondary response, high-frequency response or their combination. The simulation outcomes of these framework models not only allow REG providers and investors to analyse the effects of investing and only using ES technologies for different market interactions but also permit policy makers and regulators to visualize the potential impacts that different regulatory schemes have on the market participants. The simulation outcomes for these schemes, presented in Chapter 6, showed that the value of ES devices, at present, is greater when delivering frequency services under a non-mandatory scheme. This is because, by the nature of MFR regulations, REG providers alongside their ES systems are restricted in terms of generation not only for meeting actual frequency responses but also to comply with strict reserves for onerous cases. While profiting from MFR service only through ES technologies is possible, these devices must restrict their flexibility to comply with all MFR regulations. This is not the case of

FFR service in which ES devices are capable of interacting “freely” in the most profitable manner in the wholesale market and frequency market.

The regulatory factor for ES technologies is crucial in the way in which these devices can be used and, thus, the profitability opportunities at present and future. Since ES devices are flexible technologies, exploiting this characteristic by participating in multiple markets can increase their overall value for REG providers as shown in Chapter 5 and Chapter 6. This ES flexibility, however, cannot be considered to be beneficial only at present conditions but also at future as it might not be expected for this feature to worsen in the majority of ES devices while ES participation might be expanded to more markets or grid-applications. Ensuring the flexibility technical feature of ES devices is a key task to consider for technology developers in future ES changes. Regarding regulations, however, it is important, for the integration of low-carbon technologies into the grid, to improve or create beneficial regulations for these devices. In particular, regulations that can help ES technologies to maintain and apply their flexibility while expanding revenue streams and returns. Otherwise, the widespread inclusion of ES devices will not be compromised at future based on current investment costs. Beyond demonstrating that, at present conditions, a non-mandatory frequency scheme is more valuable for REG providers and ES devices, the important outcome from this work is to consider that ES devices must exploit its operation to improve returns as shown in Chapter 6 for MFRA and FFRA. In future, multiple market participation could be projected to occur from ES systems to increase incomes and it is advised to Policy Maker and Regulators to create or update regulations so that they can be ready to encourage or support this transition.

7.4. The influence of Selecting ES Technologies

The techno-economic assessment of this thesis allowed to investigate the influence that applying different individual ES technologies or multiple ES devices have on the total revenues of REG providers. The total number of cases examined, per framework model, involved 31 hybrid ES combinations arising from six different storage devices. The simulation outcomes showed that hybridizing an ES system could potentially achieve, under certain conditions, the highest income for REG provide, although the majority of cases that reached this highest revenue involved only a single ES device. The sensitivity analysis performed in this work showed, however, that enhancing the intrinsic technical and economic features of ES technologies could play a role in the future value of these devices. For instance, an ES system that could initially be profitable using a single ES technology for REG providers, in future, with technical and economic improvements, the ES system could reach the highest revenue if two different ES technologies are applied instead of one. This clearly depends on the types and areas of enhancement in each ES technology. Generation providers and investors must address two key points in this context, selection of ES technology depending on the tasks to be assigned (market interactions) and understanding the advances and capabilities of hybridizing their system.

In future, advances in the technical and economic feature of ES technologies, such as VRFB or supercapacitors, are likely to occur. Further reductions in the cost of power and energy of ES technologies, for instance, are predicted to arise in ES devices which, in turn, will decrease the required investment of REG providers or investors to acquire these devices. In this context, the selection process of ES devices (or a combination of them) for REG providers and investors is of highly importance since this decision-making could represent higher or lower total incomes for the system when participating in multiple markets. Technology developers are advised to also utilize the ES device selection assessment, at present and future, to prioritize or focus their efforts of enhancing specific devices based on the actual electricity industry requirements while companies that sell these technologies could visualize the future value of hybridizing a system and create innovative alternatives to incentivize the purchases from REG providers.

7.5. The influence of Interacting in Multiple Energy Markets

In all framework models of this thesis, the revenues streams of REG providers were established as income from the Wholesale Market and Frequency Market. The income for REG providers from ES technologies interacting in the Frequency Market were granted, depending on the model, from the actual provision of mandatory or non-mandatory frequency services while the wholesale market income, with ES devices, were acquired from the actual interaction on this market. Multiple market interactions assigned to ES devices, in all framework models, have shown to have the potential of further exploiting the ES capabilities while boosting the revenues of the system.

As the energy mix is evolving towards a low-carbon grid, the inclusion of technologies, such as ES devices, is imminent within the energy markets. In future, the overall value of ES technologies is likely to be increased thanks to the continuous efforts of many interested parties such as governments, policy makers, technology developers, scientists, generation providers, among others. In particular, promoting, through regulations and payment schemes, the inclusion of ES devices into different markets not only will support the transition to a low-carbon grid but also could produce higher returns to REG providers and investors for the investments in these devices. At present, the current prices of the wholesale market do not allow, on its own, the widespread deployment of ES device throughout the network. At future, however, these market prices will change, potentially to lower prices depending on the market condition, and ES technologies might not benefit from these changes. Therefore, it could be convenient for ES technologies to manage, instead, a preferential payment scheme for their participation in the wholesale market similar to CfD. CfD, based on this work results, however, does not necessarily guarantee a payment price that can be profitable to ES devices at present. This is advised to be updated so that investing in ES devices could be a viable option for investors.

For frequency markets, the simulations have shown that ES technologies could be economically viable, under certain conditions, for REG providers and investors. However, in future, the prices of frequency markets could suffer a scenario in which the prices are reduced, affecting in this way the returns on ES investments. Therefore, relying in one market interaction might not be the best alternative, at present and future, for ES systems. Instead, as mentioned in Section 7.2, the future value of ES devices can be improved if they are able to interact in multiple markets, thus increasing their revenue streams. The flexibility of ES technologies creates an advantage for these devices to deal with multiple tasks under different service duration and response time. As it is the case, for instance, of primary frequency response and the wholesale market, an ES system could be capable of managing high-power high-energy requirements, thus allowing them to profit from both markets. Moreover, there are other services, such as EFR (not addressed by this work) which require very fast response times from technologies and that could also offer higher prices for service provision. Including ES devices in such services could further expand revenues and return for REG providers.

7.6. The influence of Technical and Economic Features of ES Devices

Sensitivity analysis on technical and economic characteristics of ES technologies were performed in this thesis indicating the effects of these factors on the revenues of REG providers and on the ES sizing design. The most influential factors, in the majority of cases, were demonstrated to be the costs of power and energy used for sizing the ES technologies. These costs, ultimately, impacted the investment required by REG providers or investors for acquiring the ES system, thus reducing, in a large proportion, the TSR. ES devices, at present, are still expensive technologies which represent for investors to exploit as much as possible its capabilities to obtain returns for their investments. Technology developers and manufacturers are also required to join efforts towards enhancing the intrinsic characteristics of ES technologies, specially but not limited to the costs of power and energy. The ES technology development roadmaps show that these devices are likely to reduce their production costs in the coming years. This will, therefore, support the widespread deployment of these devices conditional to further enhancements in other techno-economic factors, as discussed in this section, such as market conditions, regulatory schemes, operation, technology selection and system hybridization. The present study, however, did not considered the maintenance costs in which ES could incur from their operation. Including these costs, in future studies, could help to have a more accurate picture of the potential economic benefits that REG providers could have from using ES technologies. It is important to mention, in this context, that alternative incomes such as availability or nomination payments were not taken into account. This could, to some extent, improve the accuracy of the results that were affected by not considering maintenance costs.

The assessment outcomes have also shown that technical characteristics such as cycling lifetime, SOC window, and efficiencies could play a very important role in the operation of the system and, thus, in the investment costs and income capabilities for REG providers. When these features are enhanced, simulating future conditions of ES devices, the system increases the TSR over the project lifetime duration. The degree in which the revenues are increased depends on the technology and operation tasks that ES perform to interact with multiple energy markets. For the future value of ES technologies, there is no single feature solution that can be said to be enhanced as priority as all of them contribute to the overall improvement to a degree. It could be simpler to mention that the costs of power and energy represent the highest priority to be enhanced for all ES technologies, based on the results values. In reality, the scenario is more complex since the operation of these devices is similarly important to meet multiple market tasks and it depends on other features which must also be addressed. Not enhancing these characteristics would produce ES devices incapable of addressing a range of applications, thus reducing their value for investors. For instance, for supercapacitors, the future effect of expanding the SOC window operation of energy showed significant increments in the incomes of REG providers while a similar effect was caused by rises in the cycling lifetime of NaS batteries. However, increasing the SOC window or round-trip efficiencies require further research as it could produce a rapid aging of the device while not behaving linearly (as it was assumed in the present work).

It is important to mention that the models of this work assumed no-degradation within the lifetime operation of the ES devices to simplify the complexity the models. In reality, the charging and discharging processes, for instance, does not behave evenly throughout the lifetime of the devices due to degradation in the technology. It is acknowledged, however, that considering circuit models and real-testing system that help to understand and quantify the degradation of ES devices could produce more accurate results that, ultimately, could support the future enhancement of these devices. In these improvements, it must be considered a number technological factors such as round-trip efficiencies (which are not going to be linear as in this work), operational changes due to degradation in the SOH of the ES system (which could involve changes in the cycling lifetime), among others features that were considered out of the scope of this research.

Chapter 8. Conclusions and Future Work

8.1. Overview

The main objective of this thesis was to investigate the techno-economic factors that influence the present and future value of energy storage technologies. The strategy to tackle this aim was to design, develop and implement a framework that allowed to perform techno-economic assessments at the planning stage of ES projects. This framework is comprised of various models not only to examine the factors influencing ES devices under different system conditions but also to carry out comparisons among them. The first model, named as Three Players Model, took into account the integration of ES technologies with Renewable Generators for the mutual provision of mandatory frequency response and for wholesale market interactions. The second model, named as MFRA Model, considered ES devices located in Renewable Stations to meet, on their own, mandatory frequency response requirements and to interact with the wholesale market. The last model, named as FFRA Model, allowed to study ES technologies applied by REG providers to participate in a non-mandatory frequency scheme FFR while also interacting with the wholesale market. A comprehensive simulation of these framework models permitted to evidence and study the most relevant techno-economic factors affecting the future value of ES devices under multiple conditions.

8.2. Conclusion

The primary contribution of the author has been to present the most influential factors of ES technologies when placed in Renewable Power Stations and utilized for multiple market applications. This provided significant information not only for REG providers and investors when considering investments in ES devices but also for technology developers to focus in specific areas of enhancement for ES technologies, for policy makers and regulators to understand the end to end effects that current regulations might produce on REG providers, and for Selling Companies to expand their range of ES technologies and hybrid ES combinations for customers while incentivizing the widespread deployment of these devices.

The key findings and contributions of this research are:

- Energy Storage Systems are capable of enhancing the income of REG providers by expanding the number of revenue streams.

  The results of this research showed that, under certain circumstances, the revenues from REG providers can increase when ES devices are interacting with multiple markets, being frequency services for income from the frequency market and wholesale market interactions for incomes from this market.

- Participating in a non-mandatory frequency scheme could be more beneficial, under certain conditions, for REG providers in terms of total revenues than being engaged in a mandatory frequency scheme when applying ES technologies.

  When comparing the revenues achieved by ES technologies under MFR and FFR conditions, in all cases, the highest income for REG providers was achieved when using these devices for delivering non-mandatory frequency response while also interacting with the wholesale market.

- The revenues of REG providers are greater when mandatory frequency services are delivered by ES devices in conjunction with Renewable Generators than using, in exclusivity, any of these technologies for the same responsibilities.

  The simulation outcomes showed that the income achieved by REG providers in the Three Players Model were superior to the revenues reached in the MFRA Model and, under certain circumstances, were also higher than the income obtained when using only Renewable Generators.

- For the provision of Mandatory Frequency Service, Renewable Power Stations could obtain more income when coupling ES technologies with Wind Generation than with Solar Generation.

  The results of this work showed that Wind Farms could present higher levels of power production to meet MFR requirements than Solar Farms. This allows them not only to reach greater income from the Frequency Market but also profiting, under the current structure of the models, to a larger extent from interacting with the wholesale market.

- The proper selection of an individual ES device or a combination of them is essential for REG providers and investors when investing in these technologies since they could produce different levels of income.

  The simulation outcomes, in all framework models, demonstrated that each ES technology and ES combinations achieve different revenues for REG providers.

While many of them were profitable, there is also a number of ES devices which are not suitable under certain conditions. In those cases, it would be more beneficial for REG providers not to invest in ES technologies.

- Although it could require a higher capital investment, applying hybrid energy storage systems, under certain conditions, could produce higher income for REG providers than using individual ES technologies or non-using any ES device.

  When providing multiple market services, the results of this thesis have shown that, under certain circumstances, hybridizing an ES system could not only be a profitable alternative for REG providers but it could actually be the choice with the highest potential in revenues.

- Enhancing the economic factors of ES devices has the potential of making a greater contribution on the revenues of REG providers than improving technical parameters of these technologies.

  In the majority of cases, the main factor that contributed with the enhancement of the total revenues of REG providers was determined to be the ES prices for their power and energy components and the Interest Rate in which the ES investment project is analysed.

- The operation window in which power-dense ES technologies are allowed to work, whether by the intrinsic characteristic of the device or by the control decision of the operator, is the technical feature with the highest contribution on the income of REG providers under current conditions of the framework models.

  The results have shown that expanding the operation window of power-dense devices, in this study, not only can generate more revenues for REG providers than the rest of ES technical characteristics but also it could also produce, in some cases, the highest income from all ES features, including both technical and economical features of power-dense devices.

- The Cycling Lifetime of energy-dense ES technologies is the technical characteristic with the highest influence on total revenues of REG providers when they are utilized, among other responses, to ensure energy reserves.

  Since Energy-dense technologies could be applied to address energy reserves, these devices might also present oversized designs. The simulation outcomes of this work have shown that enhancing their cycling lifetime could actually produce greater income for REG providers than expanding their SOC window as it occurs in power-dense devices.

8.3. Future Work

Although this thesis has presented a framework that allows to make a comprehensive assessment of the techno-economic factors influencing the future values of energy storage technologies, there are many assumptions and enhancements that are still required in the models and analyses of this work. This section identifies the main works that could be performed for the future extension of this research.

The present framework models were built on the foundation of providing frequency response, whether mandatory or not, with ES technologies while also interacting with the wholesale market. The factors influencing future values of these devices were studied on these grounds but, in reality, there are a large number of grid services and application in which ES devices can also collaborate. The next steps of this work could include the expansion of these services for ES technologies towards exploiting their flexibility. This will allow to study the factors influencing ES devices from a different perspective while also increasing the potential income of REG providers arising from using ES devices.

In this work, the payments for REG providers when delivering frequency response were assumed to be carried out from the actual provision of the service. Depending on the participation scheme, the remuneration system, under current GB regulations, could consist, instead, of additional payments such as nomination fees or availability fees. Including these payment methods, difficult to access, in the current structure of all framework models could further shape the real conditions in which REG providers are paid and, therefore, enhance the results of this work. In this context, including predictions of the future market prices is also required to be included in the present work since, through advanced forecasting methodologies, to enhance market analysis and quantifying the influence of these prices in revenues for REG providers and the value of ES technologies. It must be mentioned, however, that increasing the number of participants in energy markets will also produce direct effects in the electricity prices which is an area that requires also be addressed in future works.

Under the present framework models, the highest cost in which REG providers incur is assigned to the investment cost to purchase ES technologies. This capital cost, however, is not the only expense related to the operation of REG providers. Leaving aside any cost of Renewable Generators, ES technologies also present costs for operation and maintenances. Creating a holistic framework which include all the possible costs for REG providers will enhance the reliability of the results for the present work.

Finally, including holistic models that take into account the degradation of ES devices could create more realistic scenarios in which the actual operation of ES technologies can be further analysed. In this work, the cycling lifetime of the devices, charging and discharging processes and energy losses were not modelled with advance degrees of accuracy which, although considered, could potentially worsen to a certain extent the revenues that REG providers could obtain in long-term projects. The lifetime of ES devices is not only determined by the manufacturer but also depends on the operation of the ES device and their intrinsic characteristics. This could represent the immediate next step of the present work.

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Appendix A. Three Players Model Code

```
Set t row labels
    c column labels

Parameter
*GENERAL INPUTS
          E_gen(t)          Generator Input in kWh
          req_freq_low(t)   Required Primary Freq Response in kWh
          req_freq_high(t)  Required High Freq Response in kWh
          max_freq_low(t)   Maximun Freq Req in kWh (for 0.5Hz deviations)
          Price_frq(t)      Price of Frequency Market in £ per kWh
          Price_wm(t)       Price of Market in £ per kWh
          Iteraciones(t)    First Iteration is 0
          U(t)     Auxiliary factor: Energy Flow for Arbitrage and low freq
          V(t)     Auxiliary factor: Energy Flow for Arbitrage and high freq
          N number of samples
          D significant days of analysis /12/
          Tper sample rate in seconds /15/
          Treg regulatory reserves in mins /30/
          PT project lifetime in years /15/
          i  project interest in % /3/
          CRF capital recovery factor


* Energy Dense Technology - Characteristics
* NaS
          LT1 storage lifetime in years /15/
          cycles1  /4500/
          Selfdisc1 daily self-discharge in % /10/
          socH1 max state of charge /1/
          socL1 min state of charge /0/
          ch_eff1 /0.87/
          disch_eff1 /0.87/
          price1_e /400/
          price1_p /200/
          price_deg1
          loss1
          X1 auxiliary factor /1/
```

```
* Power Dense Technology - Characteristics
* SUPERCAPACITOR
          LT2 storage lifetime in years  /15/
          cycles2  /500000/
          Selfdisc2 daily self-discharge in % /10/
          socH2 max state of charge /1/
          socL2 min state of charge /0/
          ch_eff2 /0.9/
          disch_eff2 /0.9/
          price2_e /5000/
          price2_p /120/
          price_deg2
          loss2
          X2 auxiliary factor /1/

* Calculated Parameters
          price_e1
          price_p1
          price_e2
          price_p2

$onecho > taskin.txt
dset=t rng=A1:A69122 Rdim=1
dset=c rng=A1:P1 Cdim=1
par=E_gen rng=A1:B69122 Rdim=1
par=req_freq_low rng=C1:D69122 Rdim=1
par= req_freq_high rng=E1:F69122 Rdim=1
par=max_freq_low rng=G1:H69122 Rdim=1
par=Price_frq rng=I1:J69122 Rdim=1
par=Price_wm rng=K1:L69122 Rdim=1
par=Iteraciones rng=M1:N69122 Rdim=1
par=U rng=O1:P69122 Rdim=1
par=V rng=Q1:R69122 Rdim=1
$offecho

$CALL GDXXRW 0.Inputs_Mandatory.xlsx squeeze=N trace=3 @taskin.txt
$GDXIN 0.Inputs_Mandatory.gdx
$LOAD c t E_gen req_freq_low req_freq_high max_freq_low Price_frq Price_wm
Iteraciones U V
$OnEps
```

```
$GDXIN

Display E_gen,Price_wm,Price_frq;

price_e1 = X1*price1_e;
price_p1 = X1*price1_p;
price_e2 = X2*price2_e;
price_p2 = X2*price2_p;
price_deg1 = price_e1/(X1*cycles1);
price_deg2 = price_e2/(X2*cycles2);
loss1 =  Selfdisc1*Tper/(24*3600*100);
loss2 =  Selfdisc2*Tper/(24*3600*100);
CRF   =  (i/100)*(1+(i/100))**PT/(-1+(1+(i/100))**PT);
*CRF   =  1/15;

Display price_deg1,price_deg2,loss1,loss2,CRF;

Variables

* Battery 1
E_b12frq(t)
E_b12low(t)
E_b12high(t)
E_b1cap(t)
E_b12loss(t)
E_b12res(t)
E_b12wm(t)
E_b12wm_dis(t)
E_b12wm_abs(t)

* Battery 2
E_b22frq(t)
E_b22low(t)
E_b22high(t)
E_b2cap(t)
E_b22loss(t)
E_b22wm(t)
E_b22wm_dis(t)
E_b22wm_abs(t)
```

```
* Generator
E_g2wm(t)
E_g2frq(t)
E_g2low(t)
E_g2high(t)
E_g2res(t)

* Grid Balances
E_low(t)
E_high(t)
E_wm_dis(t)
E_wm_abs(t)

* Income - Costs
I_wm(t)
I_frq(t)
C_deg(t)
cap_costHESS

* System Outputs
ener_size1
pow_size1
ener_size2
pow_size2
F

* Results Presentation
Ifreq
Iwm

Positive Variable
cap_costHESS,I_frq(t),C_deg(t),E_low(t),E_high(t),E_g2wm(t),E_g2frq(t),E_g2
low(t),E_g2high(t),E_g2res(t),E_b12wm_dis(t),E_b12wm_abs(t),E_b12loss(t),E_
b12low(t),E_b12high(t),E_b1cap(t),E_b12res(t),E_b22loss(t),E_b22low(t),E_b2
2high(t),E_b2cap(t),E_b22wm_dis(t),E_b22wm_abs(t),pow_size1,ener_size1,pow_
size2,ener_size2;

EQUATIONS

funobj,
```

```
eq1,eq2,eq3,eq4,eq5,eq6,eq7,eq8,eq9,eq10,eq11,eq12,eq13,eq14,eq15,eq16,eq17
,eq18,eq19,eq20,eq21,eq22,eq23,eq24,eq25,eq26,eq27,eq28,eq29,eq30,eq31,eq32
,eq33,eq34,eq35,eq36,eq37,eq38,eq39,eq40,eq41,eq42,eq43,eq43;

funobj..  F =E= PT*(-cap_costHESS*CRF + (365/D)*sum(t,I_frq(t) + I_wm(t) -
C_deg(t)));

* Energy Storage Capital Cost

eq1..     cap_costHESS =E= X1*(price_p1*pow_size1 + price_e1*ener_size1) +
X2*(price_p2*pow_size2 + price_e2*ener_size2);

* Generator Operation

eq2(t)..   E_gen(t)   =E=  E_g2wm(t)   +  E_g2frq(t) + E_g2res(t);

eq3(t)..   E_g2frq(t) =E=  E_g2low(t)  +  E_g2high(t);

* Batteries Operation

eq4(t)$(Iteraciones(t) gt 0)..   E_b1cap(t-1)-E_b1cap(t) =E=
E_b12low(t)/disch_eff1 + E_b12wm_dis(t)/disch_eff1 + E_b12loss(t) -
E_b12high(t)*ch_eff1 - E_b12wm_abs(t)*ch_eff1;

eq5(t)$(Iteraciones(t) gt 0)..   E_b2cap(t-1)-E_b2cap(t) =E=
E_b22low(t)/disch_eff2 + E_b22wm_dis(t)/disch_eff2 + E_b22loss(t) -
E_b22high(t)*ch_eff2 - E_b22wm_abs(t)*ch_eff2;

* Wholesale Market

eq6(t)..  I_wm(t)   =E= (Price_wm(t)*E_g2wm(t)) + (Price_wm(t)*E_wm_dis(t))
- (Price_wm(t)*E_wm_abs(t));

eq7(t)..  E_wm_dis(t)   =E=  E_b12wm_dis(t) + E_b22wm_dis(t);

eq8(t)..  E_wm_abs(t)   =E=  E_b12wm_abs(t) + E_b22wm_abs(t);

eq9(t)..  E_b12wm(t) =E= E_b12wm_dis(t) - E_b12wm_abs(t);

eq10(t)..  E_b22wm(t) =E= E_b22wm_dis(t) - E_b22wm_abs(t);
```

```
eq11(t)$(V(t) eq 1)..  E_wm_dis(t)  =E= 0;

eq12(t)$(U(t) eq 1)..  E_wm_abs(t)  =E= 0;

* Frequency Support/Market

eq13(t)..  I_frq(t)  =E=  (Price_frq(t)*E_low(t)) +
(Price_frq(t)*E_high(t));

eq14(t)..  E_low(t)  =E=  E_g2low(t) + E_b12low(t)  + E_b22low(t);

eq15(t)..  E_high(t) =E=  E_g2high(t)+ E_b12high(t) + E_b22high(t);

eq16(t)..  E_b12frq(t) =E= E_b12low(t) - E_b12high(t);

eq17(t)..  E_b22frq(t) =E= E_b22low(t) - E_b22high(t);

eq18(t)..  E_low(t)  - req_freq_low(t)  =E= 0;

eq19(t)..  E_high(t) - req_freq_high(t) =E= 0;

* Provision of Frequency Response for the worst case (0.5Hz deviation) and
Maintaining power reserves (30 mins of response)

eq20(t)..  max_freq_low(t) =L= E_b12res(t) + E_g2low(t) + E_g2res(t);

eq21(t)..  E_b1cap(t) =G= (E_b12res(t)/disch_eff1) * Treg*60/Tper;

* Batteries - Power Constraints

eq22(t).. (E_b12low(t)/disch_eff1 + E_b12loss(t) +
E_b12wm_dis(t)/disch_eff1)*3600/Tper  =L= pow_size1;

eq23(t).. (E_b12res(t)/disch_eff1 + E_b12loss(t) +
E_b12wm_dis(t)/disch_eff1)*3600/Tper  =L= pow_size1;

eq24(t).. (E_b22low(t)/disch_eff2 + E_b22loss(t) +
E_b22wm_dis(t)/disch_eff2)*3600/Tper  =L= pow_size2;
```

```
eq25(t).. (E_b12high(t) + E_b12wm_abs(t))*3600/Tper =L= pow_size1;

eq26(t).. (E_b22high(t) + E_b22wm_abs(t))*3600/Tper =L= pow_size2;

* Batteries - Energy Limits

eq27(t)..  E_b1cap(t) =L= socH1*ener_size1;

eq28(t)..  E_b2cap(t) =L= socH2*ener_size2;

eq29(t)..  E_b1cap(t) =G= socL1*ener_size1;

eq30(t)..  E_b2cap(t) =G= socL2*ener_size2;

* Degradation & Losses

eq31(t)..  C_deg(t) =E= (E_b12wm_dis(t)/disch_eff1 + E_b12low(t)/disch_eff1
+ E_b12high(t) + E_b12wm_abs(t) + E_b12loss(t))*price_deg1   +
(E_b22wm_dis(t)/disch_eff2 + E_b22low(t)/disch_eff2 + E_b22high(t) +
E_b22wm_abs(t) + E_b22loss(t))*price_deg2;

eq32(t)..  E_b12loss(t)  =E= E_b1cap(t)*loss1;

eq33(t)..  E_b22loss(t)  =E= E_b2cap(t)*loss2;

* Power to Energy Rate

eq34(t).. pow_size1 =L= 10*ener_size1;

eq35(t).. pow_size2 =L= 10*ener_size2;

* Initial Conditions

eq36(t)$(Iteraciones(t) eq 0)..  E_b12low(t)  =E= 0;

eq37(t)$(Iteraciones(t) eq 0)..  E_b22low(t)  =E= 0;

eq38(t)$(Iteraciones(t) eq 0)..  E_b12high(t) =E= 0;

eq39(t)$(Iteraciones(t) eq 0)..  E_b22high(t) =E= 0;
```

```
eq40(t)$(Iteraciones(t) eq 0)..  E_b12wm(t)   =E= 0;

eq41(t)$(Iteraciones(t) eq 0)..  E_b22wm(t)   =E= 0;

* Results Presentation

eq42..  Ifreq =E= PT*(365/D)*sum(t,I_frq(t));

eq43..  Iwm   =E= PT*(365/D)*sum(t,I_wm(t) - Price_wm(t)*E_g2wm(t));

MODEL arbitrage_frequency_hybrid /all/;

SOLVE arbitrage_frequency_hybrid using LP maximizing F;

execute_unload "3.Results_Mand_3p.gdx" I_frq I_wm C_deg
execute 'gdxxrw.exe 3.Results_Mand_3p.gdx var=I_frq rng=B2:C69122 Rdim=1'
execute 'gdxxrw.exe 3.Results_Mand_3p.gdx var=I_wm  rng=E2:F69122 Rdim=1'
execute 'gdxxrw.exe 3.Results_Mand_3p.gdx var=C_deg rng=H2:I69122 Rdim=1'
```

Appendix B. MFRA Model Code

```
Set t row labels
    c column labels

Parameter
*GENERAL INPUTS
          E_gen(t)          Generator Input in kWh
          req_freq_low(t)   Required Primary Freq Response in kWh
          req_freq_high(t)  Required High Freq Response in kWh
          max_freq_low(t)   Maximun Freq Req in kWh (for 0.5Hz deviations)
          Price_frq(t)      Price of Frequency Market in £ per kWh
          Price_wm(t)       Price of Market in £ per kWh
          Iteraciones(t)    First Iteration is 0
          U(t)     Auxiliary factor: Energy Flow for Arbitrage and low freq
          V(t)     Auxiliary factor: Energy Flow for Arbitrage and high freq
          N number of samples
          D signicant days of analysis /12/
          Tper sample rate in seconds /15/
          Treg regulatory reserves in mins /30/
          PT project lifetime in years /15/
          i  project interest in % /3/
          CRF capital recovery factor
          Investment cap (if required) /4000000/

* Energy Dense Technology - Characteristics
* VRFB
          LT1 storage lifetime in years /15/
          cycles1  /15000/
          Selfdisc1 daily self-discharge in % /0.25/
          socH1 max state of charge /1/
          socL1 min state of charge /0/
          ch_eff1 /0.92/
          disch_eff1 /0.92/
          price1_e /280/
          price1_p /700/
          price_deg1
          loss1
          X1 auxiliary factor /1/
```

```
* Power Dense Technology - Characteristics
* SUPERCAPACITOR
          LT2 storage lifetime in years  /15/
          cycles2  /500000/
          Selfdisc2 daily self-discharge in % /10/
          socH2 max state of charge /1/
          socL2 min state of charge /0/
          ch_eff2 /0.9/
          disch_eff2 /0.9/
          price2_e /5000/
          price2_p /120/
          price_deg2
          loss2
          X2 auxiliary factor /1/

* Calculated Parameters
          price_e1
          price_p1
          price_e2
          price_p2

$onecho > taskin.txt
dset=t rng=A1:A69122 Rdim=1
dset=c rng=A1:P1 Cdim=1
par=E_gen rng=A1:B69122 Rdim=1
par=req_freq_low rng=C1:D69122 Rdim=1
par= req_freq_high rng=E1:F69122 Rdim=1
par=max_freq_low rng=G1:H69122 Rdim=1
par=Price_frq rng=I1:J69122 Rdim=1
par=Price_wm rng=K1:L69122 Rdim=1
par=Iteraciones rng=M1:N69122 Rdim=1
par=U rng=O1:P69122 Rdim=1
par=V rng=Q1:R69122 Rdim=1
$offecho

$CALL GDXXRW 0.Inputs_Mandatory.xlsx squeeze=N trace=3 @taskin.txt
$GDXIN 0.Inputs_Mandatory.gdx
$LOAD c t E_gen req_freq_low req_freq_high max_freq_low Price_frq Price_wm
Iteraciones U V
$OnEps
```

```
$GDXIN

Display E_gen,Price_wm,Price_frq;

price_e1 = X1*price1_e;
price_p1 = X1*price1_p;
price_e2 = X2*price2_e;
price_p2 = X2*price2_p;
price_deg1 = price_e1/(X1*cycles1);
price_deg2 = price_e2/(X2*cycles2);
loss1 =  Selfdisc1*Tper/(24*3600*100);
loss2 =  Selfdisc2*Tper/(24*3600*100);
CRF   =  (i/100)*(1+(i/100))**PT/(-1+(1+(i/100))**PT);
*CRF   =  1/15;

Display price_deg1,price_deg2,loss1,loss2,CRF;

Variables

* Battery 1
E_b12frq(t)
E_b12low(t)
E_b12high(t)
E_b1cap(t)
E_b12loss(t)
E_b12res(t)
E_b12wm(t)
E_b12wm_dis(t)
E_b12wm_abs(t)

* Battery 2
E_b22frq(t)
E_b22low(t)
E_b22high(t)
E_b2cap(t)
E_b22loss(t)
E_b22wm(t)
E_b22wm_dis(t)
E_b22wm_abs(t)
```

```
* Generator
E_g2wm(t)

* Grid Balances
E_frq(t)
E_low(t)
E_wm_dis(t)
E_wm_abs(t)

* Income - Costs
I_wm(t)
I_frq(t)
C_deg(t)
cap_costHESS

* System Outputs
ener_size1
pow_size1
ener_size2
pow_size2
F

* Results Presentation
Ifreq
Iwm

Positive Variable
cap_costHESS,I_frq(t),C_deg(t),E_low(t),E_high(t),E_g2wm(t),E_b12wm_dis(t),
E_b12wm_abs(t),E_b12loss(t),E_b12low(t),E_b12high(t),E_b1cap(t),E_b12res(t)
,E_b22loss(t),E_b22low(t),E_b22high(t),E_b2cap(t),E_b22wm_dis(t),E_b22wm_ab
s(t),pow_size1,ener_size1,pow_size2,ener_size2;

EQUATIONS

funobj,
eq1,eq2,eq3,eq4,eq5,eq6,eq7,eq8,eq9,eq10,eq11,eq12,eq13,eq14,eq15,eq16,eq17
,eq18,eq19,eq20,eq21,eq22,eq23,eq24,eq25,eq26,eq27,eq28,eq29,eq30,eq31,eq32
,eq33,eq34,eq35,eq36,eq37,eq38,eq39,eq40,eq41,eq42,eq43,eq44;

funobj..  F =E= PT*(-cap_costHESS*CRF + (365/D)*sum(t,I_frq(t) + I_wm(t) -
```

```
C_deg(t)));

* Energy Storage Capital Cost

eq1..     cap_costHESS =E= X1*(price_p1*pow_size1 + price_e1*ener_size1) +
X2*(price_p2*pow_size2 + price_e2*ener_size2);

* Generator Operation

eq2(t)..  E_gen(t)  =E=  E_g2wm(t);

* Batteries Operation

eq3(t)$(Iteraciones(t) gt 0)..   E_b1cap(t-1)-E_b1cap(t) =E=
E_b12low(t)/disch_eff1 + E_b12wm_dis(t)/disch_eff1 + E_b12loss(t) -
E_b12high(t)*ch_eff1 - E_b12wm_abs(t)*ch_eff1;

eq4(t)$(Iteraciones(t) gt 0)..   E_b2cap(t-1)-E_b2cap(t) =E=
E_b22low(t)/disch_eff2 + E_b22wm_dis(t)/disch_eff2 + E_b22loss(t) -
E_b22high(t)*ch_eff2 - E_b22wm_abs(t)*ch_eff2;

* Wholesale Market

eq5(t)..  I_wm(t)  =E= (Price_wm(t)*E_wm_dis(t)) + (Price_wm(t)*E_g2wm(t))
- (Price_wm(t)*E_wm_abs(t));

eq6(t)..  E_wm_dis(t)  =E=  E_b12wm_dis(t) + E_b22wm_dis(t);

eq7(t)..  E_wm_abs(t)  =E=  E_b12wm_abs(t) + E_b22wm_abs(t);

eq8(t)..  E_b12wm(t) =E= E_b12wm_dis(t) - E_b12wm_abs(t);

eq9(t)..  E_b22wm(t) =E= E_b22wm_dis(t) - E_b22wm_abs(t);

eq10(t)$(V(t) eq 1)..  E_wm_dis(t)  =E= 0;

eq11(t)$(U(t) eq 1)..  E_wm_abs(t)  =E= 0;

* Frequency Support/Market
```

```
eq12(t)..  I_frq(t)  =E=  (Price_frq(t)*E_low(t)) +
(Price_frq(t)*E_high(t));

eq13(t)..  E_low(t)  =E=  E_b12low(t)  + E_b22low(t);

eq14(t)..  E_high(t) =E=  E_b12high(t) + E_b22high(t);

eq15(t)..  E_b12frq(t) =E= E_b12low(t) - E_b12high(t);

eq16(t)..  E_b22frq(t) =E= E_b22low(t) - E_b22high(t);

eq17(t)..  E_low(t) - req_freq_low(t)  =E= 0;

eq18(t)..  E_high(t)- req_freq_high(t) =E= 0;

* Provision of Frequency Response for the worst case (0.5Hz deviation) and
Maintaining power reserves (30 mins of response)

eq19(t)..  max_freq_low(t) =L= E_b12res(t);

eq20(t)..  E_b1cap(t) =G= (max_freq_low(t)/disch_eff1) * Treg*60/Tper;

* Batteries Constraints

eq21(t).. (E_b12res(t)/disch_eff1 + E_b12loss(t) +
E_b12wm_dis(t)/disch_eff1)*3600/Tper  =L= pow_size1;

eq22(t).. (E_b22low(t)/disch_eff2 + E_b22loss(t) +
E_b22wm_dis(t)/disch_eff2)*3600/Tper  =L= pow_size2;

eq23(t).. (E_b12high(t) + E_b12wm_abs(t))*3600/Tper =L= pow_size1;

eq24(t).. (E_b22high(t) + E_b22wm_abs(t))*3600/Tper =L= pow_size2;

* Batteries - Energy Limits

eq25(t)..  E_b1cap(t) =L= socH1*ener_size1;

eq26(t)..  E_b2cap(t) =L= socH2*ener_size2;
```

```
eq27(t)..  E_b1cap(t) =G= socL1*ener_size1;

eq28(t)..  E_b2cap(t) =G= socL2*ener_size2;

* Degradation & Losses

eq29(t)..  C_deg(t) =E= (E_b12wm_dis(t)/disch_eff1 + E_b12low(t)/disch_eff1
+ E_b12high(t) + E_b12wm_abs(t) + E_b12loss(t))*price_deg1   +
(E_b22wm_dis(t)/disch_eff2 + E_b22low(t)/disch_eff2 + E_b22high(t) +
E_b22wm_abs(t) + E_b22loss(t))*price_deg2;

eq30(t)..  E_b12loss(t)  =E= E_b1cap(t)*loss1;

eq31(t)..  E_b22loss(t)  =E= E_b2cap(t)*loss2;

* Upper Bound

eq32..     cap_costHESS =L= Investment;

* Power to Energy Rate

eq33(t)..  pow_size1 =L= 10*ener_size1;

eq34(t)..  pow_size2 =L= 10*ener_size2;

* Initial Conditions

eq35(t)..  E_b12wm_abs('r0')  =E= 0;

eq36(t)..  E_b12wm_dis('r0')  =E= 0;

eq37(t)..  E_b22wm_abs('r0')  =E= 0;

eq38(t)..  E_b22wm_dis('r0')  =E= 0;

eq39(t)..  E_b12high('r0')    =E= 0;

eq40(t)..  E_b22high('r0')    =E= 0;

eq41(t)..  E_b12low('r0')     =E= 0;
```

```
eq42(t)..  E_b22low('r0')     =E= 0;

* Results Presentation

eq43..  Ifreq  =E= PT*(365/D)*sum(t, Price_frq(t)*E_b22low(t) +
Price_frq(t)*E_b22high(t));

eq44..  Iwm  =E= PT*(365/D)*sum(t,I_wm(t) - Price_wm(t)*E_g2wm(t));

MODEL arbitrage_frequency_hybrid /all/;

SOLVE arbitrage_frequency_hybrid using LP maximizing F;

execute_unload "3.Results_Mand_2p.gdx" I_frq I_wm C_deg
execute 'gdxxrw.exe 3.Results_Mand_2p.gdx var=I_frq  rng=B2:C69122 Rdim=1'
execute 'gdxxrw.exe 3.Results_Mand_2p.gdx var=I_wm   rng=E2:F69122 Rdim=1'
execute 'gdxxrw.exe 3.Results_Mand_2p.gdx var=C_deg  rng=H2:I69122 Rdim=1'
```

Appendix C. FFRA Model Code

```
Set t row labels
    c column labels

Parameter
*GENERAL INPUTS
          E_gen(t)          Generator Input in MWh
          Price_frq(t)      Price of Frequency Market in £ per MWh
          Price_wm(t)       Price of Market in £ per MWh
          Iteraciones(t)    First Iteration is 0
          High(t)   Auxiliary factor: Energy Flow for Arbitrage and low freq
          Low(t)    Auxiliary factor: Energy Flow for Arbitrage and high
freq
          N number of samples
          D signicant days of analysis /1/
          Tper sample rate in seconds /15/
          Treg regulatory reserves in mins /30/
          PT project lifetime in years /15/
          i  project interest in % /3/
          CRF capital recovery factor
          Investment /4000000/

* Energy Dense Technology - Characteristics
* VRFB
          LT1 storage lifetime in years /15/
          cycles1  /15000/
          Selfdisc1 daily self-discharge in % /0.25/
          socH1 max state of charge /1/
          socL1 min state of charge /0/
          initial_SOC1 /0.5/
          ch_eff1 /0.92/
          disch_eff1 /0.92/
          price1_e /280/
          price1_p /700/
          price_deg1
          loss1
          X1 auxiliary factor /1/

* Power Dense Technology - Characteristics
```

```
* SUPERCAPACITOR
          LT2 storage lifetime in years  /15/
          cycles2  /500000/
          Selfdisc2 daily self-discharge in % /10/
          socH2 max state of charge /1/
          socL2 min state of charge /0/
          initial_SOC2 /0.5/
          ch_eff2 /0.9/
          disch_eff2 /0.9/
          price2_e /5000/
          price2_p /120/
          price_deg2
          loss2
          X2 auxiliary factor /1/

* Calculated Parameters
          price_e1
          price_p1
          price_e2
          price_p2

$onecho > taskin.txt
dset=t rng=A1:A69122 Rdim=1
dset=c rng=A1:P1 Cdim=1
par=Price_frq rng=A1:B69122 Rdim=1
par=Iteraciones rng=C1:D69122 Rdim=1
par=High rng=E1:F69122 Rdim=1
par=Low rng=G1:H69122 Rdim=1
par=Price_wm  rng=I1:J69122 Rdim=1
par=E_gen rng=K1:L69122 Rdim=1
$offecho

$CALL GDXXRW 0.Inputs_Operation_Mix.xlsx squeeze=N trace=3 @taskin.txt
$GDXIN 0.Inputs_Operation_Mix.gdx
$LOAD c t E_gen Price_wm Price_frq Iteraciones High Low
$OnEps
$GDXIN

Display E_gen,Price_wm,Price_frq;
```

```
price_e1 = 1000*X1*price1_e;
price_p1 = 1000*X1*price1_p;
price_e2 = 1000*X2*price2_e;
price_p2 = 1000*X2*price2_p;
price_deg1 = price_e1/(X1*cycles1);
price_deg2 = price_e2/(X2*cycles2);
loss1 =  Selfdisc1*Tper/(24*3600*100);
loss2 =  Selfdisc2*Tper/(24*3600*100);
CRF   =  (i/100)*(1+(i/100))**PT/(-1+(1+(i/100))**PT);
*CRF   =  1/15;

Display price_deg1,price_deg2,loss1,loss2;

Variables

* Battery 1
E_b12frq(t)
E_b12low(t)
E_b12high(t)
E_b1cap(t)
E_b12loss(t)
E_b12res(t)
E_b12wm(t)
E_b12wm_dis(t)
E_b12wm_abs(t)

* Battery 2
E_b22frq(t)
E_b22low(t)
E_b22high(t)
E_b2cap(t)
E_b22loss(t)
E_b22wm(t)
E_b22wm_dis(t)
E_b22wm_abs(t)

* Generator
E_g2wm(t)

* Income - Costs
```

```
I_wm(t)
I_frq(t)
C_deg(t)
cap_costHESS

* System Outputs
ener_size1
pow_size1
ener_size2
pow_size2
F
* MILP
E_blow(t)
E_bhigh(t)

* Results Presentation
Ifreq
Iwm

Binary Variable MI1(t),MI2(t)

Positive Variable C_deg(t),
E_g2wm(t),E_b1cap(t),E_b2cap(t),E_b12wm_abs(t),E_b22wm_abs(t),E_b12wm_dis(t
),E_b22wm_dis(t),E_b12low(t),E_b22low(t),E_b12high(t),E_b22high(t),E_b12los
s(t),E_b22loss(t),pow_size1,ener_size1,pow_size2,ener_size2,cap_costHESS,E_
blow(t),E_bhigh(t);

EQUATIONS

funobj,
eq1,eq2,eq3,eq4,eq5,eq6,eq7,eq8,eq9,eq10,eq11,eq12,eq13,eq14,eq15,eq16,eq17
,eq18,eq19,eq20,eq21,eq22,eq23,eq24,eq25,eq26,eq27,eq28,eq29,eq30,eq31,eq32
,eq33,eq34,eq35,eq36,eq37,eq38,eq39,eq40,eq41,eq42,eq43,eq44,eq45,eq46,eq47
,eq48,eq49,eq50,eq51;

funobj..  F =E= PT*(-cap_costHESS*CRF + (365/D)*sum(t,I_frq(t) + I_wm(t) -
C_deg(t)));

* Energy Storage Capital Cost
```

```
eq1..     cap_costHESS =E= X1*(price_p1*pow_size1 + price_e1*ener_size1) +
X2*(price_p2*pow_size2 + price_e2*ener_size2);

* Generator Operation

eq2(t)..  E_gen(t)  =E=  E_g2wm(t);

* Battery Operation

eq3(t)$(Iteraciones(t) gt 0)..  E_b1cap(t-1)-E_b1cap(t) =E=
E_b12low(t)/disch_eff1 + E_b12wm_dis(t)/disch_eff1 + E_b12loss(t) -
E_b12high(t)*ch_eff1 - E_b12wm_abs(t)*ch_eff1;

eq4(t)$(Iteraciones(t) gt 0)..  E_b2cap(t-1)-E_b2cap(t) =E=
E_b22low(t)/disch_eff2 + E_b22wm_dis(t)/disch_eff2 + E_b22loss(t) -
E_b22high(t)*ch_eff2 - E_b22wm_abs(t)*ch_eff2;

* Wholesale Market

eq5(t)..  I_wm(t)  =E= (E_b12wm_dis(t)+ E_b22wm_dis(t))*Price_wm(t)  -
(E_b12wm_abs(t)+ E_b22wm_abs(t))*Price_wm(t) + (Price_wm(t)*E_g2wm(t));

eq6(t)..  E_b12wm(t)  =E=  E_b12wm_dis(t) - E_b12wm_abs(t);

eq7(t)..  E_b22wm(t)  =E=  E_b22wm_dis(t) - E_b22wm_abs(t);

eq8(t)$(Low(t)  eq 1)..   E_b12wm_abs(t) =E= 0;

eq9(t)$(High(t) eq 1)..   E_b12wm_dis(t) =E= 0;

eq10(t)$(Low(t)  eq 1)..   E_b22wm_abs(t) =E= 0;

eq11(t)$(High(t) eq 1)..   E_b22wm_dis(t) =E= 0;

* Frequency Support/Market

eq12(t)..  I_frq(t) =E= (E_b12low(t)   + E_b22low(t))*Price_frq(t)    +
(E_b12high(t)  + E_b22high(t))*Price_frq(t);

eq13(t)..  E_blow(t) =E= E_b12low(t)   + E_b22low(t);
```

```
eq14(t)..  E_bhigh(t) =E= E_b12high(t) + E_b22high(t);

eq15(t)..  E_b12frq(t) =E= E_b12low(t) - E_b12high(t);

eq16(t)..  E_b22frq(t) =E= E_b22low(t) - E_b22high(t);

eq17(t)$(High(t) eq 0)..   E_b12high(t) =E= 0;

eq18(t)$(High(t) eq 0)..   E_b22high(t) =E= 0;

eq19(t)$(Low(t)  eq 0)..   E_b12low(t)  =E= 0;

eq20(t)$(Low(t)  eq 0)..   E_b22low(t)  =E= 0;

* Maintaining power reserves (30 mins of response)

eq21(t)..  E_b1cap(t) =G= 1*(E_b12low(t)/disch_eff1 +
E_b22low(t)/disch_eff2) * Treg*60/Tper;

* Batteries - Power Constraints

eq22(t).. (E_b12low(t)/disch_eff1 + E_b12loss(t) +
E_b12wm_dis(t)/disch_eff1 + E_b22low(t)/disch_eff2)*3600/Tper =L=
pow_size1;

eq23(t).. (E_b22low(t)/disch_eff2 + E_b22loss(t) +
E_b22wm_dis(t)/disch_eff2)*3600/Tper =L= pow_size2;

eq24(t).. (E_b12high(t) + E_b12wm_abs(t))*3600/Tper =L= pow_size1;

eq25(t).. (E_b22high(t) + E_b22wm_abs(t))*3600/Tper =L= pow_size2;

* Batteries - Energy Limits

eq26(t)..  E_b1cap(t) =L= socH1*ener_size1;

eq27(t)..  E_b2cap(t) =L= socH2*ener_size2;

eq28(t)..  E_b1cap(t) =G= socL1*ener_size1;
```

```
eq29(t)..  E_b2cap(t) =G= socL2*ener_size2;

* Degradation & Losses

eq30(t)..  C_deg(t) =E= (E_b12wm_dis(t)/disch_eff1 + E_b12low(t)/disch_eff1
+ E_b12high(t) + E_b12wm_abs(t) + E_b12loss(t))*price_deg1   +
(E_b22wm_dis(t)/disch_eff2 + E_b22low(t)/disch_eff2 + E_b22high(t) +
E_b22wm_abs(t) + E_b22loss(t))*price_deg2;

eq31(t)..  E_b12loss(t)  =E= E_b1cap(t)*loss1;

eq32(t)..  E_b22loss(t)  =E= E_b2cap(t)*loss2;

* Upper Bound

eq33..     cap_costHESS =L= Investment;

* Power to Energy Rate

eq34(t)..  pow_size1 =L= 10*ener_size1;

eq35(t)..  pow_size2 =L= 10*ener_size2;

* Initial Conditions

eq36(t)..  E_b12wm_abs('r0') =E= 0;

eq37(t)..  E_b12wm_dis('r0') =E= 0;

eq38(t)..  E_b22wm_abs('r0') =E= 0;

eq39(t)..  E_b22wm_dis('r0') =E= 0;

eq40(t)..  E_b12high('r0')   =E= 0;

eq41(t)..  E_b22high('r0')   =E= 0;

eq42(t)..  E_b12low('r0')    =E= 0;
```

```
eq43(t)..  E_b22low('r0')    =E= 0;

* Results Presentation

eq44..  Ifreq =E= PT*(365/D)*sum(t,I_frq(t));

eq45..  Iwm   =E= PT*(365/D)*sum(t,I_wm(t) - Price_wm(t)*E_g2wm(t));

* BIG M TECHNIQUE

eq46(t).. E_blow(t)  =L= 0 + 200*MI1(t);

eq47(t).. E_blow(t)  =G= 1*Tper/3600 - 200*(1-MI1(t));

eq48(t).. E_bhigh(t) =L= 0 + 200*MI2(t);

eq49(t).. E_bhigh(t) =G= 1*Tper/3600 - 200*(1-MI2(t));

eq50(t).. E_blow(t)  =G= 0;

eq51(t).. E_bhigh(t) =G= 0;

MODEL arbitrage_frequency_hybrid /all/;

SOLVE arbitrage_frequency_hybrid using MIP maximizing F;

execute_unload "2.Results_Mix.gdx" I_frq I_wm C_deg
execute 'gdxxrw.exe 2.Results_Mix.gdx var=I_frq rng=B2:C69122 Rdim=1'
execute 'gdxxrw.exe 2.Results_Mix.gdx var=I_wm  rng=E2:F69122 Rdim=1'
execute 'gdxxrw.exe 2.Results_Mix.gdx var=C_deg rng=H2:I69122 Rdim=1'
```