MASTER IN ELECTRIC POWER INDUSTRY

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HYBRIDIZATION OF RENEWABLE POWER PLANTS WITH BATTERY ENERGY STORAGE SYSTEMS ("BESS"), USING GRID FORMING INVERTERS ("GFMI")

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Abstract

This master thesis investigates the integration of Battery Energy Storage Systems (BESS) with renewable power plants through the utilization of Grid-Forming Inverters (GFMI). The study encompasses a comprehensive analysis of the regulatory framework within the European and Spanish electric sector. It also explores the pivotal role of utility-scale energy storage in the context of the ongoing energy transition.

The research identifies the predominant contemporary energy storage technologies and anticipates future trends in the field. It analyzes the impact of non-dispatchable renewables on the electrical system while examining the role of grid-forming inverters, especially in high renewable penetration scenarios.

Furthermore, the thesis develops a business model to evaluate the feasibility of utility-scale storage projects, presenting various scenarios and discussing their outcomes. This work serves as a valuable contribution to the understanding of BESS integration within renewable energy systems and their economic viability in contemporary and future energy landscapes.

Key words: hybridization, non-dispatchable renewables, battery energy storage systems, grid-forming inverters

Table of Contents

Table of tables

Table of Figures

Motivation, objectives, and structure

Motivation

As discussed in previous chapters, the process of decarbonizing the planet by generating energy through 100% renewable sources is a significant challenge. One of the main ones is managing the stability systems with such a high penetration of renewables.

In this sense, grid-forming inverters have a fundamental role to play in replacing conventional generators in the task of regulating system stability. An academically stimulating task is an in-depth analysis of this technology and study of the part of grid-forming inverters in contexts of high penetration of renewable sources.

On the other hand, it is very interesting to consider the business model of this technology and to consider the economic viability of this type of project, which will allow us to know the competitiveness of BESS in the market and to present well-founded conclusions by analyzing its profitability and the opportunities found in this business.

Objectives

The main objectives of this work are described below:

1. **Analyze the regulatory context of the European and Spanish electricity systems:** Study the laws, rules, and regulations governing the electricity sector and, more specifically, those specific to battery projects. In addition, the main trends, and challenges of the electricity sector and how they are currently being addressed, both at the European level and in Spain, will be identified. By analyzing the regulatory context, it will be possible to identify opportunities and risks for companies operating in the sector and to establish strategies to adapt to regulatory changes and maintain a competitive position.

2. **Analyzing the impact of the penetration of non-manageable renewables in the electricity system:** This involves assessing the effects that intermittent energy generation, such as solar and wind, has on the electricity grid and

the stability of the system. This consists in studying the technical challenges involved in integrating these energy sources, such as the variability of generation and the difficulty of predicting their production, as well as the economic impacts on electricity prices and the cost of grid management. In addition, the role of storage technologies and other flexibility mechanisms, such as demand-side management, should be analyzed to enable greater integration of renewable energies into the electricity system.

3. **Study the different options available for storing generated energy:** This includes analyzing technologies such as batteries, thermal storage systems, hydraulic storage systems, and mechanical storage technologies, among others. This analysis will evaluate the advantages and limitations of each of these technologies, their storage capacity, efficiency, and cost. Additionally, the applications for which each technology is best suited will be studied, taking into account the specific characteristics of the energy source being stored and the electrical system into which it will be integrated.

4. **Analyze the role of grid-forming inverters in contexts of high penetration of renewable sources:** evaluate the role that these devices play in managing and stabilizing the electrical grid in systems with high penetration of renewable energies. Grid-forming inverters are electronic devices capable of controlling the frequency and voltage of the electrical grid and are becoming a key element for integrating intermittent renewable sources into the grid. This analysis involves studying how grid-forming inverters can improve the stability and flexibility of the electrical grid, allowing for the integration of larger amounts of renewable energy. It will also be necessary to evaluate how these devices can help improve the safety and efficiency of the electrical system and how they can be integrated with other technologies such as energy storage batteries and demand management to achieve a more resilient and sustainable electrical system.

5. **Develop a business plan:** Design the business model for utility-scale storage and analyze the economic viability of a battery technology project. To this end, the existing business opportunities for the installation of batteries in the geographical area where the project will be developed will be identified, and the investment and operating costs of the project's projected revenues and cash flows will be calculated, to determine the economic viability of the

project. Finally, a sensitivity analysis will be carried out to study the impact of possible variations in the most important variables of the project, such as electricity market prices and raw material costs.

Structure

In chapter 1, an introduction to the current energy context worldwide is provided. Global challenges that the world faces in achieving energy transition are explored. Factors driving this transition are analyzed, emphasizing the importance of finding cleaner and more efficient energy solutions.

Chapter 2, elves into the regulatory environment of the electric sector at the global, European, and Spanish levels. Key regulations that have emerged in recent years, influencing the transformation of the sector, are examined. The role of policies and regulatory measures in shaping the current energy landscape is highlighted.

In chapter 3, the role of utility-scale energy storage in energy transition is further investigated. A comprehensive analysis of the main energy storage technologies currently available is conducted, and emerging trends in this field are explored. Additionally, the impact of grid-forming inverters in a context with a high penetration of non-manageable renewable sources is investigated.

Finally, chapter 4 is focused on a business model designed to assess the economic viability of BESS projects. Various scenarios that reflect real-world situations are presented and discussed. This chapter sheds light on the status of BESS projects and their contribution to the energy transition.

Chapter 1. INTRODUCTION

1.1. ALIGNMENT WITH THE SDGs

The Sustainable Development Goals (SDGs) are integrated into the 2030 Agenda, which consists of 17 sustainable development goals and 169 targets. They represent a new challenge for the international community to eradicate poverty, expand access to human rights, and achieve global economic development that is sustainable and respectful of the planet and the resources it offers. These goals are graphically represented in Figure 1.

Figure 1. Sustainable Development Goals

This project, based on a business idea based on innovation and renewable energy, is aligned with many of the objectives listed in Figure 1. It mainly encompasses the following purposes: Affordable and clean energy (7), industry, innovation, and infrastructure (9), and, finally, climate action (13).

AFFORDABLE AND CLEAN ENERGY

This objective seeks to guarantee access to renewable and sustainable energy sources for all and promote energy efficiency and cleaner technologies. Energy storage through grid-forming batteries not only allows for efficient management of energy generated by renewable sources but also improves the system's stability and enhances the integration of renewables.

INDUSTRY INNOVATION AND INFRASTRUCTURE

This project studies an innovative technology such as grid forming technology, therefore, it is aligned with objective 9 as it is an innovative system that aims to

contribute to the improvement of the stability of the electricity system and allow the integration of a greater amount of renewable energy, especially solar energy.

CLIMATE ACTION

Finally, as it is a technology that improves the efficiency of renewable energy sources, it is a project that is committed to sustainability and contributes to the objectives of achieving a world with zero emissions.

1.2. CONTEXT

The energy transition implies a progressive substitution of technologies based on the combustion of fossil fuels for others with the capacity to generate electricity from renewable and non-polluting sources. However, the penetration of renewables will not be viable without the incorporation of elements that solve the limitations derived from the intermittency and variability of these technologies. On the other hand, the closure of thermal power plants in the Spanish energy sector poses various challenges related to the stability of supply that should not be omitted in the configuration of the electricity grid over the coming years.

The reason why the transformation of the electricity generation mix may pose a risk to the security of the system has to do with the disconnection of thermal power plants and their progressive replacement by generation resources which, like wind or solar power, are intermittent and their availability cannot be assured when needed, nor to correct deviations between generation and demand in real-time.

Therefore, the decarbonization of the electricity generation mix must be accompanied by the simultaneous deployment of innovative solutions that ensure the stability of the system, such as, in this case, batteries with grid-forming inverters, whose operation will be controlled through an algorithm that will allow them to virtually emulate the behavior of a synchronous machine, mitigating the negative impacts on the grid generated by the simultaneous connection of renewable plants with traditional inverters and the expected closure of thermal power plants in the coming years. This situation leads to a reduction in the amount of inertia in the system, which is a grid parameter that determines the magnitude of the impact on the grid frequency in the event of production-consumption imbalances. The fewer rotating generators present in the system (gas turbines,

combined cycle, flowing hydroelectric power plants/reservoir), the less inertia, and therefore the more significant variations in grid frequency will occur in the event of any imbalance, a situation that puts grid stability at risk.

For this reason, it is necessary to develop technologies, such as the one to be studied in this paper, grid-forming inverters, which provide inertia to the grid and can replace the function currently performed by conventional power plants. These systems are very useful in areas of high renewable penetration where generation is subject to climate conditions and consequently presents certain stochasticity. In addition to optimizing the plants in these areas by minimizing curtailment, this technology can provide inertia to the system and help maintain system stability.

Chapter 2. REGULATORY CONTEXT

The Spanish electricity sector is highly regulated, and is subject to directives and other legal acts issued by different European bodies, as well as national legislation issued by the Ministry of Energy and the CNMC ("Comisión Nacional de los Mercados y la Competencia". This chapter aims to analyze the main regulatory initiatives carried out in recent years to set the energy transition objectives.

2.1. GLOBAL CONTEXT

The first international agreement that put the problem of climate change on the table was the Kyoto Protocol, which was concluded in 1997 by the member countries of the United Nations, and proposed a series of measures to reduce emissions of the main greenhouse gases generated by the member countries that signed the agreement [1]. In addition, this agreement proposed the promotion of sustainable growth in developing countries [1].

Several years later, in December 2015, the Paris Agreement took place. This international treaty on climate change was adopted by 196 countries with the common goal of achieving carbon neutrality by 2050 [2]. To achieve this goal, a series of objectives were established to reduce GHG emissions by 37% compared to 1990 levels. Subsequently, this figure was updated to 43% with the implementation of the Green Deal.

2.2. EUROPEAN CONTEXT

Several directives have been launched in Europe in recent years to regulate issues related to the European electricity market, emission rights, and renewable energies. These directives are approved by all EU member states.

The first directive, Directive 96/92/EC, was created in 1996 but did not come into effect until the following year. This is the EU directive focused on the creation of an internal electricity market, which established the rules for creating a single electricity market in Europe [3]. This directive represented a significant change in the organization of the European electricity market by introducing liberalizing measures in all areas (generation, transport, distribution, and commercialization).

Directive 96/92/EC was repealed in 2003 with the approval of Directive 2003/54/EC; this directive contained the measures included in the previous directive but delved deeper into some aspects related to the opening of the European electricity market [3].

That same year, Directive 2003/87/EC was established, which created a regime for trading greenhouse gas emission allowances (EU ETS) in the European Union [4]. The creation of this regime was key to combat the effects of climate change by reducing greenhouse gas emissions in a cost-effective and economically efficient manner. The EU ETS is based on the principle of "cap and trade," which establishes a cap on emissions in factories, generators, and other installations. Over time, this cap is reduced, so that total emissions decrease. This system was created to increase the bids in the wholesale markets of carbon power plants, which are inherently quite inefficient. By requiring these coal-fired power plants to purchase more emission allowances than combined-cycle plants, which are more efficient (and less polluting, due to their use of natural gas as fuel instead of coal), the direct consequence has been the systematic exclusion of coal-fired power plants from the market. This situation has inevitably led to the closure of most coal-fired power plants, as they could not recover their costs since they had not sold electricity during enough hours to offset their fixed operation and maintenance expenses, thus forcing them to shut down.

Continuing the timeline, in 2009, Directive 2009/28/EC on the promotion of the use of energy from renewable sources was introduced. This directive aims to promote the installation of renewable energy sources [4].

In 2019, the European Commission launched the regulation on the governance of the Energy Union and Climate Action. This regulation establishes the objectives and mechanisms for implementing the Paris Agreement and the transition towards a low-carbon economy in the EU. This regulation required EU countries to develop their integrated national energy and climate plan, which details each country's plan to achieve the objectives set for 2030 in the Paris Agreement, as well as ensuring a just and cost-effective transition to a climate-neutral economy for all [5].

Finally, in 2021, the Fit for 55 targets was published, which outlines the EU's energy transition plan. This package of measures is a set of proposals aimed at reviewing

and updating EU legislation and launching new initiatives to ensure that EU policies align with the climate objectives agreed upon by the Council and the European Parliament [6]. This legislation increases the emissions reduction target compared to 1990 set in the Paris Agreement to 55% [6], to achieve global climate neutrality of emissions by 2050.

2.3. SPANISH CONTEXT

The energy policy of Spain aims to decarbonize the economy by 2050. In this regard, the Spanish Government, following the objectives set by the European Union, has established and promoted a series of increasingly ambitious regulatory measures and objectives with the firm intention of accelerating the energy transition.

The objectives to combat climate change in Spain are concentrated in the PNIEC 2021-2030, whose central objective is to reduce greenhouse gas emissions by 23% compared to 1990 [7]. As mentioned earlier, the EU requires this plan to know the measures and objectives proposed by each EU country.

To ensure the contribution to these common objectives, the European Commission established 2018 a Governance Regulation by which all Member States were required to develop a National Energy and Climate Plan (NECP) for the period 2021-2030 and submit a version to the European Commission for evaluation during 2019. The NECPs must detail the objectives to be achieved and the policies and instruments in five fundamental areas: decarbonization, energy efficiency, energy security, the internal energy market, and research, innovation, and competitiveness. An important part of the NECPs is the economic impact analysis. Member States must include an analysis of the implications of measures in the five mentioned areas, as well as accompany it with a comprehensive analysis of their economic and social impacts.

Lastly, it is worth noting that Spain has released a revised version of the NECP with more ambitious targets than the previous one. With this plan update, it is projected to achieve 62 gigawatts (GW) of installed wind power, along with 76 GW of photovoltaic, 4.8 GW of solar thermal, 1.4 GW of biomass, and 22 GW of energy storage by the year 2030 [8].

Chapter 3. CONTEXT

3.1. THE ROLE OF UTILITY-SCALE STORAGE IN THE ENERGY TRANSITION

As mentioned above, under the challenges of the current climate crisis, the global energy system is facing a process of structural change, known as the energy transition. This implies reducing dependence on fossil fuels and, on the other hand, boosting the use of renewable energies, increasing their efficiency and their integration into the energy system [9].

The path towards so-called "climate neutrality" through the deployment of clean energy from renewable sources implies a profound transformation of the electricity system towards a decentralized and flexible model. The variability of non-conventional renewable sources (solar and wind) requires the implementation of technological solutions that provide flexibility and support to the system, and that are available at any time to generate and/or inject electricity, thereby guaranteeing the security of supply.

Currently, this system support role is performed by thermal power plants due to their flexibility and short response time, however, these technologies must be phased out to meet EU targets for reducing GHG emissions without compromising the security of supply.

The main alternatives to meet these challenges are demand-side management, flexibility by conventional generation sources, or flexibility through energy storage systems (ESS) [9]. Particularly the GFMI (Grid-forming Inverters, driven by technological advances and the reduction of their development costs thanks to economies of scale, are postulated as the main solution to replace thermal power plants and provide the necessary flexibility to the system. This technology will be key to achieving the objectives of decarbonization of the electricity system by providing flexibility in the generation of energy from renewable sources and guaranteeing its integration into the electricity system [9].

The latest report of the NECP prepared by the Ministry for Ecological Transition and the Demographic Challenge (MITECO), as it is mentioned above, plans to have

22 GW of storage installed in Spain by 2030. Thanks to the development of the ESS and renewable energy sources, the goal is to cover 48% of total demand with renewable energy sources and thus reduce GHG emissions by 32% compared to 1990 [10].

Thanks to this new storage capacity, it will be possible to contribute to mitigating the limitations of renewable facilities caused by intermittency and reducing curtailment, thereby enhancing facility profitability, and enabling the management of the substantial generation ramps already occurring today and expected to become more pronounced by 2030.

The primary benefit of energy storage is associated with the intermittency of renewables, primarily solar energy, which can only be generated during specific hours of the day. Due to this limitation in its production profile, even if the installed photovoltaic capacity is increased, it will never be able to cover the thermal gap. To bridge this thermal gap, it will be necessary to incorporate storage into the system. This allows for the storage of energy during solar generation hours and the supply of energy to the system during hours when demand cannot be met with renewable energy only. This situation can be visually observed in Figure 1, which illustrates the surplus of solar energy that can be stored to address the thermal gap.
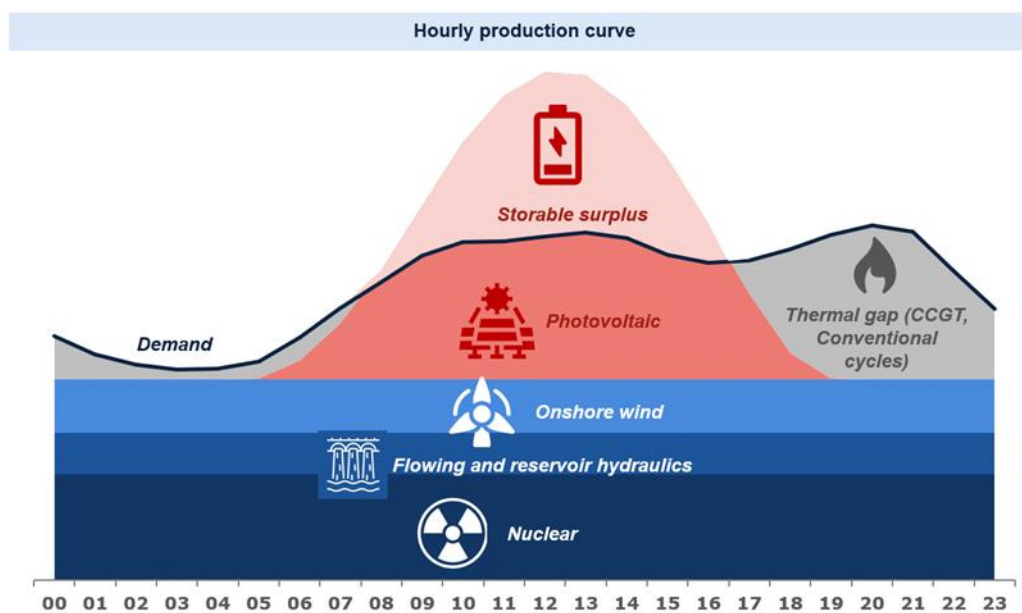

Figure 1. Hourly production curve with integrated storage

The second benefit provided by energy storage is related to curtailment reduction. This concept refers to situations of surplus energy that occur when the installed solar capacity exceeds the minimum peak demand of the system. There are two types of curtailment:

- Economic curtailment, stemming from the clearing of wholesale markets. This situation arises due to the increase in solar capacity; increasing solar supply leads to situations where it exceeds total demand, resulting in many offers from solar plants not being accepted in the daily market clearing. Figure X illustrates how during photovoltaic generation hours, there is a surplus which, if unable to be stored, results in curtailment.

- Technical curtailment occurs independently of whether renewable capacity exceeds certain thresholds than national demand. This curtailment is associated with the parameter of the system explained earlier, inertia. In some grid nodes, due to a high renewable capacity and limited thermal capacity, not enough inertia is entering the grid. Therefore, the grid operator (such as REE in Spain) cancels the offers made by renewable plants in the energy-only markets during the clearance of the technical restrictions market (the first of the ancillary services), resulting in curtailment.

As a result of the above, renewable plant operators will find that they are selling less energy due to the two types of curtailment explained earlier, and the energy they sell will be at a very low price. Since solar plants can only generate during hours of solar irradiation, they can only sell energy during these hours. During these hours, prices are plummeting precisely because there is an excess of solar energy supply. Figure 2 graphically depicts how the daily market price falls during peak photovoltaic generation hours due to the excess supply of solar energy during those daytime hours.
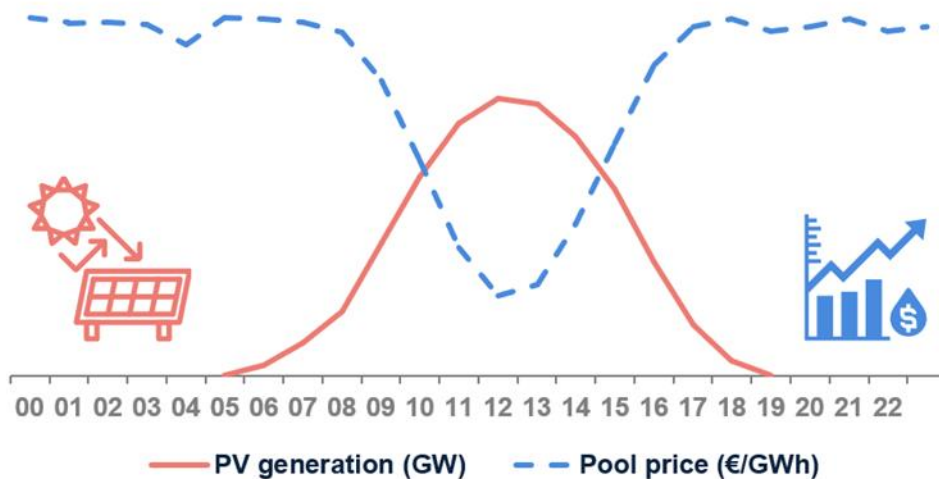
Figure 2. Evolution of hourly electricity prices as a function of PV generation.

The solution to these situations involves the installation of storage capacity within the electrical system. Incorporating storage capacity allows plant operators to 'schedule' the generation of their facilities by charging BESS during solar generation hours and discharging for the rest of the day.

The installation of new storage capacity will reduce the impact on prices of new solar photovoltaic plants, whereas prices during the remaining hours will gradually decrease as more storage is installed, effectively flattening the daily price curve. Furthermore, energy storage will help reduce curtailment by storing surplus energy, enabling the efficient integration of a larger amount of photovoltaic capacity into the system and contributing to emissions reduction.

However, storage can provide more benefits in terms of guaranteeing stability of electricity supply, through its participation in the ancillary services, as well as supplying inertia to the system when using Grid-Forming Inverters (GFMI). The first role involves replacing thermal power plants in system regulation tasks, thanks to the batteries' short response time and versatility, allowing them to inject or consume energy from the grid easily. On the other hand, if batteries are complemented with GFMI, they can help eliminate the inertia problem, reduce technical curtailment, and, most importantly, ensure the reliability of the power supply.

3.2. ANALYSIS OF THE MAIN EXISTING STORAGE TECHNOLOGIES

Currently, there are three main technologies capable of providing firmness and flexibility to the system. On the one hand, smart demand management allows large consumers to voluntarily modulate their consumption; on the other hand, conventional power generation plants, such as combined cycle plants, are the ones that have provided these services so far; and finally, Energy Storage Systems (ESS) can accumulate electricity and release it to the system as needed, improving the management of renewable production and positioning themselves as the main sustainable alternative in the long term.

In this way, utility-scale ESSs are particularly important to solve the challenges of the transition, as their large size and connection to the distribution or transmission grids means they have a greater capacity to provide the services required by the system operator, providing backup and generating stable price signals. Thus, some of the advanced grid services that ESSs could provide are as follows [11]:

1. Frequency regulation and stabilization (ancillary services)
2. System restoration capability (Black-Start)
3. Support for conventional generation (covering outages or ramps)
4. Reduction of renewable generation waste (curtailment)

In this line, there are different types of ESSs depending on the technology they use, among which hydrogen, batteries, or hydro pumping stand out, and not all of them are capable of providing all the services mentioned above. Each type of ESS has specific technical characteristics that enable it to meet or not meet the requirements necessary to provide each of these services.

Table 1. Main characteristics of existing ESS technologies [11]

		Advantages	Disadvantages	Services it can provide	Useful life/Nº cycles	Capacity [MW]	Cost [€/kWh]
	Hydrogen (H2)	High capacities in the future	High costs and low maturity	Mobility, arbitration, seasonal storage	Low nº of cycles	High in the future	4 - 10 €/kg H2
Electrochemical	Lithium-ion batteries	High maturity and big capacity	High costs and loss of capacity after a certain nº of cycles	Flexibility, frequency, and voltage regulation	5.000 - 10.000 cycles	< 240	250 - 500
Electrochemical	Flow batteries	They allow the decoupling of	High costs and loss of capacity after a certain nº of cycles	Flexibility, frequency, and voltage regulation	> 10.000 cycles	20 - 60	400 - 800

		power and energy		of discharges			
	Supercapacitors	High maturity, high power density and cyclability	High costs	Stability, frequency regulation, inertia synthetics	> 1.000.000 cycles	< 10	10.000
Mechanical	Hydropumping	High maturity, big capacity	High investment, specific localization	Seasonal storage	40 - 80 years	> 5 GWh	350 - 1.500
	Compressed air	Maturity	Low response	Stability, black start, seasonal storage	40 - 100 years	2,5 - 3.000 MWh	200 - 250
	Flywheel unit	High maturity, rapidity, cyclability, and decoupling between power and energy	High costs	Frequency and voltage regulation, inertia synthetics	> 1.000.000 cycles	5 kWh	3.000
Thermal		High capacity of energy and power	Low response, high costs, and low performance	Seasonal storage	-	80 - 200	High
Hybrid		Combine technologies with different capabilities	Complexity	All	-	-	-

Therefore, it is essential to specify the services to be provided by the ESS and to use an appropriate methodology to select the most suitable technology to optimize the investment to be made and the operation of the system. A summary table with the main types of ESSs [11], as well as their main advantages, disadvantages, and characteristics, are presented in Table 1.

Of all of them, batteries have positioned themselves as the main ESS for providing grid services, due to their accelerated technological development, scalability, and the expected large reduction in their costs, although batteries cannot cover seasonal needs due to their limited duration.

In this sense, batteries are currently already providing grid services in leading countries, such as the United States or Australia, although they depend on regulatory support for their development. In terms of their economic model, utility-scale batteries today derive their revenues from 3 main sources: 1) through price arbitrage, buying electricity when it is cheaper and selling it when the price is high; 2) through their participation in balancing services, helping to guarantee the

supply-demand balance; or 3) from other regulated revenues, such as payments for guaranteeing capacity (articulated through the so-called capacity auctions).

It is worth noting that price arbitrage is particularly linked to the introduction of large solar PV capacity, as it generates large price differences between the hours of the day when there is solar irradiance and non-solar hours. Batteries can take advantage of this differential while contributing to flattening the price curve and reducing this prices differences. This last term concept refers to the difference between the average price of the market and the hourly price of what is sold electricity [12], batteries can reduce this difference between prices by storing energy in periods of high generation and low demand, and injecting that energy in periods of higher demand and consequently higher price, obtaining higher economic benefits.

Along these lines, utility-scale battery projects are configured in 2 possible business models. On the one hand, "stand-alone" systems are those Utility-scale batteries directly connected to the electricity grid that operate in isolation.

Within battery storage systems, there are several types of technologies depending on the construction materials and their technical specifications. In the following, the study will focus on the technology that is the subject of this study, batteries with grid-forming inverters.

This technology is directly related to the need to control the frequency of the electrical system, keeping it at a stable value to guarantee the safety of the system. As mentioned above, thermal power plants are currently responsible for maintaining system stability thanks to the inertia of their synchronous machines and their short response speed. However, over the next few years, this type of non-renewable power plant will be eliminated from the system to meet decarbonization objectives and, therefore, alternatives will have to be sought to cover the role played by thermal power plants in guaranteeing system stability thanks to frequency control.

Batteries with grid-forming inverters will play a key role in this respect to be able to dispense with non-renewable power plants and guarantee the stability of the system from renewable energy sources.

Grid-forming inverters are electronic devices that generate frequency and voltage signals to emulate the characteristics of a traditional electrical grid. These inverters use advanced control algorithms to regulate the output frequency and voltage, thereby maintaining system stability. Control is based on feedback from the grid and the inverters' ability to respond to changes in demand and generation. The role of this technology in the electricity system will be analyzed in more detail in section 3.4.

3.3. IMPACT OF PENETRATION OF INTERMITTENT RENEWABLES IN THE ELECTRICITY SYSTEM

This section of the master's thesis delves into a comprehensive analysis of the impact generated by the increasing integration of non-manageable renewable energies into the electric system. This phenomenon, characterized by the expansion of generation sources such as solar and wind power, poses challenges both from a technical perspective, related to the operational stability of the system, and from an economic perspective, concerning fluctuations in electricity prices during periods of peak renewable generation [13].

Technical Perspective: Electric System Stability

The stability and reliability of an electric system are fundamental elements to ensure a continuous and efficient supply of electric power. However, the growing incorporation of non-manageable renewable energy sources introduces a new dynamic into this equilibrium [11]. Solar and wind generation technologies are highly dependent on unpredictable environmental factors, such as solar radiation and wind speed, introducing significant variability in energy production. The direct consequence is the difficulty in accurately anticipating generation levels and, consequently, adjusting them to match demand at all times [11].

The real-time matching of electric demand with non-manageable renewable energy generation becomes a complex technical challenge [13]. To counter this variability, system operators implement ancillary services that act as safeguards against imbalances between generation and demand. These services, under the control of regional or national grid operators, include backup generators that can inject or absorb energy according to the ever-changing needs of the system. As the proportion of non-manageable renewable energy increases, the deployment

and efficiency of these adjustment services become crucial points to ensure the stability and security of the electric supply.

Economic Perspective: Fluctuations in Electricity Prices

The expansion of installed solar generation capacity, while environmentally beneficial, has economic repercussions that warrant in-depth analysis. Since generation plants bid at the opportunity cost, and the opportunity cost for renewables is zero as they depend on non-manageable natural resources, wind for wind power and sunlight for solar power, they offer at zero or very close to zero cost to ensure their participation in the pool. For these plants, it is preferable to produce regardless of the clearing price in the market than to miss the opportunity to generate. This leads to a noticeable decrease in electricity prices [13] in wholesale markets during periods of high solar generation.

However, this apparent price reduction does not satisfy all stakeholders involved. Most consumers experience peak demand hours that extend beyond the hours of solar generation, so they do not directly benefit from this price drop. Simultaneously, developers of solar projects face a challenging landscape, as reduced prices during solar generation hours imply a reduction in their potential revenues. The escalation of installed solar capacity intensifies competition in the market [13], leading to situations where supply surpasses demand, making the sale of solar energy more difficult, especially for projects that have not secured long-term agreements with buyers.

In summary, the increased participation of non-manageable renewable energies in the energy matrix entails a series of technical and economic implications for the electric system as a whole. The stochastic nature of solar and wind generation and fluctuations in electricity prices during renewable generation hours are critical aspects that require careful attention in the planning, operation, and regulation of the electric system to ensure its sustainability and proper functioning.

3.4. THE ROLE OF GRID-FORMING INVERTERS IN CONTEXTS OF HIGH PENETRATION OF RES

Presently, the constant evolution of electrical systems towards greater sustainability and efficiency has given rise to innovative technologies, among

which GFMI, also known as grid-forming inverters, hold a prominent position [14]. These specialized electronic devices have emerged as essential components to ensure the reliable and optimal operation of modern electrical systems, particularly in an environment characterized by the increasing integration of renewable energy sources and dynamic electrical demand.

The primary function of GFMI lies in their ability to precisely and controllably emulate the fundamental characteristics of a conventional electrical grid [14]. This essential achievement enables various sources of generation and load systems to operate in a synchronized and coordinated manner, creating a delicate balance that is crucial for the reliability and stability of the entire system [11]. This aspect gains even more significance in a scenario where energy sources are becoming increasingly diverse and variable.

The engineering behind GFMI relies on a combination of advanced hardware and highly sophisticated control algorithms [14]. Control algorithms play a pivotal role by operating in real-time, regulating both the frequency and voltage output of the inverters. This capability is of vital importance to ensure precise synchronization between generation and load, thus preventing imbalances in the system and maintaining operational coherence.

Particularly concerning frequency regulation, its importance for the reliable operation of the electrical grid becomes evident. GFMI must be capable of adjusting the speed of generators and electric motors [14] in response to changes in demand and generation to maintain frequency at optimal levels. This results in a smooth and stable operation of the entire electrical system.

Feedback from the electrical grid forms the cornerstone of GFMI operation. Through constant monitoring, these devices gather vital information about frequency, voltage, and other relevant grid parameters [15]. This information is leveraged to adjust the operational parameters of the inverters, enabling an instantaneous response to changes in demand and generation. The ability of GFMI to maintain coherence with the existing grid, even under changing and dynamic conditions, is essential for ensuring the overall stability of the system [14].

The versatility of GFMI is also highlighted by their ability to respond to fluctuations in electrical demand and generation. These devices must be agile in adapting to

16

variations in load and the availability of generation, needing adjustments to their output to maintain balance and prevent potential challenges such as frequency drops or overvoltages [15]. This feature is particularly valuable in systems with a significant proportion of intermittent renewable energy sources, where conditions can change rapidly. Furthermore, ensuring protection against overcurrents and extreme events remains a top priority in the development and application of this technology.

In conclusion, GFMI represent a key innovation on the path towards more resilient and adaptable electrical systems. Their ability to generate controlled voltages and maintain coherence in terms of frequency and voltage positions them as essential components in the operation of contemporary electrical systems. This is of particular significance in contexts where the incorporation of renewable energy sources is increasingly prominent. With advanced control algorithms and the capability to respond to dynamic changes, GFMI contribute to maintaining stability and coherence in an environment characterized by the complex interaction between energy generation and consumption.

Chapter 4. BUSINESS PLAN

4.1. UTILITY-SCALE BESS BUSINESS MODEL

4.1.1. Configurations of Utility-scale Batteries

Utility-scale batteries can be incorporated into the electricity system in two different configurations: the stand-alone installation, and the hybridization configuration.

Stand Alone configuration

The stand-alone configuration involves the installation of energy storage systems as independent entities, without a direct link to a specific generation source or a particular load [11]. In this case, the battery installation is connected to the grid, charging when prices are low and injecting energy when prices are higher. Figure 3 shows graphically the stand-alone configuration, the installation consists only of the battery array, an inverter, and a power line that connects the battery to the grid and allows the exchange of energy.
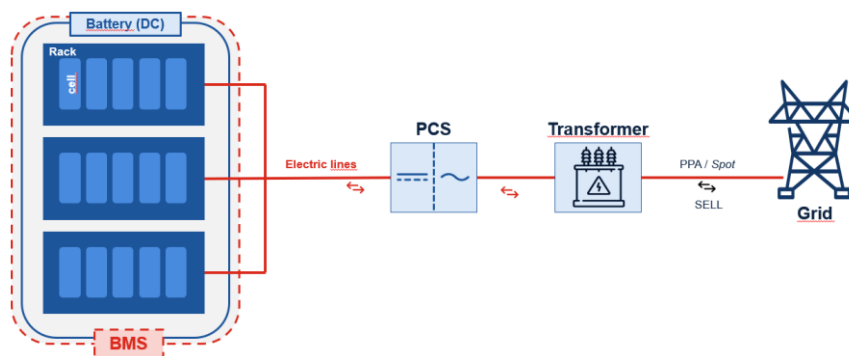
Figure 3. Stand Alone configuration scheme

One of the main advantages of this configuration is its flexibility and versatility. As these installations are not tied to a specific generation source, they can be located in strategic locations on the grid, such as areas with high solar energy penetration, maximizing their capacity to respond to changing situations.

However, an inherent challenge in this configuration lies in the need to manage and coordinate the operation of the batteries efficiently, as their autonomous operation implies precise planning and control. In addition, the initial investment

and costs associated with stand-alone batteries can be significant, requiring careful cost-benefit analysis.

Hybrid configuration

The hybridization configuration, on the other hand, involves the integration of energy storage systems with specific generation sources, such as solar or wind power plants. In this arrangement, batteries are directly connected to the generation infrastructure and, in some cases, may also be linked to specific loads. A standard schematic of a battery installation hybridized with a PV plant and connected to the grid is shown in Figure 4.
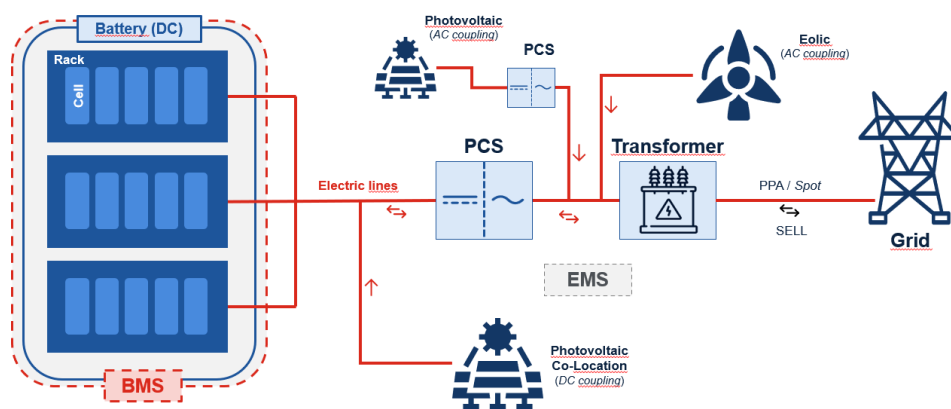

Figure 4. Hybridization configuration scheme

This configuration offers significant advantages in terms of resource utilization and efficiency [11]. By working in conjunction with renewable generation sources, hybrid batteries can store excess energy at times of high production and release it when demand is higher or when weather conditions are not favorable for renewable generation. This not only optimizes the use of sustainably generated power but can also reduce the need for costly investments in transmission and distribution infrastructure.

However, the hybridization configuration also brings challenges. Precise coordination and control between batteries and generation sources is crucial to ensure efficient operation. In addition, the implementation of storage systems in existing generation facilities may require significant infrastructure modifications, which must be considered in terms of costs and logistics.

In conclusion, the choice between stand-alone and hybridization configurations for Utility-scale battery integration in power systems depends on several factors,

19

including specific operational objectives, grid conditions, and economic considerations. Both approaches offer unique advantages and challenges, and their selection must be supported by detailed analysis and careful planning to maximize benefits and efficiency in grid operation.

4.1.2. Sources of income of a BESS

In terms of their economic model, utility-scale batteries today derive their revenues from 3 main sources [11]: 1) through price arbitrage, buying electricity when it is cheaper and selling it when the price is high; 2) through their participation in balancing services, helping to match generation and demand; or 3) from other regulated revenues, such as payments for guaranteeing back-up (capacity markets).

Price arbitrage

Batteries manage to obtain a margin through arbitrage between peak and off-peak hours, i.e. buying when electricity is cheaper and there is more supply, and selling when there is less supply and the price is higher [11]. This margin is highly dependent on daily production and demand and will be reduced in the future as the price curve flattens with the entry of more solar and battery capacity [11].

It is worth noting that price arbitrage is especially linked to the introduction of large solar PV capacity, as it generates large price differences between the hours of the day when it comes in to generate because there is sun and the hours when there is not. Batteries can take advantage of this differential [11], while contributing to flattening the price curve and improving the performance of PV plants.

Thanks to this arbitrage, batteries will contribute to the flattening of the demand curve, buying energy during the hours of higher photovoltaic generation and selling it during the hours of higher prices, a situation that is reflected graphically in Figure 5.
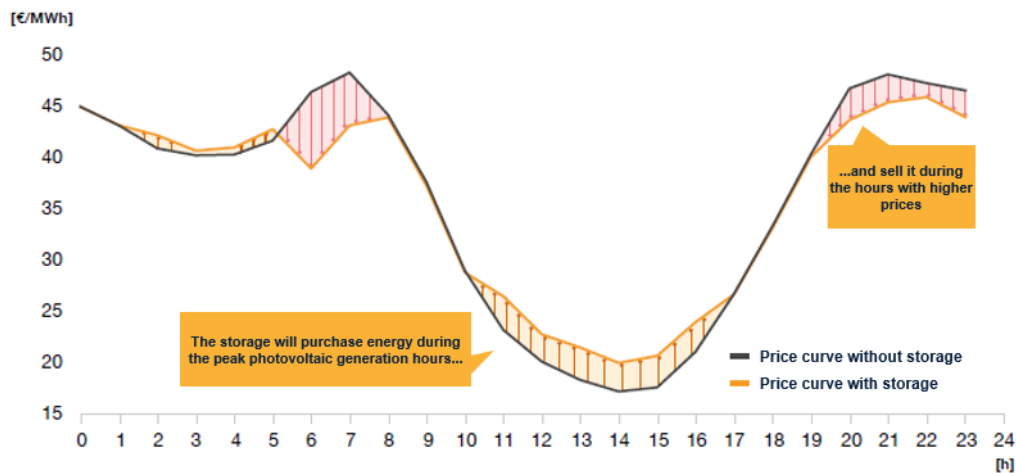
Figure 5. Illustrative price curve with and without storage [11]

Balancing services

Another source of revenue from batteries, as mentioned above, is adjustment or system regulation services. These services are regulated by the system operator and are used to ensure that the supply and demand for electricity remain balanced at all times [11]. These services are essential to maintain the security and stability of the electricity system, as fluctuations in demand and generation can cause imbalances that could lead to blackouts or interruptions in power supply.

Storage systems, thanks to their ability to inject and store energy quickly, can be remunerated for coming on or offline at exactly the right time to match production and demand or to regulate the frequency of power supply.

Next, we will explain the balancing services currently provided by BESS, which are as follows: Primary Regulation, Secondary Regulation, and Tertiary Regulation.

Primary Regulation is a decentralized frequency control carried out by grid-connected generators with the capability to provide it. Certain generators can offer significant primary regulation due to their inertia, measuring the deviation between the actual frequency and the theoretical grid frequency (50 hertz in the ENTSO-E area) and counteracting the deviation by decreasing or increasing their electrical generation within the first 20 seconds. Subsequently, centralized regulation systems come into play to compensate for the excess or shortfall in generation, respectively [16]. BESS with GFI are capable of providing this service as they have available energy that provides inertia to counteract changes.

21

Currently, this service is mandatory but not remunerated in the Spanish electrical system, thus it does not represent an additional cost to the supplied demand.

On the other hand, secondary regulation is a centralized supplementary frequency-power regulation service that operates between 20 seconds and 15 minutes of the imbalance. At this point, generators no longer act independently as in primary regulation; instead, the regulation setpoint is calculated by a central system called the Peninsula Shared Regulation (RCP), managed by Red Eléctrica de España. Its mission is to maintain the target frequency of the grid and the scheduled energy exchanges in international interconnections with other countries [16]. This service is enabled at the discretion of the generator facilities that meet the enabling requirements and is offered obligatorily by them. The day before the supply, following the daily market and the technical restrictions process, authorized producers submit their available power fluctuation range, receiving compensation for it [16].

Finally, tertiary regulation represents the third level of restoring the generation-demand balance, operating within a 15-minute horizon from the moment orders are given to participating generators in the service [16]. It is a system in which facilities participate through mandatory bids if they are enabled for the service, which is optional. Producers are compensated based on the price of the last bid accepted to meet the requirements [16].

There are other system balancing services, such as replacement reserves and additional power reserves to increase, which have not been considered in determining the economic model of BESS. Replacement reserves address local deviations between generation and demand, making them location-dependent, and therefore not considered. On the other hand, the additional power reserve to increase is a service created to schedule thermal producers that require several hours of advance notice to start generating electricity due to their lengthy startup processes. They can be scheduled to be available at their technically lowest viable production level and can be called upon in intraday markets or balancing mechanisms to cover deviations in demand scheduling or other generators. BESS do not face this issue, so it is not a service suited for this technology.

Capacity mechanisms

The integration of renewable energies into the system represents a significant challenge for system operators. Consequently, they are implementing various measures to support the integration of renewable technologies, including batteries, in the system's regulation.

This mechanism has been designed to counteract the gradual closure of thermal power plants, which poses a significant challenge for the electricity sector in ensuring generation to support periods when there is insufficient renewable resource to meet demand. Therefore, various mechanisms are being established to compensate certain technologies that can replace the role of thermal power plants, such as BESS, enabling them to earn benefits by simply reserving capacity to generate when needed.

In Spain, in 2021, the Ministry of Energy issued a Draft Order aimed at compensating the power availability of batteries, known as capacity markets. This involves a mechanism for allocating a "capacity" product by offering a limited amount of power within a specified period. Companies that offer their firm power at the lowest cost secure contracts within a defined time frame, as outlined in the auction terms, during which they receive revenue for making this power available to the system.

In conclusion, it is important to highlight that the analysis of battery projects operating in the market indicates that currently, between 30% and 70% of their revenue comes from participation in backup mechanisms or auxiliary services [11]. The profitability of these plants ranges from 4% to 23%, with lower returns when there is greater exposure to market prices [11]. Thus, pure price arbitrage cannot be the sole source of revenue for batteries. Other mechanisms, as discussed earlier, must complement them to ensure profitability for investors and to send appropriate price signals.

4.1.3. Costs Associated with Utility-scale Battery Installations

In the realm of Utility-scale battery installations, it is crucial to conduct a comprehensive cost analysis that encompasses both Capital Expenditures (CAPEX) and Operational Expenditures (OPEX). This analysis serves as a

fundamental framework for assessing the economic viability and sustainability of such energy storage systems.

Capital Expenditures (CAPEX)

- Cell Costs: This component pertains to the expense associated with procuring storage modules, including the batteries themselves. The choice of battery technology, its capacity, and its quality significantly influence this cost.

- Transformers and Inverters: The conversion of direct current (DC) energy stored in batteries into alternating current (AC) for grid integration requires the implementation of transformers and inverters. The capital cost here depends on system capacity and voltage requirements.

- Engineering, Procurement, and Construction (EPC) Costs: The planning, engineering, procurement, and construction phases entail substantial expenses. This includes the cost of designing the system, acquiring materials, and physically constructing the battery installation.

- Balance of System (BOS) Costs: BOS costs refer to the electrical infrastructure needed to interconnect the battery system with the grid. This includes wiring, switching equipment, protection systems, and other auxiliary equipment necessary for efficient operation.

Operational Expenditures (OPEX):

- Operations and Maintenance (O&M) Expenses: These ongoing costs cover routine maintenance and operational monitoring of the battery installation. They include expenses related to personnel, diagnostics, and the maintenance of critical components such as cooling systems and control systems.

- Warranty-Related Costs: Batteries often come with warranties that ensure performance and longevity. The cost associated with these warranties, including any claims or replacements, is considered an OPEX expense.

- CAPEX Replacement Costs: Over time, batteries may experience degradation, resulting in a reduced capacity. To maintain the nominal storage capacity and extend the system's lifespan, periodic replacements or

upgrades of battery modules may be necessary. These costs are categorized as OPEX expenses.

In conclusion, a comprehensive understanding of the cost structure for Utility-scale battery installations, encompassing both CAPEX and OPEX elements, is fundamental for project planning and management. This enables precise financial assessments, supports decision-making processes, and aids in the development of strategies to optimize the economic performance and reliability of these energy storage systems. Furthermore, as battery technologies continue to advance, ongoing cost analyses will remain essential to ensure the profitability of Utility-scale energy storage solutions in the evolving energy landscape.

4.2. ECONOMIC MODEL FOR THE PROFITABILITY STUDY OF BATTERY

This section of the paper focuses on the presentation and development of an economic model designed to assess the profitability of utility-scale battery installation projects. This model represents a fundamental tool for accurately discerning the economic viability of such projects. Its operation is based on the incorporation of various parameters, such as the technical specifications of the battery and hybrid plant, and the values of the relevant energy markets, among other crucial factors. The synergy of these inputs enables the generation of detailed economic projections, allowing a full assessment of the potential investment and facilitating informed decisions about the suitability of Utility-scale battery installation projects as investment opportunities.

4.2.1. Economic model inputs

The foundation of the economic model in question rests on a set of crucial inputs, which are essential for the formulation and execution of the financial models that determine the profitability of utility-scale battery installations. These inputs can be divided into two main categories: project-specific variables, such as the technical characteristics of the battery and the generating plant that is coupled to the battery, and constant, unchanging data, such as electricity prices, macroeconomic indicators, and the regulated revenues and costs inherent to each technology involved in the project. A summary of all model inputs by category is included in Table 2.

Table 2. Inputs BESS economic model

Installations	Storage batteries	BESS/PV capacity ratio, target grant, capacity, Capex, Opex, %curtailment
	Hydration plant	Technology, installed power, project start date, Capex, Opex, operating years...
Prices per activity covered	Stand Alone	Arbitrage, TR, SR, and RES charges
	Hybridized	Arbitrage, TR, SR, and grid charges
Economic model	Macroeconomics	CPI and discount rate
	Regulated incomes/costs	PaG, unbalanced costs, DdOs revenues

In the first group of variables, the specificity and uniqueness of each installation emerge as key elements. The parameters related to the battery installation, such as its capacity, efficiency, and lifetime, as well as the attributes of the hybrid plant, including its generation capacity and operation patterns, represent data that must be provided to the model and that vary from one project to another.

The second set of inputs, on the other hand, are the invariant elements that underlie the economic evaluation. Projections of electricity prices are crucial for estimating revenues. In addition, macroeconomic variables, such as interest rates and inflation, have a substantial impact on the financial viability of the project. Finally, regulated revenues and costs associated with the technologies used are also integrated as constant inputs for the analysis.

In the following, each of these input variables will be explored in more detail, revealing their importance and how they influence the economic evaluation process of utility-scale battery installations.

4.2.1.1. Facilities inputs

Among the input variables related to battery installations and the hybrid plant coupled with these batteries, several critical parameters stand out, directly affecting the project's profitability assessment. The following key variables will be detailed:

- BESS/PV Capacity Ratio (Battery installed power relative to Photovoltaic installed power): This ratio establishes the relationship between the battery's storage capacity and the photovoltaic generation capacity of the plant. This relationship determines how much energy generated by the photovoltaic system can be stored and utilized later. An appropriate ratio is crucial for optimizing battery utilization and ensuring maximum project profitability.
- Battery Storage Capacity: Battery capacity refers to the maximum amount of energy that can be stored within it. This capacity is typically expressed in kilowatt-hours (kWh) and is fundamental in determining how much energy can be stored and subsequently delivered to the electrical system when needed, although the model expresses it in terms of power, namely, megawatts.
- Service Life: The service life of the installation refers to the period during which the batteries and the hybrid plant are expected to function effectively before requiring replacement or significant renovation. This variable is essential for projecting cash flows over time and determining the investment's duration. Unitary Capex (Capital Expenditure Cost per Unit): Unitary Capex represents the initial investment cost per unit of installed capacity, whether for the battery or the photovoltaic plant.
- Required Subsidy: This variable refers to the capital needed to finance the project to make it viable. The required subsidy can have a significant impact on project profitability by reducing initial costs and increasing revenue.

Collectively, these variables define the technical and financial characteristics of the battery installations and the hybrid plant. They are essential for accurately calculating the economic viability of Utility-scale energy storage projects. Each one plays a critical role in economic modeling and strategic decision-making related to investments in such projects.

4.2.1.2. Inputs prices per activity covered

The unit revenues of the installation, which constitute an essential part of the inputs in the economic model, are intrinsically linked to the activity that the battery performs in the energy market. These revenues, expressed in k€/MW of capacity, represent the remuneration that the facility receives for offering its services

according to the different activities in which a battery can participate, which are: arbitrage, secondary regulation, and tertiary regulation.

The variability in these revenues is directly related to the versatility of the battery and its ability to adapt to changing market needs. Each activity involves a particular revenue structure, which depends on demand, supply, and market conditions at any given time.

In addition, the configuration of the installation also influences unit revenues. In case the battery is in a stand-alone configuration, network charges will apply, which will affect the net revenues generated by the installation. Conversely, if the battery is hybridized with a renewable generating plant, the charges related to renewable energy generation apply.

All the above factors have been considered in making the price projections, with the estimates being made by a specialized company whose source cannot be provided for data protection reasons.

4.2.1.3. Economic inputs

Within the economic inputs crucial for assessing the profitability of utility-scale battery installations, two fundamental categories stand out: macroeconomic variables and revenues/expenses related to regulated activities. These factors play a critical role in economic modeling and strategic decision-making. The following are these key elements:

Macroeconomic Variables

We find the Consumer Price Index (CPI) and the discount rate.

Revenues/Expenses Associated with Regulated Activities

- Payments and Grid (PaG): Payments and grid price refers to the combination of earnings a renewable energy plant gets from payment agreements and the price it sells electricity for in the market.
- Unbalance Cost: It is a cost incurred by the photovoltaic plant for deviating from its bid in the daily or intraday market.
- Guarantees of Origin: It is an income received by renewable plants for selling certificates that guarantee their energy is renewable. These

certificates are sold to electricity retailers that wish to offer clean energy to their customers. The system of guarantees of origin was created with the aim of boosting the profitability of renewables by adding an additional income stream to this technology.

Lastly, although not categorized specifically, we have the curtailment percentage, which is a critical factor to consider. As explained in other sections, curtailment represents the amount of energy generated by the battery installation that cannot be used or sold due to network restrictions or other limitations. Efficient management of this percentage is essential for optimizing project revenues and profitability.

All these inputs are essential for the accurate evaluation of utility-scale battery installation profitability. Incorporating these factors into the model allows for a more comprehensive representation of the financial dynamics of the projects and facilitates strategic decision-making.

4.2.2. Development of the economic model

After defining the inputs for the economic model, the next step involves formulating the calculations necessary to obtain the financial projections of the installation. In this case, we will estimate the Profit and Loss (P&L) statement and the project's cash flow. Once the economic estimates for the project are completed, a series of economic indicators will be calculated to assess the project's profitability and feasibility.

The following section will provide a detailed explanation of the calculation methodology employed in the model to determine the P&L and cash flow of the project.

4.2.2.1. Estimating the P&L

Calculating the project's revenues and costs over its lifecycle is crucial for evaluating the installation's profitability. This account encompasses revenue from sales, production costs, operating expenses, interest, and other financial elements that impact the company's financial results.

Firstly, focusing on the company's revenue, there are two possible ways to generate income depending on the configuration of the installation:

1. Revenue associated with activities performed by the battery installation: As mentioned earlier, BESSs can engage in price arbitrage, participate in ancillary services, and capacity markets. However, the latter has not been considered in the model as it is not entirely defined currently, and there is no database with prices to determine its remuneration.

2. Revenue associated with activities performed by the hybridized plant: These revenues only occur in the case of hybrid projects. They are the benefits obtained by the solar or wind plant through certain mechanisms such as merchant revenues or the sale of guarantees of origin.

Revenue associated with BESS

The revenue associated with the battery installation depends solely on the battery's capacity (MW) and the activities it carries out during its operation. The model allows for automated calculations based on the selected activities using a selection panel that includes the three possible activities the battery can cover:

- Arbitrage
- Arbitrage + Tertiary Reserve
- Arbitrage + Tertiary Reserve + Secondary Reserve

The estimates of unit revenues in k€/MW of battery capacity associated with each activity have been obtained from a study conducted by a company whose name cannot be disclosed due to data protection regulations.

Annual revenues are calculated by multiplying the battery's capacity by the income associated with the activities covered by the battery.

Revenue associated with the hybrid plant:

The revenues of the hybrid plant will vary depending on the technology of the generation plant, i.e., they will vary depending on whether it is a solar plant or a wind farm. The revenues of the hybrid plant include merchant revenues and those associated with the sale of guarantees of origin.

Once the annual revenues of the installation are estimated, we proceed to calculate the fixed and variable costs of the project. Similar to revenues, costs will vary depending on the plant's configuration, with some costs associated with the battery installation and others with the hybrid plant.

Among the fixed costs, the investment in the battery installation and the hybrid plant (if it exists) stands out. Operating costs include land cost (in the case of leasing), insurance, legal expenses, and administrative and management expenses of the plant. After estimating project revenues and expenses, we obtain EBITDA, amortization and depreciation, and EBIT of the installation.

Table 3. Summary of Revenues and Expenses for BESS Installations

Benefits	Stand alone	BESSs revenues
	Hybrid	BESSs revenues
		Merchant Revenue
		GdOs revenues
Costs	Stand alone & hybrid	O&M cost
		G&A
		Insurance
		Land
		IBI
		IAE
		BESS O&M cost

In Table 3, all revenues and expenses are summarized based on the configuration of the installation.

Once the project's revenues and expenses have been estimated, we calculate the EBITDA, amortization and depreciation, and EBIT of the installation.

4.2.2.2. Cash Flow

After projecting the annual profit and loss (P&L) account of the project over its useful life, the project's cash flow is calculated based on the results obtained in the P&L. The primary objective of calculating the installation's cash flow is to determine the operational cash flows, which are essential for calculating various economic Key Performance Indicators (KPIs) to evaluate the investment's profitability.

Another significant aspect considered in the model is the possibility of including subsidies to finance the cost of battery installation, as such projects often have a portion of their capital expenditure (capex) funded through subsidies.

The economic indicators calculated to determine the project's feasibility include payback period, internal rate of return (IRR), and net present value (NPV) of the project. These indicators provide a quantitative assessment of the project's profitability and financial performance, aiding in making informed investment decisions.

4.3.1.   Model Analysis: Formulation of Different Scenarios

To analyze the model and determine the current profitability of utility-scale storage projects, several scenarios have been formulated, and the outcomes within each have been systematically evaluated. Two primary scenarios have been defined: one encompassing a standalone plant configuration, and another involving the use of battery systems to hybridize with photovoltaic plants.

Within the framework of these two scenarios, various parameters will be subjected to modification. These alterations include variations in the activities undertaken by the installations and considerations regarding the presence of financing. The results derived from each of the proposed scenarios will be used to calculate key economic indicators. Additionally, a sensitivity analysis will be conducted to assess how these results react to changes in the project's fundamental parameters, such as investment levels and the range of activities covered by the installations.

4.3.1.1.   Scenarios definition

The subsequent section provides an outline of the scenarios formulated to analyze the economic viability of battery projects. The initial scenario features a standalone plant configuration with a capacity of 30 MW and a battery lifespan of 15 years. Table 4 illustrates all the inputs considered for this scenario.

Table 4. Inputs scenario 1: Stand Alone BESS

Ratio capacity BESS/PV	*100%*
BESS Capacity (MW)	*30*
BESS useful life	*15*
BESS O&M cost (K€/MW)	*25,0*
Capex / BESS (M€/MW)	*0,9*

TV/BESS (% of total capex)	*10,5*
Capex / BESS (M€)	*117,0*
Target Grant % of Capex	*0,0*
Target Grant (M€)	*0,0*
Capex net of Grant (M€)	*117,0*

This will serve as the base scenario upon which several modifications will be implemented, specifically concerning the percentage of subsidized capex and the range of activities covered by the installation. The following variations, as outlined in Table 5, will be considered.

Table 5. Variations in Scenario 1

Scenario	Capacity BESS [MW]	Target Grant % of Capex	Acivity
Scenario 1.a	30	0	Arbitrage
Scenario 1.b	30	0	Arbitrage + TR
Scenario 1.c	30	0	Arbitrage + TR + SR
Scenario 1.d	30	25	Arbitrage + TR + SR
Scenario 1.e	30	50	Arbitrage + TR + SR
Scenario 1.f	30	75	Arbitrage + TR + SR

In the second scenario, a hybrid plant is considered, consisting of a 30 MW battery installation and an existing 150 MW photovoltaic plant. The battery specifications remain the same as in the first scenario, while the details of the photovoltaic plant are outlined in Table 6.

Table 6. Inputs PV plant

Tech	*PV*
Project Name	*Scenario 2*
COD	*2023*
MW	*150,0*
EOH	*1200,0*
Capex M€/MW (Year COD -1)	*0,0*
O&M cost k€/MW	*20,0*
G&A k€/MW/Y	*0,0*
Insurance during operation €/MW/Y	*0,0*
Land €/MW/Y	*0,0*
IBI €/MW	*0,0*
IAE €/MW	*0,0*
Annual degradation	*0,5%*
Income tax rate	*25,0%*

Average D&A annual rate%	3,3%
TV (% of total capex)	10,0%
Ke unlevered full merchant	5,2%

As in scenario 1, in this case, various scenarios will be considered, altering the amount of subsidy and the activities carried out by the BESS. The key data for the cases proposed in the second scenario are detailed in Table 6.

Table 7. Variations in scenario 2

Scenario	Capacity FV [MW]	Capacity BESS [MW]	Target Grant % of Capex	Acivity
Scenario 2.a	150	30	0	Arbitrage
Scenario 2.b	150	30	0	Arbitrage + TR
Scenario 2.c	150	30	0	Arbitrage + TR + SR
Scenario 2.d	150	30	25	Arbitrage + TR + SR
Scenario 2.e	150	30	50	Arbitrage + TR + SR
Scenario 2.f	150	30	75	Arbitrage + TR + SR

4.3.1.1. Analysis of scenario results

In this section, the results of the previously outlined scenarios are detailed, drawing the main conclusions regarding the profitability of utility-scale storage projects.

Table 8 presents the results of the key economic indicators for the various scenarios considered.

Table 8. Scenario results

Scenario	Payback (Years)	TIR (%)	VAN (M€)
Scenario 1.a	0	-8,00	-28,37
Scenario 1.b	0	-6,27	-22,23
Scenario 1.c	0	-0,63	-9,84
Scenario 1.d	0	1,78	-4,54
Scenario 1.e	12	5,71	0,77
Scenario 1.f	7	12,66	6,07
Scenario 2.a	26	3,04	-4,79
Scenario 2.b	18	4,98	-0,04
Scenario 2.c	10	9,82	10,64
Scenario 2.d	8	13,75	15,73
Scenario 2.e	5	19,71	20,78
Scenario 2.f	3	28,82	25,83

Upon analyzing the results of both scenarios, it becomes evident that utility-scale storage projects, with the existing mechanisms currently in place, are not profitable without subsidies, regardless of the activities they engage in. Only in specific cases where a profit-generating generation plant is hybridized can it contribute to making the project viable. However, it can be concluded that the primary means of making storage projects economically viable is through subsidies.

This situation aligns with the package of funds that the European Union has introduced to finance such technologies, known as the Next Generation EU funds, which will play a pivotal role in the short to medium-term future of storage. Nevertheless, to achieve the ambitious goals set in the latest update of the NIECP (22 GW of storage by 2030), mechanisms must be introduced to enable BESS to generate the necessary income to be economically viable without the need for subsidies.

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