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OFFICIAL MASTER'S DEGREE IN THE ELECTRIC POWER INDUSTRY

MASTER’S THESIS

Energy storage systems and its integration in Iberian electricity Wholesale market

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ABSTRACT

This Master Thesis project delves into the profitability and impact of energy storage systems in the Iberian day-ahead electricity market, driven by the increasing implementation of renewable generation systems and the EU's "Fit for 55" package for a sustainable, zero-emission future. The main objectives are to assess the profitability of various ESS technologies, predict the evolution of day-ahead market prices with increasing energy storage penetration, and analyze the impact of ESS on the thermal gap and the price electricity profile.

The study begins by introducing energy storage systems and their current global situation, The energy market context is explored, focusing on initiatives such as the Spanish INECP, the European “FIT for 55”, and market coupling mechanisms. Emphasis is placed on the significance of energy efficiency and decarbonization in achieving a sustainable future by discussing challenges related to renewable energy integration and CO_2 reduction are, highlighting the role of ESS in balancing the grid, integrating renewable sources, and supporting grid stability.

To achieve the objectives, the study develops a prediction model to forecast day-ahead market price evolution in an increasing energy storage penetration scenario. Additionally, an optimization model is implemented to assess the profitability of different ESS technologies obtain through the price arbitrage activity.

The results and observations section provides an in-depth economic analysis of BESS and PHS, including sensitivity analyses. The study also examines the impact of different ESS combinations on the system to optimize day-ahead market efficiency.

In conclusion, this Master Thesis offers valuable insights into the potential of energy storage technologies in the Iberian electricity market. It provides a comprehensive understanding of the profitability of various ESS technologies and their impact on electricity prices and the thermal gap. The research is essential for policymakers, investors, and stakeholders in the energy sector as they work towards a decarbonized and sustainable energy future.

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ABBREVIATIONS

BESS	Battery energy storage system
BTM	Behind-the-meter
CAPEX	Investment costs
ETS	Emissions trading system
ESS	Energy storage system
GHG	Greenhouse gases
IRR	Internal rate of return
MLRM	Multiple linear regression model
NPV	Net present value
OMIE	Iberian Electricity Market Operator
OPEX	Operational & maintenance costs
PCR	Price coupling of regions
PHS	Pumpes hydro storage
RES	Renewable energy resources
SDAC	Single-day ahead market coupling
TES	Thermal energy storage
TG	Thermal gap

1 INTRODUCTION

This initial chapter describes the motivations behind the election and development of this Master Thesis Project. In addition to this, the objectives of the project are clearly defined and outlined.

This research work has been developed for and with the collaboration of Iberian electricity market operator (OMIE).

1.1 Motivation

In the current energy situation, the increasing implementation of renewable generation systems in the electricity sector is a fact. This is following the proposed package by the EU "Fit for 55" for a green transition and decarbonization process for a sustainable, zero-emission future. In the past 15 years, the generation mix has changed from a predominant share of fossil fuel plants to a mix in which in most days the higher production percentage corresponds to renewables, even achieving a 70-80%.

The huge penetration of renewables is going to have, and is already having, an important impact in the wholesale market electricity prices in Spain. Since the variable costs of these technologies are extremely low, there is a direct relation between the increasing renewable plants installation and the decrease in the day-ahead electricity market price. On the other hand, traditional generation technologies have seen an increase in its production costs due to the extreme rise in natural gas and coal prices and the mandatory CO_2 allowances imposed by the EU. (European Comission, 2019)

These two extremes have resulted in a sharp demand curve shape showing an exorbitant difference between the highest and lowest prices. This problematic can be addressed by using energy storage systems to charge and discharge when prices show a sufficient spread in prices to cover their total costs, by doing this the demand curve can be reshaped in an efficient way and obtain a smaller spread in prices. This performance is already carried by pumped hydro storage systems, act as giant batteries and they account for the highest share of energy storage capacity globally. However, the diversification in other available ESS is needed, others that do not imply such a huge capital initial investment, have a higher efficiency and are not that environmental invasive. Lithium-ion batteries can be used in a variety of applications, from small residential buildings to public facilities.

Advances in battery technology have reduced costs, increased efficiency, and made them more competitive with pumped power plants. Ongoing research and development efforts focus on improving battery energy density, lifetime, and safety of the technology, as well as exploring new compositions, chemistry technologies and raw materials.

Widespread use of battery energy storage systems will increase the flexibility and reliability of the power grid. It enables rapid response to changes in demand and supply, helps integrate intermittent renewable energy sources in a shorter time horizon, raises their value, and supports grid stability.

The purpose of this master thesis is to study the profitability for energy storage systems investors when introducing them in the Spanish Wholesale electricity market, given the different technologies and an optimised electricity arbitrage behaviour. In addition to this an analysis of the impact of ESS in the evolution of the day-ahead energy prices and thermal gap throughout the years due to a major energy storage capacity, will be carried out.

The future of the electricity sector being based on the energy storage is a reality in the current situation, thus the relevance and interest of this thesis for obtaining a glimpse of what the path towards decarbonization implies.

1.2 Objectives of the Master Thesis

As stated in the introduction the major objective of this research work is to assess the profitability of energy storage technologies implemented in the Iberian day-ahead market and how these impact in the electricity prices and evolution of the thermal gap.

To achieve a deep and comprehensive analysis in depth the following points will be developed throughout the thesis.

- **Profitability for each ESS through its lifetime:** Exhaustive research will be carried out to identify the most relevant techno-economic parameters for each energy storage technology (BESS and PHS). This information will be taken out and gathered from different articles, past projects and even (in the case of batteries) the manufacturer’s webpages. This will conclude, given its characteristics and the current situation of the sector, in which ESS an agent should invest its money. An optimization model will be implemented to study this aspect.

- **Predict day-ahead market prices as storage penetration increases:** Once the evolution of the thermal gap curve is studied, it is relevant to examine and predict how prices will evolve as penetration of energy storage increases. While it is normally expected that because of the penetration of renewable energy, electricity prices decrease, the penetration of energy storage technologies has a different impact. It is expected that there will be an increase in lowest prices and a decrease in the highest prices.
- **Evolution of the thermal gap as ESS penetration increases:** In addition to the economic analysis, it is important to study the effect that the increase in energy storage capacity has in the reduction in the usage of fossil fuels, this is, in the reduction of the thermal gap or price-dependent demand. The thesis will start with an analysis of an initial thermal gap, using information provided by OMIE and predict how it will be influenced by the penetration of ESS.
- **Impact of a mix ESS combinations in the system:** Finally, various mixes of energy storage systems will be introduced with the aim of studying the behavior of the system due to these incorporations. The purpose is to assess the different combinations and how it is maximised the efficiency of the day-ahead market.

The starting sections will provide an overview and review of the energy storage systems, including their characteristics and applications, as well as setting an understanding of the energy market context and its influence on ESS focusing on the initiatives like the Spanish INECP, the European “Fit for 55” and the market coupling mechanism.

The next chapter delves into the main targets for a decarbonized future economy: energy efficiency and decarbonization, studying the key points to discuss the challenges such as renewables integration and CO_2 reduction and the contribution of ESS to address them, among others. Consecutively, the model and the methods used in the study are described, delving in the input data, the mathematical fundamentals behind the prediction and optimization models, as well as the initial hypothesis. Lastly, the results and comments on the research will be presented, assessing the different ESS, and making relevant comparisons between them.

2 STATE OF THE ART REVIEW

This section delves into the state-of-the-art energy storage technologies that have proven to be highly influential in the energy landscape: pumped hydro and battery storage systems. We will explore the key characteristics, advantages, and challenges of these systems, shedding light on their vital contributions to modern energy storage solutions and their role in shaping a more sustainable and efficient energy future.

2.1 Introduction

Energy storage has emerged as a pivotal and critical element in the energy value chain, playing a vital role in enhancing grid stability, facilitating the integration of renewable energy sources, optimizing energy system efficiency, conserving fossil resources, and mitigating the environmental impact of power generation. These paramount factors have driven intensive research and development efforts in recent years, making energy storage a cornerstone of the ongoing energy transition.

One of the most significant applications of energy storage is electricity arbitrage, wherein storage devices capitalize on charging during periods of low electricity prices and discharging during times of high electricity prices. Depending on their technical characteristics, storage devices can actively participate in day-ahead or intraday markets or even both. Bulk energy services are frequently provided by large-capacity and slow discharge time electricity storage systems, such as pumped hydro, which effectively narrows the gap between peak and valley electricity prices by shifting low-cost electricity to peak demand periods. However, accurate simulations are essential to derive the true benefits of electricity arbitrage, as assuming perfect foresight of electricity prices might lead to an overestimation of its value. (Zhang, et al., 2021)

In systems with a high proportion of intermittent renewables, electricity prices tend to be low during hours with significant renewable energy generation, leading to energy storage predominantly contributing to smoothing out the net load. (IRENA, 2020)

2.2 Description of Energy Storage Systems

Currently, a diverse range of energy storage systems exists, serving distinct purposes that can be broadly categorized into two main groups. On one hand, there is electrical energy storage, which involves storing energy in the form of electricity, and on the other hand, there is thermal energy storage, where energy is stored and later released as heat.

Electricity, being one of the most readily accessible forms of energy, boasts a robust global infrastructure. Presently, the energy sector relies on centralized electricity production, with large-scale power plants situated at considerable distances from end consumers. However, the ongoing energy transition and decarbonization efforts are driving a notable shift towards decentralized and self-consumption-based energy solutions. This trend indicates that the existing centralized electric power system, predominantly reliant on fossil fuels, will be replaced by decentralized and renewable energy-based alternatives in the near future. (United States of America Department of Energy, 2011)

Managing electricity loads involves predictive analysis of daily and seasonal demand patterns derived from historical data. In scenarios where production falls short, specialized power plants are utilized to meet peak demand requirements. However, the increasing integration of renewable energy sources and the trend towards decentralization introduce challenges in stabilizing the energy grid due to intermittent generation and imbalances between supply and demand.

The aforementioned trends and challenges underscore the need for developing, implementing, and utilizing energy storage systems. Directly storing raw electricity is not feasible; hence, conversion into a more stable form of energy becomes essential, allowing for re-conversion back into electricity when required.

Researchers are exploring various storage applications with the primary goals of cost reduction and enhancing system longevity. Nonetheless, challenges remain, particularly concerning initial capital investment and ongoing operational expenses, making cost-effectiveness a crucial consideration. Moreover, ensuring minimal negative environmental impact is a priority, prompting continuous efforts to develop environmentally sustainable storage solutions.

Electric energy storage systems can be classified into four main categories: mechanical storage systems, electrochemical systems, chemical storage systems, and thermal storage systems. (Olabi, et al., 2021)

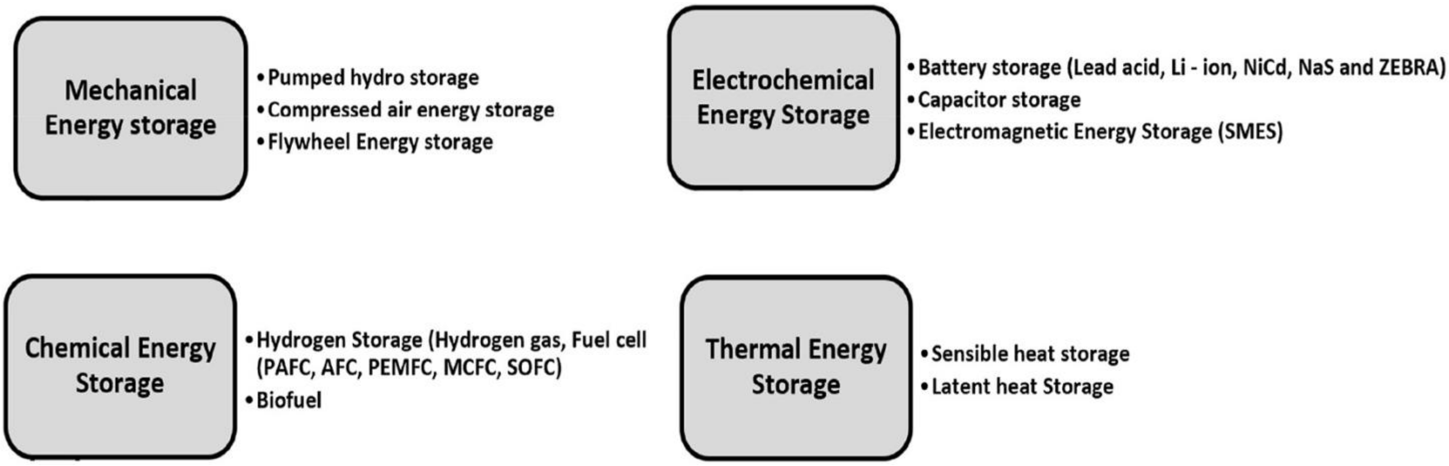

Figure 1. Classification of energy storage technologies (Olabi, et al., 2021)

Given their immense potential, technological maturity, and current significance in the electric market, the following will highlight the key characteristics of the most relevant ESS.

2.2.1 Pumped Hydro Storage Systems

Hydraulic Pumped Storage is the most widely adopted and commercially implemented option of energy storage nowadays. This energy storage system is currently the most widespread technology globally, covering approximately 90 percent of storage capacity in Europe. Additionally, its first large-scale use dates to the late 19th century, making this technology one of the most longstanding. (ESAE, 2021)

Applied in hydroelectric power plants, its remarkable flexibility and storage capacity enable its utilization for enhancing electricity production stability and mitigating the effects caused by the intermittency of other renewable energy sources like solar or wind.

The efficiency of pumped hydro storage systems relies on effectively managing the gravitational potential energy of water. During periods of low power demand, water is pumped from a lower reservoir to an upper reservoir. When power demand rises, the water flows from the upper reservoir to the lower one, driving turbines that generate electricity. The volume and elevation of the water determine the storage capacity for energy. This process involves pumping water uphill using off-peak electricity and then allowing it to flow downhill, activating the generator to produce electricity for power grids as required. (Olabi, et al., 2021)

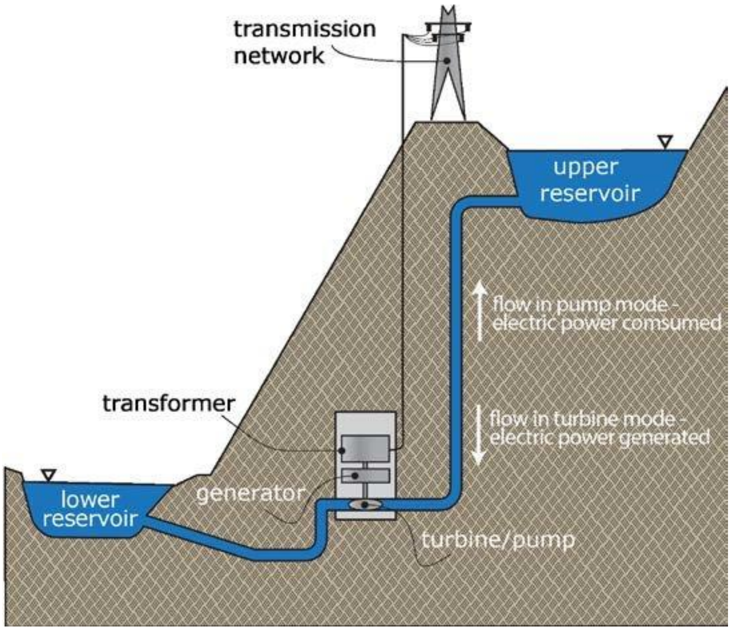

Figure 2. Schematic of pumped hydro storage system (Viadero, et al., 2017)

The volume and elevation of water are fundamental parameters in pumped hydro storage, but they also represent the primary limitations of this technology. Its operation is contingent on specific topographic characteristics, making widespread implementation challenging. The need for suitable geological conditions, such as the availability of two reservoirs at different elevations, restricts the potential locations for pumped hydro storage facilities.

Moreover, the construction of such facilities can have a significant environmental impact, often necessitating the creation of artificial reservoirs and the modification of natural landscapes. These alterations may disrupt ecosystems, affect local biodiversity, and lead to changes in water flow patterns and sediment transport, which can have cascading effects on aquatic life and vegetation. (EnergySage, 2019)

It is worth highlighting the capability of pumped hydro storage systems to safely supply large amounts of energy to the grid within short timeframes, typically taking around a minute to initiate regular discharge. Moreover, these systems exhibit efficiency levels ranging from 65% to 85%. These factors, combined with their relatively straightforward technical and economic design and implementation, have justified their status as the dominant energy storage technology to date.

Additionally, pumped hydro storage systems boast an extended operational lifespan, lasting approximately 50 years, and have achieved a high level of technological maturity. This stability, coupled with low-risk considerations for long-term energy storage, makes them an attractive choice for storing energy on a large scale, with the capacity to store energy in the order from tens to thousands of megawatts. (Olabi, et al., 2021)

2.2.2 Battery Energy Storage Systems

Energy storage in electrochemical batteries involves converting electrical energy into chemical energy through electrochemical reactions, which depend on the specific type of battery used. These batteries can be constructed in various sizes, ranging from less than 100 kW to 100 MW. Their cycle efficiency falls within the range of 80% to 95%, depending on the operating cycle and the type of reaction employed in the battery.

Nowadays, BESS ranks second globally in installed capacity for grid solutions, following pumped hydro and before thermal storage, with an approximate capacity of 8,3 GW. The most widely used types of electrochemical batteries in utility applications include lead-acid, lithium-ion, sodium-sulfur, nickel-cadmium, and flow batteries. (IRENA, 2017)

Notably, among all BESS, lithium-ion batteries hold the largest market share, with an installed capacity of 1,74 GW in grid solutions in 2020, showing a significant upward growth trend in the realm of electrochemical batteries. They are valued for their high efficiency, long lifespan, high power output, and impressive energy density, which have led to their rapid growth in recent years. However, the main challenge facing lithium-ion batteries is the high capital cost required for commercial use. (IEA, 2022)

BESS offers considerable potential for hybridization with renewable energy generation. They have a wide range of applications both in the electricity grid and for behind-the-meter or self-consumption purposes. On the grid, they can perform energy arbitrage and provide ancillary services during peak demand periods, among other functions. For BTM applications, they are often combined with photovoltaic installations to mitigate intermittency or serve as backup power sources, always aiming to reduce electricity costs. (Directorate General for Energy, 2020)

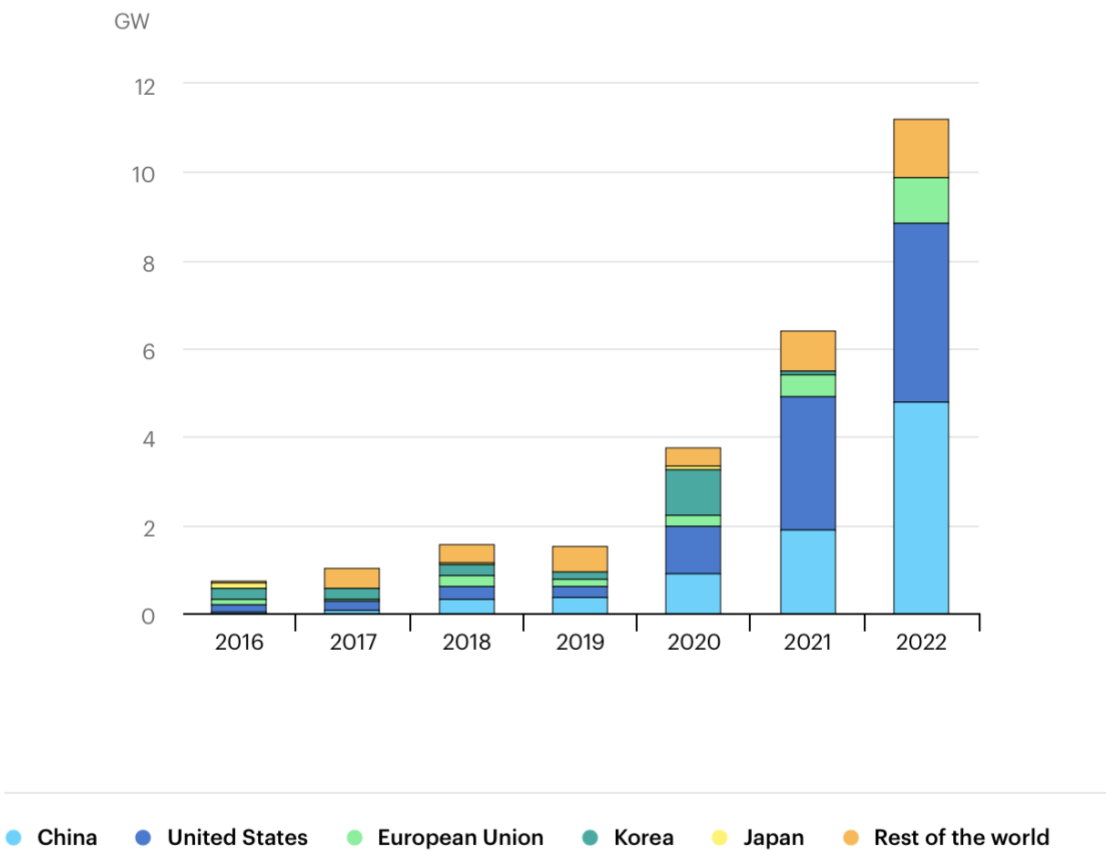

Figure 3. Annual grid-scale battery storage additions (2017-2022) (IEA, 2022)

Electrochemical Batteries are becoming a key technology in the energy transition. Notably, batteries are currently the fastest-growing ESS, with projections estimating hundreds of gigawatts of installed capacity by 2030. With this immense potential, they are expected to surpass pumped hydro storage as the leading energy storage technology in terms of installed capacity.

However, despite their promising prospects, one significant challenge still hinders their widespread adoption, their relatively high initial investment costs. While costs have decreased, attributed to economies of scale, especially for lithium-ion batteries, they remain significant and may present a barrier to their implementation on a larger scale.

Efforts are being made to address this challenge through ongoing research and innovation in battery technology, seeking further cost reductions and improvements in performance.

2.2.3 Thermal Energy Storage

Thermal Energy Storage ranks as the third-largest energy storage technology in terms of installed capacity, as it has been recently and slowly surpassed by the battery storage systems. Thermal storage systems store electricity or residual heat from industrial processes in the form of thermal energy. There are three main types of TES: sensible heat storage, which involves changing the temperature of a material; latent heat storage, where the material undergoes a change of phase; and thermochemical storage, achieved through thermally induced changes in the chemical structure of a compound. (IRENA, 2017)

TES is a promising technology that has the potential to significantly reduce reliance on fossil fuels. It finds extensive use in providing greater flexibility and stability in concentrated solar thermal power generation. However, its growth potential is currently limited by associated financing risks. TES projects often require substantial upfront investments, resulting in long return on investment periods and high capital costs.

Solar thermal power plants utilize TES systems to supply electricity to the grid during peak demand periods. Among the commercially dominant solutions for TES, molten salt technologies stand out, constituting approximately 75% of TES systems applied in the global electricity sector. Molten salts can store energy for an average of 9 hours, and some systems can reach up to 12 hours, effectively helping to balance energy supply and demand. Thermal energy storage exhibits a relatively low overall cycle efficiency, typically ranging from 30% to 50%. However, despite this drawback, TES offers several notable advantages that make it a valuable and useful technology. One such advantage is its high energy capacity, allowing for significant amounts of energy to be stored efficiently. One of the key benefits of TES is its environmentally friendly nature. TES systems utilize materials and processes that have minimal negative impacts on the environment, contributing to sustainable and green energy solutions.

Despite its advantages, the widespread adoption of TES faces challenges related to cost and financing. However, ongoing research and development efforts aim to improve the economic viability of TES, making it an increasingly attractive solution for enhancing grid flexibility and supporting the integration of renewable energy sources in the future energy landscape. (Olabi, et al., 2021)

2.3 Current Status of Energy Storage Systems

As seen in the following chart, while energy storage system projects are distributed relatively evenly across the world's developed countries, the storage capacity varies significantly between countries with higher installed power and those with less. USA leads the way with an installed capacity of 46 GW. Following the USA are China, Japan, Spain, and Germany, with 31,7 GW; 28,9 GW; 8,9 GW, and 8,3 GW, respectively. (DOE, 2023)

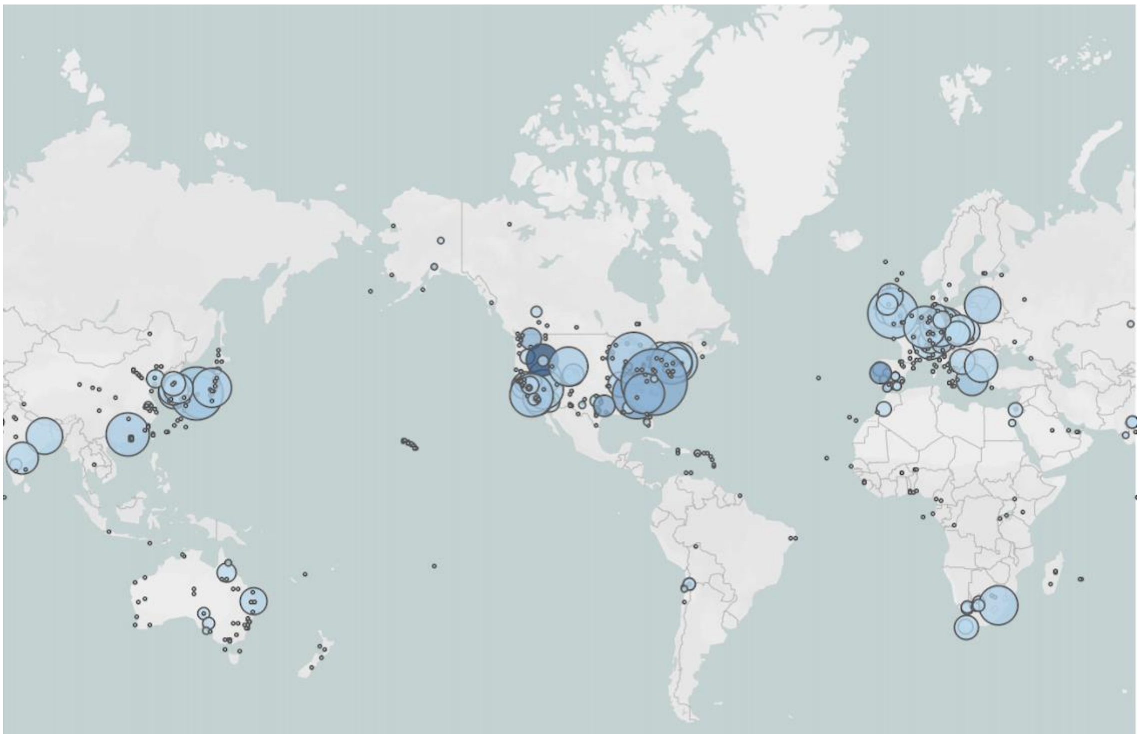

Figure 4. Global Map of Energy Storage Installations of year 2023 (DOE, 2023)

Although the previous information only includes grid-connected systems and excludes behind-the-meter or self-consumption devices, the provided information is valuable for analyzing the current state of these technologies on a global scale.

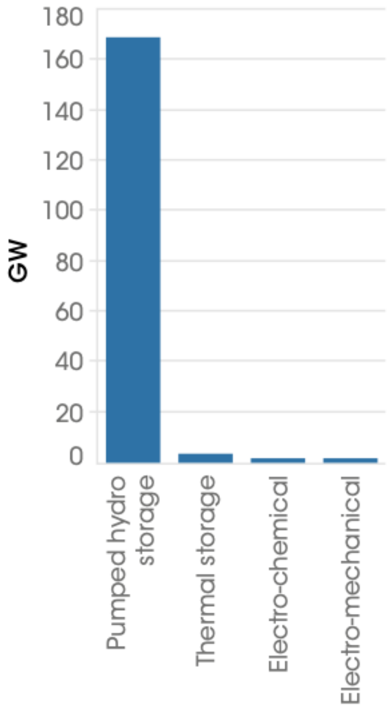

Figure 5.Global energy storage power capacity by technology group (2017) (IRENA, 2017)

It is noteworthy to observe the remarkable increase in BESS projects in recent years. In the graphic above, which dates to 2017, thermal storage held the second-largest position globally among energy storage systems. However, as of the current year 2023, batteries have surpassed thermal storage and now occupy the second position among installed ESS.

Additionally, pumped hydro storage maintains its leading position in terms of total installed capacity, with an impressive 178,02 GW of operational storage capacity. Nevertheless, as mentioned earlier and will be further analyzed, both batteries and hydrogen are expected to undergo significant growth in the upcoming decades. Currently, in the domain of grid services, batteries, and hydrogen lag considerably behind PHS, with 8,3 GW and 2,5 MW installed, respectively. Thermal Energy Storage now stands at the third position, with 3,1 GW of installed capacity. (DOE, 2023)

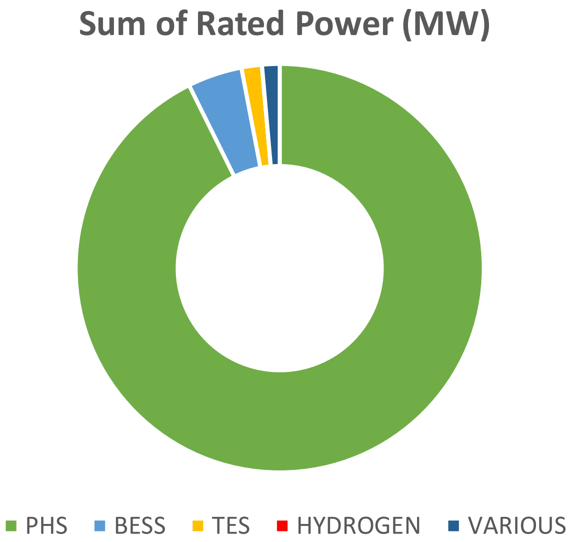

Figure 6. Global energy storage power capacity by technology group (2023)

3 ENERGY MARKET CONTEXT

The global landscape of energy markets is undergoing a transformative shift as nations and international organizations strive to address the pressing challenges of climate change, sustainability, and energy security. In this ever-evolving context, several initiatives have emerged to shape the future of energy markets, both at national and international levels. This section delves into three significant initiatives: "Fit for 55," the Spanish INECP plan, and the functioning of the European market coupling. Through these subsections, we will explore the objectives, strategies, and policies aimed at achieving emissions reduction, enhancing energy efficiency, and promoting the integration of renewable energy sources.

Energy storage solutions play a key role in each of these national and international initiatives, acting as enablers of sustainable, efficient, and flexible energy systems. By understanding the significance of energy storage in this rapidly evolving energy market context, we gain insights into the transformative potential of these technologies in shaping a cleaner, more sustainable energy future for nations and the global community.

3.1 FIT FOR 55

The "Fit for 55" package, proposed by the European Union in the year 2021, is a comprehensive and ambitious European set of proposals aimed at tackling the pressing challenges of climate change and achieving the European Union's commitment to a greener and more sustainable future. The “Fit for 55” name alludes to the EU’s target of reducing net greenhouse gas emissions by at least 55% by 2030. compared to 1990 levels, and ultimately reach climate neutrality by 2050. (Council of the European Union, 2023)

The following climate and energy EU targets for 2030 are outlined:

- 55% reduction in greenhouse gas emissions relative to 1990 levels.
- 40% of renewable energy resources in final energy consumption.
- 36% improvement in energy efficiency compared to 2005 levels.

One of the main pillars of the "Fit for 55" plan is the expansion of renewable energy sources and the promotion of energy efficiency. Amendments to the Renewable Energy Directive (RED II) aim to accelerate the transition to a greener energy system, setting a 2030 target of 40% energy production from renewable sources, with specific targets for renewable energy use in transport, heating, cooling, buildings, and industry. (European Commission, 2021)

Energy storage plays a critical role in the successful integration of renewable energy into the grid and ensuring a stable and reliable energy supply. The "Fit for 55" plan recognizes the importance of energy storage technologies, such as battery storage systems and pumped hydro storage, in balancing the variable nature of renewable energy sources like wind and solar. These technologies allow excess energy to be stored during periods of high production and then released when demand is high or generation is low, helping to match supply with demand and maximize the utilization of renewables. (Brozyna, et al., 2023)

The plan also emphasizes the importance of enhancing energy efficiency across various sectors. Energy-efficient buildings, transportation, and industries will play a pivotal role in reducing overall energy consumption and carbon emissions. The EU intends to improve energy efficiency by at least 36% by 2030, paving the way for a more sustainable and resource-efficient economy. Effort Sharing Regulation sets stricter emission reduction targets for each Member State, considering their GDP per capita and cost-effectiveness, focusing on buildings, road transport, domestic maritime transport, agriculture, waste, and small industrial sectors.

In addition to decarbonizing the energy sector, "Fit for 55" addresses emissions from transportation, which is one of the major contributors to greenhouse gas emissions. environmentally friendly. A new Regulation sets stricter CO_2 emission standards for cars and vans, requiring a 55% reduction in average emissions from new cars by 2030 and 100% by 2035, making all new cars registered from 2035 emission-free. The revised Alternative Fuels Infrastructure Regulation ensures increased charging capacity in proportion to zero-emission car sales.

To foster a just and inclusive energy transition, the plan emphasizes the importance of social policies and measures that support vulnerable communities and workers in industries affected by the shift to cleaner technologies. Ensuring a fair transition is at the core of the EU's commitment to leaving no one behind in this transformative journey. Furthermore, the "Fit for 55" plan recognizes the role of carbon pricing as an essential tool to incentivize emission reductions and steer investment towards low-carbon solutions. The package includes various measures, such as changes in the emissions trading system, aiming to further reduce carbon dioxide emissions and phase out free emission allowances for aviation while including shipping emissions for the first time in the EU ETS. (Deloitte, 2022)

Finally, the plan underscores the significance of international cooperation and engagement to tackle global climate challenges effectively. The EU aims to work closely with other nations, both in terms of sharing expertise and setting common and increasing goals to achieve a sustainable and climate-resilient world.

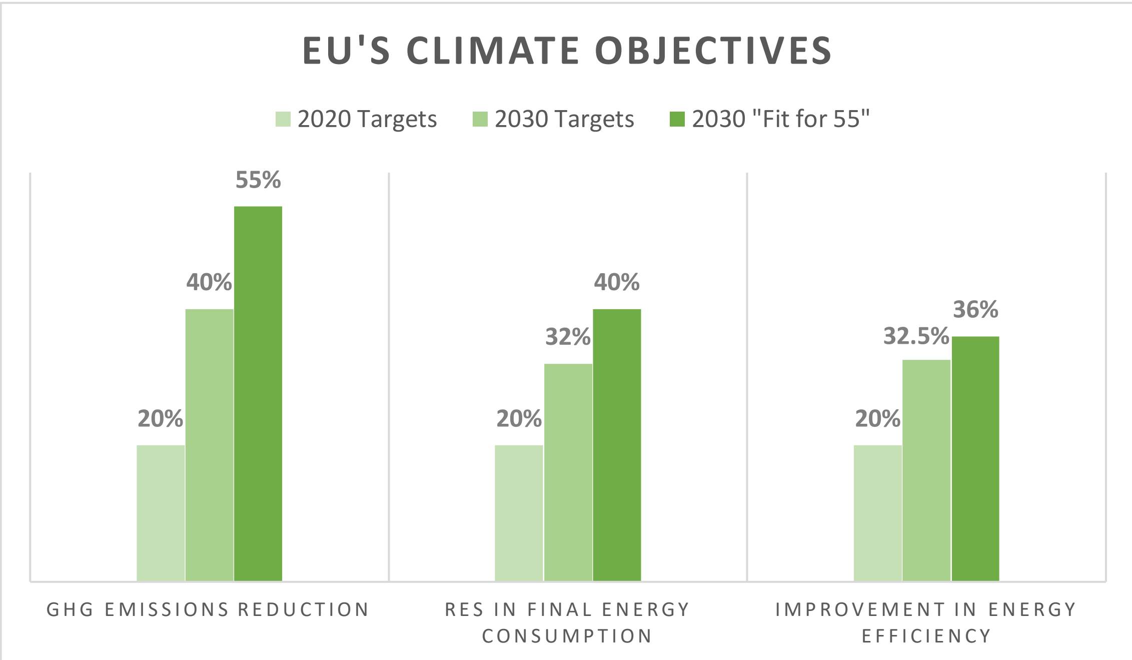

Figure 7. European Union Climate Objectives evolution (CEOE, 2022)

3.2 INECP

Within the context of national energy policies, Spain has developed its INECP, that stands for the Integrated National Energy and Climate Plan. This plan identifies the country's energy transition dimensions and strategies for the period from 2021 to 2030: decarbonization, energy efficiency, energy security, the internal energy market, and research, innovation, and competitiveness. Energy storage plays a pivotal role in balancing intermittent renewable energy sources, optimizing electricity distribution, and ensuring a stable and secure energy supply. As we examine the Spanish INECP plan, we will emphasize the critical contributions of energy storage in meeting Spain's energy goals and fostering a sustainable and climate-resilient future, following Europe’s climate neutrality.

The main goal of the plan is to increase Spain's energy self-sufficiency by efficiently harnessing the country's renewable potential, particularly solar and wind power. This would ensure national energy security by reducing the current dependence on fossil fuels, which are highly volatile due to geopolitical and macroeconomic factors, impacting the final price of electricity. The key objectives proposed by the INECP for 2030 are as follows:

- 23% reduction in greenhouse gas emissions relative to 1990 levels
- 42% of renewable energy resources in final energy consumption
- 39,5% improvement in energy efficiency
- 74% of renewable energy in electricity generation.

According to the plan, the total installed power capacity in the Spanish electrical system by 2030 will be 161 GW. This includes approximately 50 GW from wind energy, 39 GW from photovoltaic solar, 27 GW from combined cycles, 16 GW from hydropower, 9,5 GW from pumped hydro storage (pure and mixed), 7 GW from solar thermal energy, and 3 GW from nuclear energy. The actual share of each technology in the energy mix between 2021 and 2030 will depend on their evolving relative costs, viability, and flexibility of implementation. The plan also states that coal-fired power plants will cease operations by 2030 due to their environmental impact and difficulty competing with other technologies. (Ministry for Ecological Transition and the Demographic Challenge, 2020)

	Actual Scenario (MW)	Target Scenario INECP (MW)	
Year	2023	2025	2030
Hydro	17.097,22	14.359	14.609
Pumped storage	3.331,40	4.212	6.837
Nuclear	7.117,29	7.399	3.181
Coal	3.464,37	2.165	-
Combined cycle	26.250,15	26.612	26.612
Hydroeolian	11,32	11,32	11,32
Wind	30.279,41	40.633	50.333
Solar photovoltaic	21.595,03	21.713	39.181
Thermal solar	2.304,01	4.803	7.303
Other renewables	1.094,18	1.096	1.729
Cogeneration	5.639,22	4.373	3.670
Waste and others	595,78	470	341
Fuel + Gas, Gas & Steam Turbine	2.407,91	2.781	1.854
Storage	-	500	2.500
Total	123.210,27	133.152	160.191

Table 1. Installed capacity in MW. Actual scenario and INECP scenario (Ministry for Ecological Transition and the Demographic Challenge, 2023) (Red Eléctrica de España, 2023)

It can be observed that the actual installed capacity of some renewable resources already exceeds or almost reach the target scenario foreseen for year 2025. Between 2019 and 2022, renewable installed capacity in Spain witnessed significant growth, increasing by 27,3% from 2019 to year 2022. The most notable surge in generation came from solar photovoltaic sources, which experienced a remarkable 129% growth during this period, rising from 8,747 GW to 21,6 GW. Additionally, wind power capacity also saw a notable increment of 17.1%, climbing from 25.678 MW in 2019 to 30.279 MW in 2023. (Ministry for Ecological Transition and the Demographic Challenge, 2023)

The INECP aims for 74% of total electricity generation to come from renewables by 2030. Regarding battery energy storage, there are plans to have an installed capacity of 2,5 GW by 2030 to enhance generation operation, promote flexibility and demand management, integrate renewable energy into the system, and contribute to energy supply security. The plan also anticipates new regulations to govern the important role played by energy storage systems.

As for installed capacity, the Spanish government estimates that renewable energies will account a 72,93% of the total capacity in the target scenario by 2030. The energy storage systems, with an estimated 2.500 MW of capacity, excluding pumped hydro storage, will represent 1,55% of Spain's installed capacity in the objective scenario.

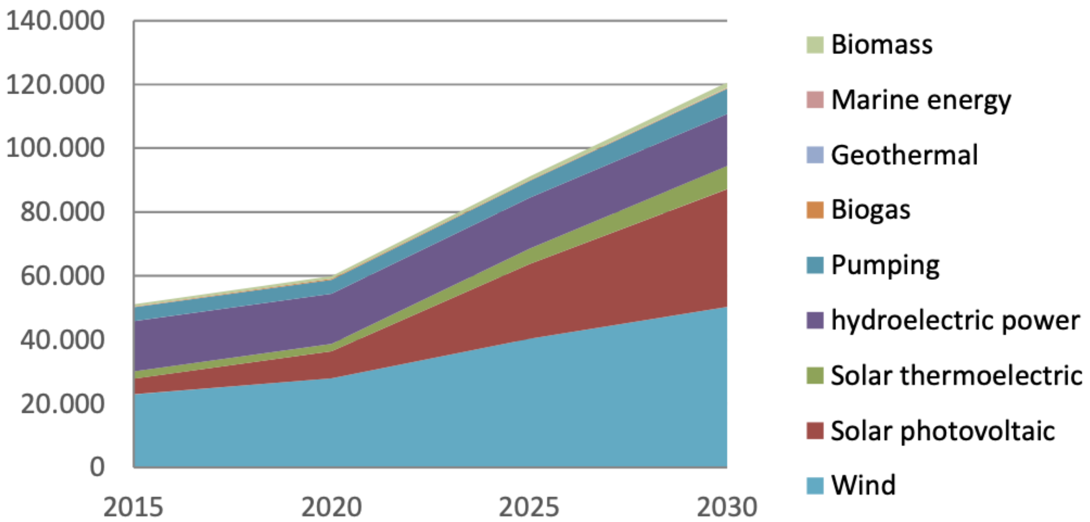

Figure 8. Installed capacity of RES (MW) (Ministry for Ecological Transition and the Demographic Challenge, 2020)

Regarding electricity generation, the INECP predicts that renewable energy will represent 76,96% of the total generation by 2030. The energy storage systems will also play a significant role, accounting for 3,46% of total electricity generation in the objective scenario by 2030, with a capacity of 11.960 GWh, including pumped hydro storage represented by turbine and pumping systems.

We acknowledge that the official INECP presented in the year 2020 is used as a reference for this project. However, it is important to note that in June 2023, a new draft for the INECP update has been introduced, featuring ambitious goals in coherence with the European context and the new proposals stemming from the "Fit for 55" and "REPowerEU" packages. The updated version aspires to add 105 GW of new renewable capacity by 2030, along with 22 GW of energy storage and the definitive closure of coal plants to 2025. The new updated INECP targets become: (Acosta, 2023)

- 32% reduction in greenhouse gas emissions relative to 1990 levels
- 44% of renewable energy resources in final energy consumption
- 42% improvement in energy efficiency
- 81% of renewable energy in electricity generation.

3.3 Market Coupling

A crucial element in achieving emissions reduction targets and ensuring an affordable and reliable electricity supply is the European Union's vision of creating a unified and interconnected electricity market. This vision is founded on the principle of market coupling, which involves the integration of individual national markets to enable seamless electricity trading across a vast geographical area. (Schönheit, et al., 2021)

Over the past two decades, the concept of a unified energy market in Europe has been put forth through the so-called Internal Energy Market. This strategy has three primary objectives in mind: ensuring affordable energy, enhancing competition within the European electricity market, and fostering environmental sustainability by promoting the integration of renewable energy resources. In the IEM's initial stages, the Price Coupling of Regions project has successfully interconnected the day-ahead markets of various countries, including GME in Italy, EPEXSpot which includes France, Germany, and Austria, APX in the Netherlands, Belpex operating in Belgium, Nord Pool Spot in the Scandinavian market, OTE in Czech Republic and in the Iberian Peninsula OMIE which are only some of them. (Lam, et al., 2018)

Figure 9. SDAC geographical scope (entso-e, 2023)

The single day-ahead market coupling has achieved remarkable progress, now involving 27 countries. With the recent addition of Bulgaria on March 2021, SDAC now covers more than 98% (equivalent to 1.530 TWh/year) of the European Union's electricity consumption. This significant expansion reflects the growing commitment to creating a unified and integrated energy market across the EU. (entso-e, 2023)

At the core of the PCR lies the development of a single market clearing algorithm, known as the Pan-European Hybrid Electricity Market Integration Algorithm, known as EUPHEMIA. EUPHEMIA serves the crucial function of calculating energy distribution and electricity prices across Europe. Its primary objective is to address the specific conditions of each participating power exchange simultaneously while delivering a solution within a reasonable timeframe. EUPHEMIA plays a vital role in achieving the seamless integration of Europe's diverse electricity markets, advancing the vision of a unified and interconnected energy landscape. (Lam, et al., 2018)

The effect of exporting and importing electricity due to market coupling is one of the significant outcomes of the integrated European electricity market. For exporting countries with surplus electricity generation, market coupling provides an opportunity to sell their excess power to neighboring countries. For example, countries with favorable renewable energy conditions, such as abundant wind or solar resources, can export their excess clean energy to regions with higher demand but less renewable capacity. By doing so, it facilitates the integration of renewable energy into the overall energy mix, leading to a more sustainable and greener energy system for the entire continent.

On the other hand, importing countries can benefit from market coupling by accessing electricity from neighboring regions when their domestic supply may be insufficient to meet demand. In this market integration framework, power flows in a more efficient manner, driven by economic principles. Electricity moves from regions with lower prices to areas with higher prices, resulting in a balancing effect on prices. Consequently, the overall average price level tends to decrease compared to pre-integration conditions. This process fosters a more optimal use of power resources, benefiting consumers and promoting a more cost-effective and competitive energy market. (Böckers, et al., 2013)

As the European electricity market coupling continues to expand and improve, the significance of energy storage technologies will only grow. Their ability to facilitate efficient energy use, support renewable integration, and provide essential grid services makes them indispensable components in achieving a truly interconnected and sustainable European electricity market.

4 ENERGY EFFICIENCY AND DECARBONIZATION

In the pursuit of mitigating climate change and achieving sustainable energy goals, the European Union has placed great emphasis on energy efficiency and decarbonization. These two interconnected pillars form the backbone of the EU's strategy to transition to a low-carbon, sustainable energy future. Within this context, energy storage systems play a critical role in addressing the challenges and complexities associated with energy efficiency and decarbonization.

4.1 Renewable energy penetration

Renewable power generation has made significant strides in the European power mix, currently accounting for 30% of gross generation. It is anticipated that these shares will further surge to 50% or more by 2030, primarily driven by the decreasing costs of renewable technologies and the ongoing decarbonization efforts in the energy system. The expansion of renewables is predominantly led by wind and solar power, both of which rely on variable natural resources, leading to fluctuating power output. (Barberi, et al., 2018)

As the reliance on non-dispatchable energy sources increases, the operation and structure of the electricity system will be significantly impacted. To effectively integrate and accommodate this new production, the deployment of appropriate flexibility technologies becomes imperative. These technologies play a vital role in counterbalancing the inherent variations in renewable energy output, always ensuring a constant equilibrium between supply and demand in the grid. By providing the necessary flexibility, these technologies contribute to grid stability and reliability, enabling the seamless integration of large-scale renewable power generation into the energy landscape.

These flexibility technologies are energy storage systems, such as batteries and pumped hydro storage, serving as crucial enablers of renewable energy penetration. They help mitigate the intermittency issue by capturing excess energy generated during peak renewable production periods and storing it for later use when energy demand exceeds supply. By providing a reliable backup, energy storage ensures that renewable energy can be dispatched to the grid consistently, enhancing grid stability and reducing the reliance on fossil fuels during low-renewable generation periods.

4.2 Renewable energy curtailment

One of the significant challenges during the energy transition is the potential overloading of the grid due to the increasing injection of renewable energy sources. This situation can lead to the exceeding of maximum permissible currents, jeopardizing grid stability. To address this issue, grid operators may resort to curtailment, which involves intentionally spilling excess energy from renewable sources to prevent grid instability.

However, curtailment results in the wastage of valuable renewable energy resources. To minimize this energy spillage and enhance grid stability, the use of congestion forecasts becomes crucial. By accurately predicting grid congestions and potential overloads, grid operators can proactively plan the integration of renewable energy and optimize the commitment of flexibility options, such as energy storage. (Memmel, et al., 2021)

When variable renewable resources production exceeds national demand and its surplus cannot be offset via energy storage systems, export or raised demand, it needs to be curtailed. Curtailment involves restricting intermittent renewable energy production when the system lacks the required flexibility to integrate renewables seamlessly.

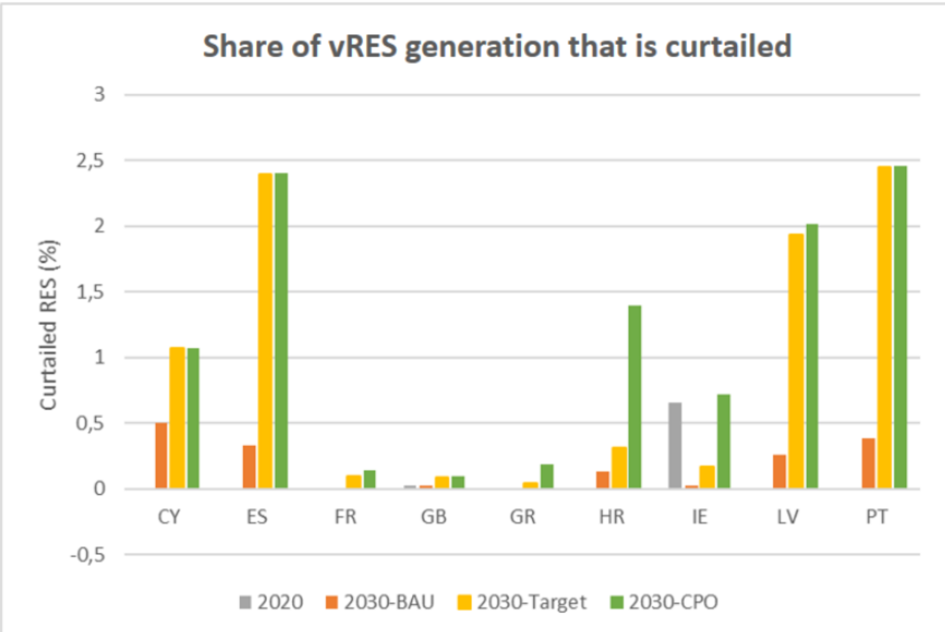

Figure 10. Percentage of curtailment across Europe (Barberi, et al., 2018)

A closer examination of the 2030-Target Scenario highlights significant quantities of renewable energy production being curtailed in Spain, reaching up to 3,9 TWh, and Portugal, mainly due to the high share of photovoltaic and wind production coupled with limited interconnection to the rest of Europe. This results, in *Figure 10*, shows nearly 2,5% of all variable renewable energy generation being curtailed. (Barberi, et al., 2018)

These forecasted curtailment levels underscore the importance of enhancing system flexibility and deploying efficient energy storage solutions to optimize the utilization of renewable energy resources and minimize wastage, thereby contributing to a more sustainable and efficient energy transition.

4.3 CO_2 Reduction

Reducing carbon dioxide emissions is at the forefront of the EU's efforts to combat climate change. The energy sector is a major contributor to CO_2 emissions, accounting for around 75% of the total emissions in the EU.

To combat and try to reduce greenhouse gases emissions produced by the energy sector the European emissions trading systems was implemented in year 2005. The EU ETS is a cornerstone of the EU's policy to combat climate change and its key tool for reducing greenhouse gas emissions cost-effectively. It is the world's first major carbon market and remains the biggest one.

The EU ETS operates on the principle of 'cap and trade.' A cap is set on the total amount of specific greenhouse gases that can be emitted by the covered operators within the system. Over time, this cap is progressively reduced to achieve overall emission reductions. Under the cap, operators can either buy or receive emissions allowances, which can be traded among each other as needed. The limited availability of allowances ensures they hold value. This price signal incentivizes operators to reduce emissions and encourages investments in innovative, low-carbon technologies. Additionally, trading allows for flexibility, ensuring emissions are reduced where it is most cost-effective to do so. This trading system nowadays covers around 40% of the EU's greenhouse gas emissions and will eventually also cover emissions from maritime transport from 2024.

At the end of each year, operators must surrender sufficient allowances to cover their emissions fully. Failure to do so results in heavy fines. If an installation reduces its emissions, it can retain spare allowances for future use or sell them to other operators in need of allowances. This mechanism promotes emission reductions across the system and creates economic incentives for adopting cleaner technologies and practices. (European Commission, 2023)

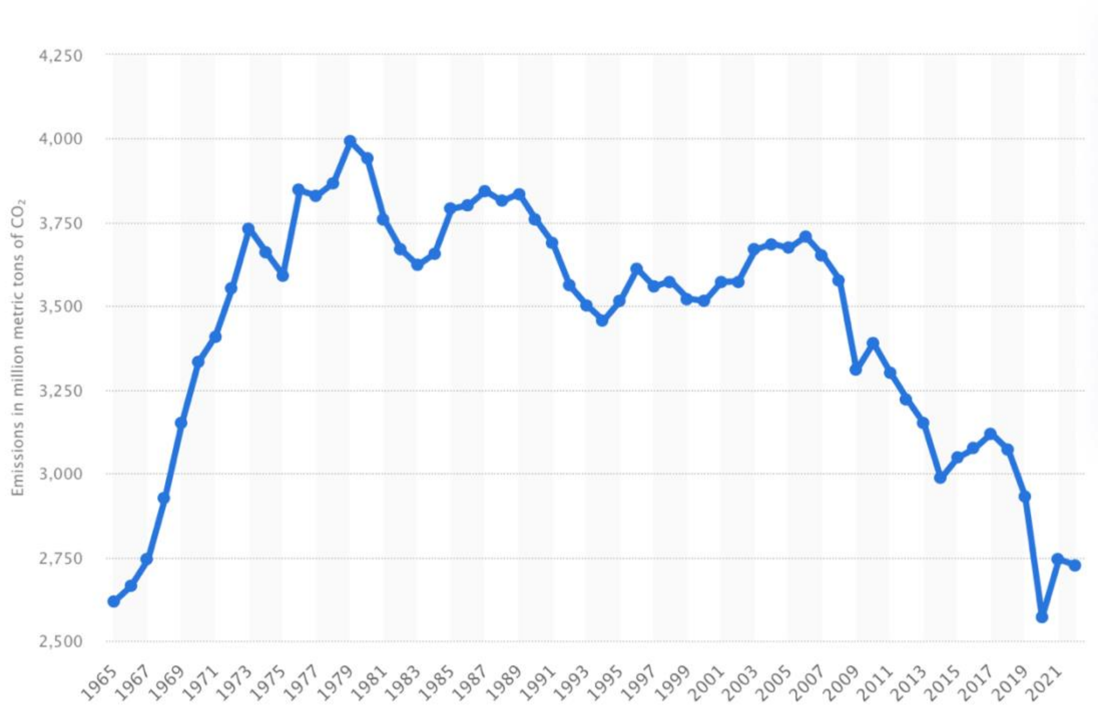

Figure 11. Carbon dioxide emissions in the European Union from 1965 to 2022 (Tiseo, 2023)

One of the actual key points of debate is the role of carbon removal by natural sinks. Preserving, restoring, and expanding these natural sinks play a crucial part in offsetting anthropogenic emissions. However, it is essential to ensure that reliance on natural sinks does not lead to a decrease in ambition levels for reducing human-induced emissions.

Notably, the European Climate Law sets a limit on the contribution of net removals to the 2030 climate target, capping it at 225 million tons of CO_2 equivalent. This restriction ensures that any additional carbon removals beyond this limit can only be utilized to surpass the initial 55% reduction target. This approach emphasizes the importance of achieving substantial emissions reductions through direct actions while also recognizing the value of natural sinks in mitigating carbon emissions. (Van Hoof, 2021)

Energy storage systems play a significant role in facilitating the energy transition, particularly by enabling larger shares of low-carbon generation. Their potential in reducing emissions becomes evident when examining results for less carbon-intensive energy systems. By optimizing the dispatch profile of energy storage systems through wholesale arbitrage and considering the marginal cost of available generation technologies, a CO_2 price can effectively minimize the emissions generated during energy storage operation, even though they are relatively negligible.

Through their ability to provide flexibility and grid balancing, energy storage systems effectively manage the integration of renewable energy generation. This allows for the displacement of fossil fuel-based power plants, leading to a reduction in CO_2 emissions associated with electricity production. In essence, energy storage contributes to a cleaner and more sustainable energy landscape by promoting the adoption of low-carbon and renewable energy sources, ultimately driving the shift towards a decarbonized future. (Beuse, et al., 2021)

5 MODEL

In this section, we present the methodology and mathematical models utilized to optimize energy storage systems in the context of the Iberian wholesale electricity market. The objective is to analyze the economic benefits and overall welfare of integrating two common energy storage technologies into the energy mix: Lithium-ion batteries and Pumped Hydro Storage.

5.1 Input Data

INPUT	UNITS	SOURCE
THERMAL GAP	MWh	**OMIE**
GAS PRICE	€/MWh	**OMIE**
CO_2 PRICE	€/tCO_2	**OMIE**
POWER CAPACITY	MW	(Baumgarte, et al., 2020), (Ministry for Ecological Transition and the Demographic Challenge, 2020)
NUMBER OF CYCLES	-	(Jülch, 2016), (PwC España, 2021), (Castro, 2006)
CYCLE LENGTH	hours	(Andrey, et al., 2020), (Baumgarte, et al., 2020), (Nguyen, et al., 2017)
EFFICIENCY (η)	%	(Kumar, 2020), (TESLA, 2023), (Instituto para la Diversificación y Ahorro de la Energía, 2006)
INTERES RATE (i)	%	(Aguas del Júcar S.A., 2007), (CNMC, 2018), (Navarro Uriel, 2012), (CNMC, 2018)
INVESTMENT COSTS (C_{INV})	€	(Jülch, 2016), (TESLA, 2023), (LAZARD, 2021), (Navalés, 2021), (Enseñat y Berea, 2021)
O&M COSTS ($C_{O\&M}$)	% CAPEX	(TESLA, 2023), (LAZARD, 2021), (Jülch, 2016), (IRENA, 2017)

Table 2. Input parameters

5.1.1 Techno-economic parameters

Before categorizing different energy storage systems, it is essential to outline the main parameters that define and differentiate them from one another. These particularities are fundamental as they determine the most suitable technology based on the situation and circumstances. After extensive research over numerous publications (sources presented in *Table 2*) the primary factors, which are commonly found in most studies, are as follows:

- **Technological maturity**: This distinguishes the level of technological development of the energy storage system in question. Mature technologies are usually preferred due to a higher level of operational expertise and lower uncertainty. Moreover, increased maturity often leads to decreased costs. Developed technologies have achieved technological milestones and are commercially available, but their large-scale applications have not yet been widely adopted. PHS can be considered a mature technology in the energy storage sector. It has been in operation for several decades and has proven its reliability and efficiency on a large scale. PHS facilities are well-established and widely used for grid-level energy storage and load balancing. Due to their long-standing presence and operational expertise, PHS systems are relatively low-risk options for energy storage investments. They are commercially available and have demonstrated their ability to contribute to grid stability and supply-demand management effectively. The level of technological maturity of PHS leads to reduced uncertainties and lower overall costs, making it a preferred choice for many energy storage projects. (Nguyen, et al., 2017)

  BESS, on the other hand, can be categorized as a developed technology. While battery-based energy storage has made significant strides in recent years, especially with the rise of lithium-ion batteries, large-scale applications of batteries are still in the process of widespread adoption. Batteries have achieved various technological milestones, and commercial products are readily available in the market. However, certain questions remain regarding their competitiveness and long-term reliability, especially for applications involving very high power and energy capacities. Despite these questions, BESS continues to gain popularity in various energy storage applications due to its modularity, flexibility, and ability to respond quickly to changing grid conditions. (Olabi, et al., 2021)

- **Power capacity**: expressed in megawatts, is a crucial parameter that measures the maximum power output an energy storage system or pumped hydro storage facility can deliver at any given time. It represents the installed capacity of the system and significantly influences its performance and operational capabilities. Higher power capacity allows for faster charging and discharging rates, enabling the system to respond promptly to fluctuations in demand or supply. PHS projects typically have power capacities ranging from several megawatts to hundreds of megawatts, while battery-based storage systems can also span a wide range, from a few kilowatts to several hundred megawatts.

- **Roundtrip efficiency**: roundtrip efficiency describes the relationship between the amount of energy introduced into the storage device and the amount of energy extracted from it during a charge/discharge cycle. It considers energy losses that occur due to the process of storing and extracting energy from the device. Higher efficiency implies less energy loss during storage and retrieval processes, resulting in greater economic benefits.

  PHS systems typically exhibit high round-trip efficiencies, commonly around 70% to 85%. However, battery-based energy storage systems' efficiency presents even higher efficiency, with typical values ranging from 80% to 95% depending on the battery composition and design.

- **Number of cycles**: The number of cycles refers to the total count of charging and discharging cycles an energy storage system can undergo during its useful lifetime. For ESS, it represents the number of times the batteries can be charged and discharged, while for PHS, it reflects the number of times water is pumped uphill and released to generate electricity. Under equal conditions, from an economic standpoint, investing in systems with a long lifespan is more appealing.

  In this project, the lifespan of battery storage technologies has been carefully assessed, considering various factors such as battery chemistry, depth of discharge, and maintenance practices. To determine the system's practical lifespan, we have chosen to set a specific number of cycles. Through extensive research and analysis, it has been determined that a conservative estimate of 7.500 cycles aligns with an approximate operational lifetime of 12 years. This operational lifetime of 12 years can further translate to an extended calendar life of around 20 years, showcasing the robustness and durability of the battery-based energy storage systems. (Jülch, 2016)

PHS facilities are known for their ability to handle an exceptionally high number of cycles throughout their operational lifetime, ranging from tens of thousands to over one hundred thousand cycles. Leveraging this extensive operational lifespan, we can draw a meaningful comparison with batteries. To establish a reference point, we consider the "equivalent hours" of a hydroelectric power plant with an installed capacity between 10 and 50 MW, which typically falls within the range of 2000 to 3000 equivalent hours (Castro, 2006).

"Equivalent hours" in the context of a hydro plant refers to the number of hours during which the plant would generate an amount of energy equal to its rated output over a given period. In other words, it is a measure of how many hours per year the hydro plant would operate at its maximum capacity. For this study, we have chosen a conservative estimate of 2500 equivalent hours as the reference figure. (REE, 2009)

$$Total\ cycles\ per\ year = \frac{Equivalent\ hours\ (h)}{cycle\ length\ (h)}$$

$$Total\ lifetime\ cycles = \frac{Equivalent\ hours\ (h)}{cycle\ length\ (h)} *\ time\ horizon\ (years)$$

From the previous section *2. State of the art review*, we know that the lifespan of a pumped storage system can exceed the 50 years.

- **Cycle length/duration**: Cycle length refers to the duration of a single charging and discharging cycle in an energy storage system. It is measured in hours and varies based on the specific application and operational requirements. Shorter cycle lengths are preferred for applications like frequency regulation, where rapid response times are crucial. In contrast, longer cycle lengths are more suitable for energy shifting and storage purposes.

  PHS facilities can have cycle lengths ranging from few hours to multiple days, depending on the specific design and operational strategy. Battery-based energy storage systems, on the other hand, can have cycle lengths ranging from a few minutes to several hours, depending on the application's demands and the need for rapid response or longer-duration energy storage. (Nguyen, et al., 2017)

- **Capital and Operational costs**: Costs are one of the most critical factors for the industrial application of energy storage technologies. Capital cost refers to the investment required to carry out the installation project of an energy storage system.

  The capital costs of pumped storage projects can vary significantly depending on factors such as project size, location, and system structure. The costs may differ based on whether the project utilizes one existing reservoir, two reservoirs, or follows a greenfield development model. Typically, the capital costs for PHS projects can range from 0.5 M€ up to 2 M€ per megawatt of installed capacity (Navalés, 2021). On the other hand, for battery-based energy storage systems, the capital costs depend on factors like the specific battery technology used, the duration of each charging and discharging cycle, and the overall system design. Typical capital costs for BESS projects usually fall within the range of 1 M€ to 4 M€ per MW of installed capacity. In this study, the investment costs for the battery-based energy storage systems were derived from a real manufacturer's webpage, with the Tesla Megapack lithium-ion battery serving as the reference technology. (TESLA, 2023)

  On the operational side, energy storage systems incur operation and maintenance costs, which encompass various expenses related to the ongoing functioning of the systems. O&M costs are usually represented as a percentage of the initial capital expenditure and can vary depending on the technology used, project scale, and geographical location. For battery-based energy storage systems, operational costs are generally lower, typically amounting to around 1% of the total CAPEX. This is attributed to the relatively self-sufficient nature of batteries, requiring minimal additional operations once they are installed and operational. In contrast, pumped hydro storage projects tend to have slightly higher O&M costs, typically ranging from 1% to 2% of the CAPEX per year. For this specific project, a value of 1,4% has been selected to represent the O&M costs of the pumped hydro storage system. (Andrey, et al., 2020)

- **Interests rate/discount rate**: The interest rate, expressed as a percentage, represents the cost of borrowing or the return on investment over time. In the context of energy storage projects, the interest rate plays a critical role in evaluating the financial feasibility of the project.

  The interest rate for financing energy storage projects can vary significantly depending on factors such as the financial market, country, and specific project terms. For pumped storage energy projects, typical interest rates ranged from 5% to 7% annually based on the research conducted. In this project, a discount rate of 6% has been selected. (Aguas del Júcar S.A., 2007)

  In the case of battery storage systems, the National Commission of Markets and Competition calculated a rate of return of 7,05% in their 2018 report on the financial remuneration rate for electricity production from renewable energy sources, cogeneration, and waste during the period 2020-2025. This rate of return holds considerable significance as it directly impacts the financial feasibility and attractiveness of investments in the renewable and storage energy sector. (CNMC, 2018)

5.1.2 Future variables

As stated before, to calculate the prediction of prices and simulate the behavior of the energy storage system in the market along the future years, a future estimation of the variables is needed.

These future values of variables chosen for the prediction model, later explained, is information shared by OMIE for this master thesis. The Spanish market operator has developed several models and internal programs to forecast prices in the long-term in the electricity market based on estimated futures scenarios, such as the INECP target model for the energy mix, the changes of CO_2 prices in the European emissions trading system, the actual European gas crisis and the gas prices' seasonality. The components determined to be relevant in the dynamic formation of the electricity market price are the thermal gap, the market gas price (MIBGAS) and the CO_2 price in the EU ETS.

The thermal gap is defined as part of the demand which is covered by conventional thermal power plants and combined cycle gas turbine (CCGT) power plants. In the last years, the Spanish thermal gap has been reduced due to the massive penetration of renewables technologies, mainly solar and wind. On this basis, the thermal gap magnitude is found as follows:

$$\boldsymbol{TG = D - N - H - S - W}$$

where D is the demand, N the nuclear installed capacity and H, S and W the power corresponding to renewable technologies small hydro, solar and wind energy respectively in megawatts. Given that the thermal gap is covered by the power plants with the highest marginal costs, this is directly related with the location of point of price clearing and thus with the dynamic of electricity prices.

The before mentioned non-renewables technologies present their bid in the electricity market internalizing characteristic factors among which are the fuel prices and the price of the European carbon emissions allowances. Thus, gas and carbon prices, but significantly more gas prices, have a huge impact in the electricity price, given that normally around 20% of the demand is covered by gas power plants; in the year 2022 a 22,1% of the Spanish electricity consumption was generated by CCGTs. In 2015, MIBGAS is designated as the Gas Market Operator by Spanish law, consolidating the Iberian Gas Market later in 2016, where gas trading takes place. (OMIE, 2022), (MIBGAS, 2023)

On the other hand, the emissions allowance price is set in the European emissions trading system, the aim of which is to reduce greenhouse gases emissions by setting an upper limit to the GHG emissions produced by a power plant. In this platform the agents sell and buy the emissions allowances within all European Union, in which each emissions allowance is equivalent to emitting one ton of carbon dioxide. (European Commission, 2023)

The future values of these three variables are computed by OMIE using forecasting models that adjust to datasets that presents a seasonality pattern.

In the case of gas prices, they normally exhibit clear seasonality given that they include the variability of the demand and the supply fluctuations. Gas demand presents a periodic peak of consumption during winter months because of its use in heating and as a household fuel. Thus, gas prices also experience an upward trend during this season while on the contrary in the summer period, as heating needs decrease, gas prices are on a downward trend. In the next figure it is clearly exposed the periodic peak of consumption during winter season. (Rogel-Salazar & Sapsford, 2013)

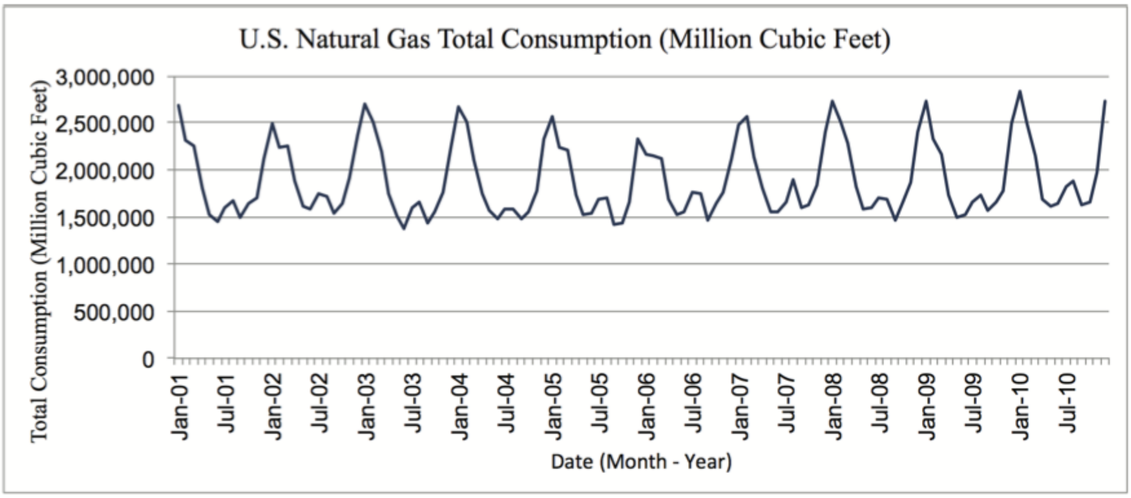

Figure 12. U.S. Natural Gas Total consumption 2001-2010. Gas seasonality (Rogel-Salazar & Sapsford, 2013)

On the other side, the seasonality of CO_2 emissions allowances is inevitable affected by factors, such as changes in the regulatory framework, in relation to the functioning of the emissions trading market. In the initial phases of the EU ETS, functioning since 2005, the carbon market mechanism lacked in efficiency, and it did not generate enough relevant transformations or evolution towards a low carbon energy mix or renewable technologies as it was supposed. Due to these deficiencies in phase three (2013-2020), a market reform was introduce changing the mechanism in which allowances were allocated from mainly for free allocation to a 57% of allocations auctioned. For the forecasting of this variable, OMIE considered that historical CO_2 data before 2017 has may have a limited relevance given the lack of regularity and consistency of carbon allowances until this point in time. However, after this year, several European policies and new energy regulations were introduced to increase awareness and relevance in the fight against climate change which caused that carbon prices started to develop a more linear and regular trend. (Chandreyee & Velten, 2014)

As in the case of gas prices, CO_2 prices can also present a seasonal trend related to the specific design of the EU ETS. For example, prices may experience high spikes each year around the end of March and beginning of April when operators need to submit enough allowances to cover their emissions for the preceding calendar year and hand over their emission report for its publication. In addition to this as gas prices increase due to a higher gas usage during cold months, carbon prices could relate with this too, since it can lead to higher CO_2 emissions coming from conventional thermal power plants. (Balietti, 2016), (ICAP, 2022)

Once the seasonality patterns of the variables have been exposed and clarified the forecasting models employed are going to be explained, these are: Seasonal Autoregressive Integrated Moving Average (SARIMA) and Holt-Winters methodology.

SARIMA is an extension of the ARIMA model, but SARIMA allows particularly to predict and model seasonal time series. It is a widely common-used time series forecasting model, as it considers both seasonal and non-seasonal components of the data, as well as autoregressive and moving average components to identify the patterns and trends in the dataset. For this project scenario given the seasonality patterns of the variables explained above, it is a particularly well-suited model. This methodology can capture the seasonal dynamics and obtain reliable prediction by setting the appropriate order of the autoregressive, integrated moving average and seasonal components.

Holt-Winters is an alternative seasonal prediction model, consisting of an exponential smoothing method based on the solution of three equations: one considering the level, one for the trend and the last one for the seasonality component. Normally this forecasting model is more suitable for datasets that present additive or multiplicative seasonality. Both SARIMA and Holt-Winters have proven to be reliable in modelling and predicting datasets with a seasonal pattern.

Given that both methods can be equally used for the forecasting of the data to select the most suitable one for each of the variables the prediction results obtained are validated using historical data, studying which has presented a smaller percentage of error. The model that presents a better fit, considering seasonal changes, is the suitable for the forecasting of that specific variable. This fitting process is done by using an 80% of the selected data to train the model and compare these results with the 20% remaining data. (MARINO, et al., 2021)

The results obtained from these prediction models provide comprehension about the dynamics of the chosen variables and will help in this project later, in developing the prediction model for the electricity market prices and understanding the strategic electricity market planning.

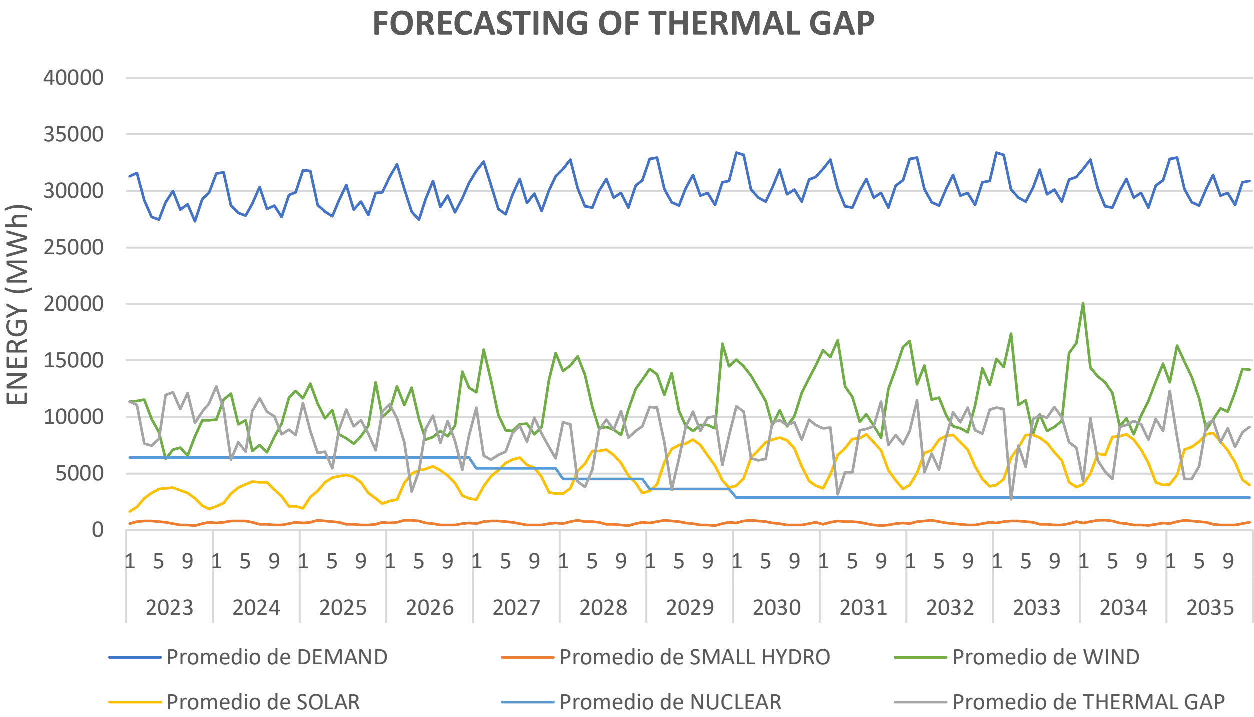

Figure 13. Forecasting of thermal gap 2023-2035

In the graph above, the prediction of the computation of the thermal gap (in grey) is shown. The seasonal prediction model provides the evolution of the several low-carbon technologies and the future demand, considering future scenarios in our country such is the achievement of the INECP targets in renewables penetration or the planned shut-down of nuclear power plants, which can be clearly distinguished in the figure, to be able to compute the shape of the future thermal gap in between 2023 and the year 2035.

In addition to this, in the following figure not only is the computed forecasting of the thermal gap displayed but also the predicted gas and carbon prices. As it is expected both parameters, present a clear seasonality due to winter periods and represent future scenarios such as an expected rise in gas prices in the year 2025 or an expected upward linear trend in the dynamics of CO_2 emission allowances prices.

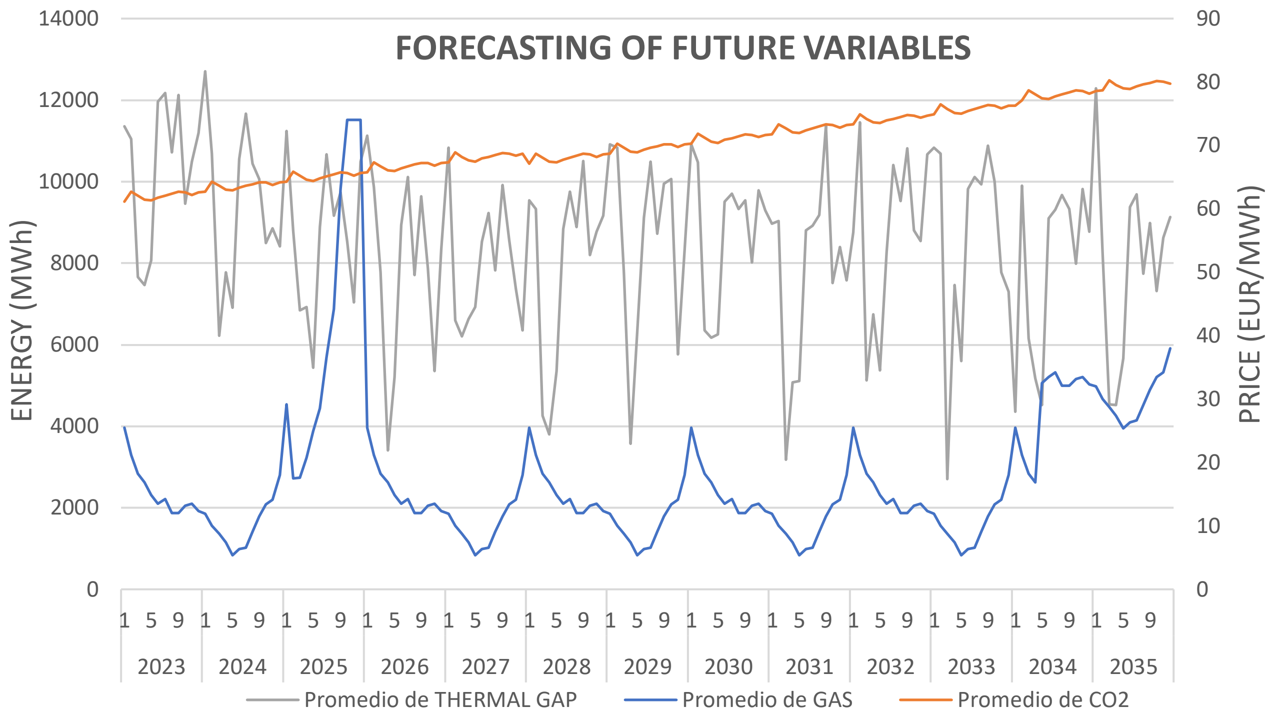

Figure 14. Results of the Forecasting model for the chosen variables 2023-2035

5.2 Prediction model

To predict the day-ahead market prices for the years 2023-2035, years between which the functioning and behavior of the ESS will be analyzed, the relevance of the variables chosen to compute the calculation of the electricity price needs to be studied. This section addresses the mathematical methodology behind the computation of these future prices. The analysis has been carried out with the help Python software's and Microsoft Excel.

In this thesis to address the prediction of day-ahead electricity prices, a multiple linear regression model was chosen, based on a historical data base, from 2017 to 2022, considering the past values for electricity prices and the independent variables chosen, the thermal gap (THERMAL_GAP) and the gas (GAS) and emission allowances (CO2) prices.

This multiple linear regression model evaluates the relation between the dependent term and the explanatory variables, considering the methodology this will be the representative equation:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3}$$

Where the components correspond to the following values:

y_i = Quantitative dependent variable, in our case the predicted electricity price.

x_{in} = Different independent variables (THERMAL_GAP; GAS; CO2)

β_0 = Y-intercept, being this parameter a constant value.

β_n = Slope coefficients corresponding to each independent variable.

To analyze the validity of the model chosen and find the relation between the variables of the multiple linear regression model and the electricity price correlation coefficients are applied in this master thesis project. (Uyanık & Güler, 2013)

The correlation coefficient also known as the Pearson's correlation coefficient, represented normally by symbol r, points out the linear relation between the two variables. It is an indicator that standardises and dimensions the covariance to be able to compare the covariances of several pair of processes, in such a way that $|r_{xy}| \leq 1$, $r_{xy} = 1$, being the case where the correlation is perfectly linear between the two variables x and y. It should be noticed that although the sign specifies the direction of the coefficient value, the relation shown by +1 is equally strong as the one presented by a -1 value of the correlation coefficient. The r is stablished as the following: (López de la Nieta Polonio, 2022)

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

On the other hand, the determination coefficient, which is normally denoted by r^2 or R^2 is a statistical index that studies the proportion of the variation of the dependent variable explained by the explanatory variables presented in the linear regression model. The coefficient of determination is the square root of the above-explained correlation coefficient, thus the higher the r-squared value, the greater the variability explained by the multiple linear regression model. Its expression is defined as:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y_i})^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}$$

where the $\hat{y}_i$ factor refers to the value of the prediction of dependent variable by the regression for the ith data point. (Kasuya, 2019)

For the analysis of the accuracy of the project's MLRM the coefficient of determination is going to be applied. Its range is between 0 and 1, being 1 the perfect variation fit of the model to the historical data introduced.

Once the multiple linear regression model is defined, in the Python code developed, and the historical data from 6 years, 2017 to 2022, is introduced, twelve different MLRM have been computed, one for each month of the year. This distinction between months has been made to display the different energy mix scenarios depending on the time of the year. Months in which hydro generation has a more relevant role, such as February and March, are expected to present a lower correlation. While as stated in the previous sections, winter months where gas consumption rises, and conventional thermal plants set the clearing bids in the market are expected to obtain an importantly high determination coefficient value. Not only these factors, but also the huge generation of wind farms during the cold months and the peak production of solar along the summer period, will detach the relation between the explanation variables and the prediction of future prices.

In the following table, there is a summary for each one of the multiple linear regression equations obtained by the model, corresponding to each month:

MULTIPLE LINEAR REGRESSION EQUATIONS					
MONTH	**R^2**	**INTERCEPT**	**THERMAL_GAP COEFFICIENT**	**GAS COEFFICIENT**	**CO_2 COEFFICIENT**
JANUARY	0,794813476	-8,05085651	0,00216717	1,13777411	0,34617034
FEBRUARY	0,765321335	8,40844169	0,00206577	0,77442672	-0,24270606
MARCH	0,707151652	-3,27087098	0,00239288	0,76354374	0,30239307
APRIL	0,806605435	-18,54799849	0,00200323	1,67946681	0,59254664
MAY	0,844720566	-16,51272089	0,00234434	1,46045306	0,53099766
JUNE	0,934069412	-7,76554008	1,53E-03	1,57E+00	5,36E-01

JULY	0,930217497	-4,33809174	1,28E-03	1,59E+00	4,58E-01
AUGUST	0,938102595	-9,06122506	1,53E-03	1,74E+00	3,93E-01
SEPTEMBER	0,9719422	-11,21393108	1,47E-03	1,83E+00	5,16E-01
OCTOBER	0,947952745	-26,72903	0,00276507	1,90862858	0,44816687
NOVEMBER	0,965400117	-26,81022977	0,00213413	1,79584316	0,75480744
DECEMBER	0,939877275	-35,49288374	0,00301743	1,99831285	0,28467783

Table 3. Multiple linear regression equations per month

In the initial examination, it is evident that all equations present a r-squared value exceeding 0,7 which are highly satisfactory. The highest obtained r-squared value of 0,97, achieved with a reduced number of independent variables, it indicates the accuracy and effectiveness of the prediction model. These results confirm the validity of the initially selected explanatory variables and show the model's capability to explain an important proportion of the variance in the electricity prices.

Upon studying values of coefficients of the independent variable, it is seen that coldest months October, November, and December, receive the highest influence on a greater extent by gas prices, as expected. On the contrary, during summer period characterized by good weather conditions and longer daylight hours, there is a high increase in solar electricity production. As a result, both gas and carbon coefficients present lower values during this period, traducing in a smaller impact on the objective variable.

To ensure the effectiveness of the developed model, it has been validated using real historical data from year 2021. This decision has been made given that year 2022 was characterized by uncommonly high and volatile electricity prices, due to the European energy crisis and the Ukraine war, which might have compromised the accuracy of the predicted result. The following outcome was obtained from the validation process:

```
r2_list: [0.8439008426216599, 0.872308156102895, 0.7049776565334878, 0.72009615277
09141, 0.9003772619286952, 0.9262936792702982, 0.9288839358397927, 0.9236098614698
157, 0.9306020948194839, 0.8664939480457853, 0.87658258851042, 0.838576471042584]
```

Figure 15. R-squared for the year 2021

As it can be observed, despite removing two years, 2021 and 2022, from the historical data for this trial, the model consistently provides high r-squared values for all twelve months, showing minimal deviation from the results calculated in Table 2. The following figure helps to visually assess the accuracy of the model, by depicting both real and predicted electricity prices for the year 2021.

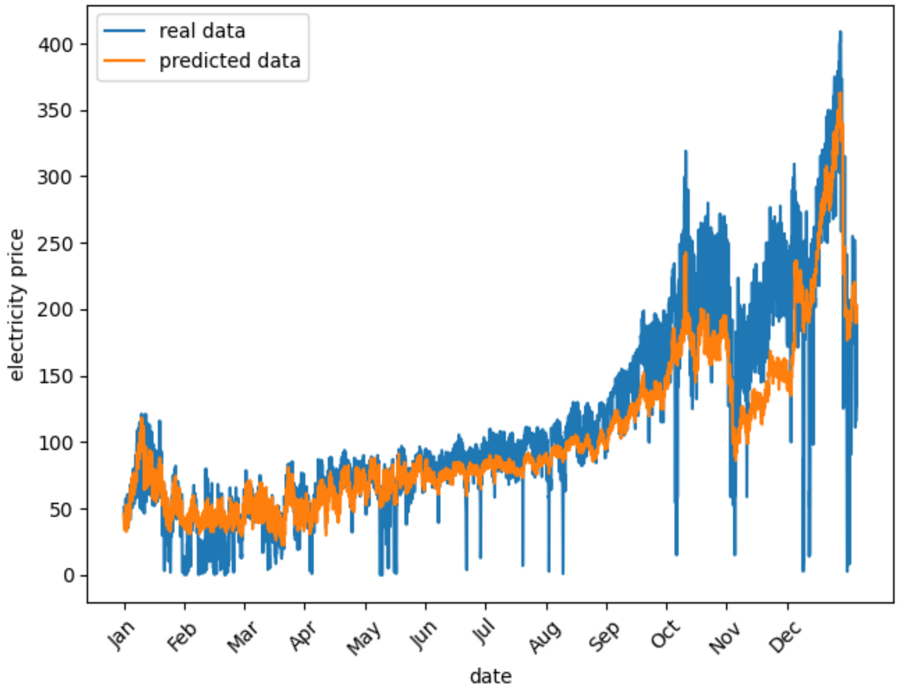

Figure 16. Real and predicted electricity prices for year 2021

It is worth noticing that mostly during price peaks and valleys, is where the prediction model is slightly compromised. However, this could be attributed to the unusual behavior of electricity market prices in 2021, reaching record highs and lows. Wholesale market prices increased by 98,5% between December 2020 and June 2021, with higher CO_2 allowance costs accounting for one-fifth of the rise, while higher gas prices would contribute for nearly half of it. (Pacce, et al., 2021)

The figure presented below shows the evolution of the energy mix, along with the values of the predicted variables and the electricity price forecast covering the period 2023-2035. This representation provides an extensive insight into the behavior of electricity prices, corresponding to the dark red curve, and its relationship with the before mentioned explanatory variables.

Upon further inspection, it becomes clear that the prices curve presents peaks that coincide with peaks observed in the gas prices curve (dark blue) during the years 2025, 2034 and 2035. In addition to this, a remarkable correlation can be observed between the

CO_2 prices variable, represented by the orange curve, and the day-ahead electricity price forecast since both show an upward trend over the years.

Additionally, it becomes apparent the positive correlation between the shape of the thermal gap curve and the shape, peaks, and valleys, of the electricity price curve (in €/MWh) drawn in light red. This correlation aligns with the expected results based on the multiple linear regression model designed. The variations in the electricity price curve seem to follow the corresponding fluctuations in thermal gap curve, thus supporting the correlation established by the forecast regression model.

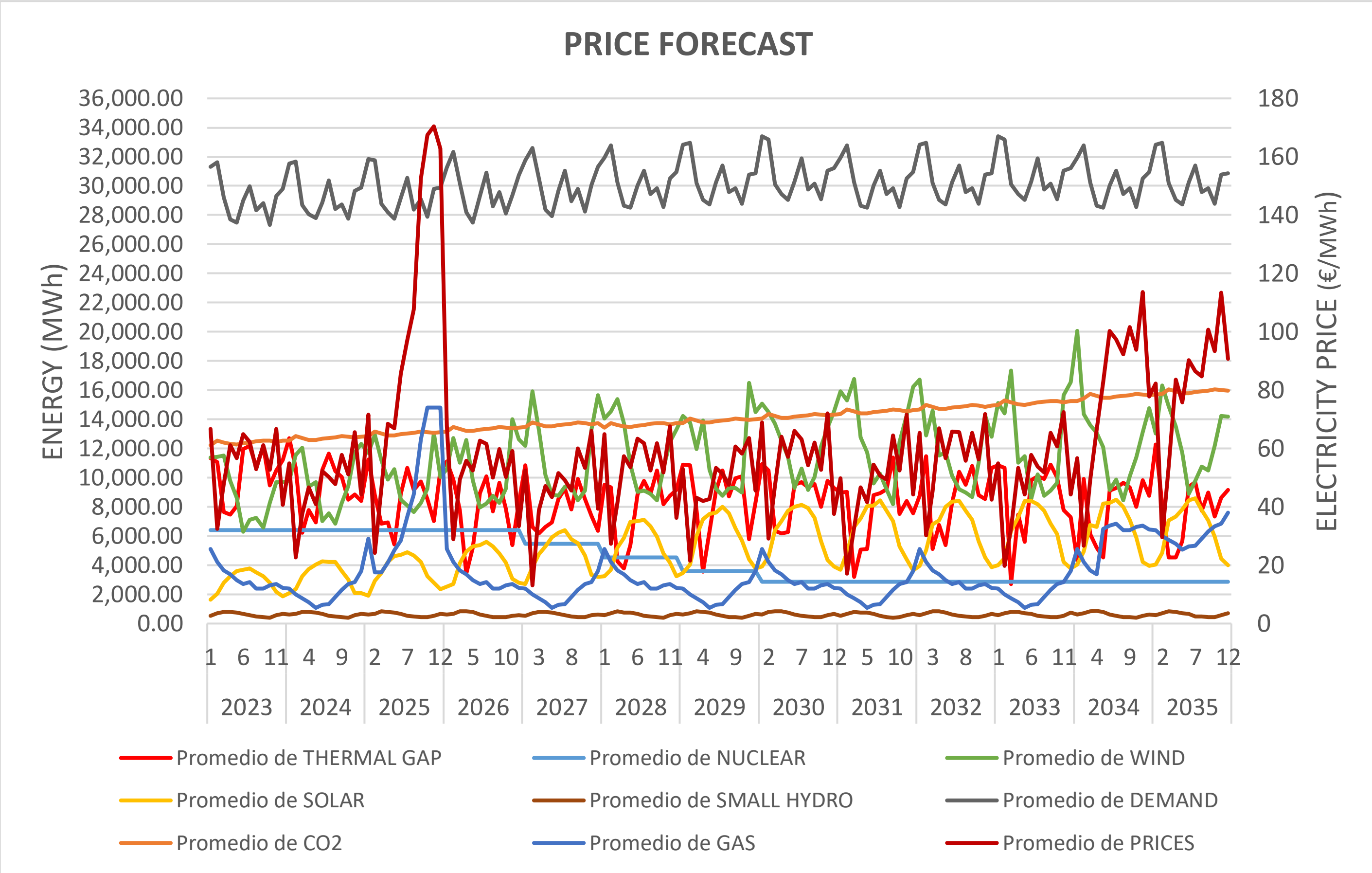

Figure 17. Price forecast results 2023-2035

5.3 Optimization model

Energy storage systems can provide a solution for demand and generation imbalance, aggravated with the massive and fast-growing integration of renewables to the grid. In addition, while doing this ESS also generate economic benefits through the arbitrage in terms of difference in the energy pricing. In the present research project, a program to value the potential income of common energy storage systems is built. The revenues are considered as the earnings from the energy storage technology with a defined roundtrip efficiency. Consequently, an optimization model has been developed to find the highest income generated by the sale and purchase actions based on the electricity pricing profile.

In this study, the optimized methodology is applied to the Iberian wholesale electricity market to analyze the economic benefits and overall electricity system welfare of introducing energy storage into the energy mix: Lithium-Ion Batteries and Small Pumped Hydro Storage.

The main advantage of price arbitrage in the wholesale electricity market for energy storage systems is absorbing energy from the grid (charging) in low-price intervals and releasing energy to the network at high-price hours. The net revenue is equal to the price variation, also called the captured spread if expressed in €/MWh.

The proposed optimization process for the price arbitrage plan is structured on an hourly basis. The electricity price profile is determinant for the energy storage actions, which can be the following three for each different hour:

1) Purchase of energy or charging process
2) Sale of energy or discharging process
3) No action

In this project's optimization code, these three possible operations are defined in vector x_i which contains the state of energy of the system for each hour.

$$x_i \begin{cases} -1, & energy\ charge \\ 0, & no\ action \\ 1, & energy\ discharge \end{cases}$$

By defining this vector, it is ensured the correct behavior of the energy storage system where charging and discharging processes can never be carried out simultaneously at the same hour.

The following figure shows the simulation flow chart, in which the code is based on to build the optimal price arbitrage strategy. (Zhang, et al., 2021), (Feng, et al., 2022)

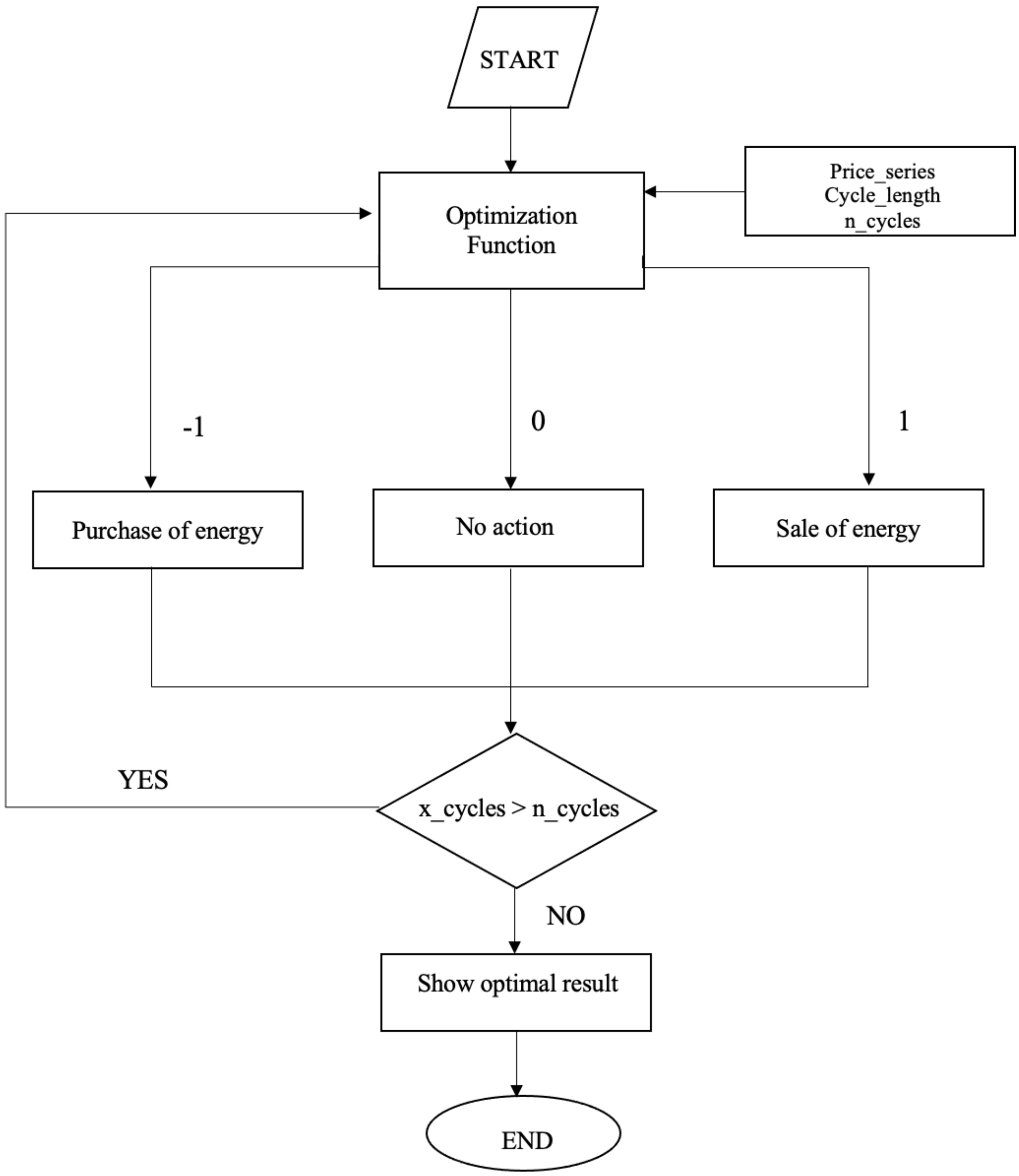

Figure 18. Optimization model flow chart

The main objective of the optimization model is to maximize the electricity price spread captured by the storage technology, thus, buy energy when market prices are low and sell when they are high. To achieve this, the optimization algorithm has been divided into different steps for the simplification of the design.

1) First the global optimization function is defined (optimize_buy_sell), serving as the entry point of the optimization model. As observed in the flow chart figure, it has three arguments as input data:

    a) price_series: represents the hourly series of electricity prices obtained from the MILP prediction model, for the chosen tims the hourly series of electricity prices obtained from the MILP prediction model, for the chosen time horizon.

    b) cycle_length: indicates the desired duration, in hours, of each cycle.

    c) n_cycles: corresponds to the maximum number of cycles that the system can run, thus its useful lifetime.

2) After this, several intermediate functions are built to carry out the optimization strategy. The following function (calculate_moving_sum) is employed to compute the moving sum of the energy prices series. This moving sum is computed by grouping the prices into cycles of duration "cycle_length", which allows the identifying the "cycle_length" hours with the lowest and highest prices. This standardization of the problem facilitates the optimization for different values of the cycle length. Afterwards, a new function (identify_ monotonicity_changes) is used to analyze the moving sum series and detect monotonicity changes. It assigns a 1 for local maximum, a 0 for points in which no change is observed and a -1 where a local minimum is found. As stated before, these values are stored in vector x_i.

3) The "identify_cycles" function is used to identify cycles in the vector x_i, considering a cycle as a sequence of -1 followed by 1, both sequences of length "cycle_length. The output is saved in a Dataframe (df_cycles) including the initial and final position of each cycle as well as the price difference between them, also known as the spread.

4) Given that there is a maximum number of cycles (n_cycles) that can be done, if the number of previously identified cycles exceeds this upper limit, the optimization process takes place. This is the main technical constraint that the problem presents.

$$n\_cycles\_x \leq n\_cycles$$

A new function (eliminate_cycles) is built to remove the less profitable cycles. For each cycle three options are evaluated: merge it with the previous cycle, merge it with the next one or fully delete the cycle, the option that maximizes the total captured spread is the chosen one.

5) Finally, a small function is used to ungroup the moving sum series and thus the vector x_i, and a series of buy and sell positions is obtained for each hour. These results are returned in the "positions_b_s" variable, by the initial main function (optimize_buy_sell).

The methodology followed by the optimization model has been already exposed in the above procedure. However, to ease the analysis of the results and simplify the use of the full model, further algorithms have been implemented and afterwards combined with the optimization strategy.

On the one hand a code was built to count the cycles done by the ESS based on the given output from the optimization model: the "positions_b_s" variable, containing the list of positions (-1,0,1) indicating the buy, no action and sell positions respectively. Taking this list and the cycle length as inputs, the "count_cycles" function returns a list that assigns a cycle number to each buy and sell position. The code goes through the sequence of positions and puts a cycle number each time a buy or sell position is detected. Cycles are labelled sequentially, incrementing the cycle number when a full cycle of the specified length is completed.

On the other hand, an execution code that coordinates the complete implementation of the price arbitrage optimization process has been designed. This code takes the input parameters such as, the desired storage capacities, the numbers of cycles, cycle length, historical and future data, and the initial thermal gap. It runs and combines the previous codes and stores the list containing the buy and sell positions (positions_b_s) and the cycle count list. This new execution code, updates the thermal gap hourly values after the purchase and sale operations, implementing a loop based on the number of iterations to carry out in the optimization process. The thermal gap is updated as follows:

$$TG_n = TG_{n-1} - capacity * positions\_b\_s_{n-1}$$

For each iteration, not only is the thermal gap updated, but also the forecasted prices and thus a new optimization strategy is applied. The iterations are used to introduce different energy storage systems with their corresponding capacities, cycle length and number of cycles, and study their impact on the thermal gap, the price predictions, and the optimization of the system as iterations pass. After all iterations have been executed, the loop ends and the output results are saved to a .CSV file, with the following columns: prices, buy/sell positions, number of cycles and updated thermal gap.

Prices_0	Position_b_s_0	n_cycles_0	tg_post_0	Prices_1	Position_b_s_1	n_cycles_1	tg_post_1	Prices_2	Position_b_s_2	n_cycles_2	tg_post_2
65,8119899	0	0	9674,81707	65,8119899	0	0	9674,81707	65,8119899	0	0	9674,81707
69,7799181	0	0	11505,7474	69,7799181	0	0	11505,7474	69,7799181	0	0	11505,7474
73,3036914	0	0	13131,7303	73,3036914	0	0	13131,7303	73,3036914	0	0	13131,7303
74,6938635	0	0	13773,2007	74,6938635	0	0	13773,2007	74,6938635	0	0	13773,2007
76,4932537	0	0	14603,4975	76,4932537	0	0	14603,4975	76,4932537	1	1	13103,4975
76,1850395	0	0	14461,2774	76,1850395	1	1	13461,2774	74,0178744	-1	2	14961,2774
74,9445143	1	1	12888,859	72,7773492	1	1	11888,859	70,6101841	1	1	10388,859
72,9142876	1	1	11952,0468	70,7471226	1	1	10952,0468	68,5799575	1	1	9452,04681
71,3667321	1	1	11237,9547	69,1995671	1	1	10237,9547	67,032402	1	1	8737,9547
71,4950007	1	1	11297,142	69,3278357	1	1	10297,142	67,1606706	1	1	8797,14197
74,1570224	1	1	12525,4848	71,9898573	1	1	11525,4848	69,8226923	1	1	10025,4848
78,9454199	1	1	14735,0062	76,7782549	1	1	13735,0062	74,6110898	1	1	12235,0062
84,3330923	1	1	17221,0524	82,1659273	1	1	16221,0524	79,9987622	1	1	14721,0524
85,9360502	1	1	17960,7089	83,7688851	1	1	16960,7089	81,6017201	1	1	15460,7089
84,6593588	1	1	17371,6023	82,4921937	1	1	16371,6023	80,3250287	1	1	14871,6023
84,3750822	1	1	17240,4279	82,2079172	1	1	16240,4279	80,0407521	1	1	14740,4279
80,7704039	1	1	15577,1128	78,6032388	1	1	14577,1128	76,4360737	1	1	13077,1128
77,9477888	1	1	14271,0653	75,7806238	0	0	14271,0653	75,7806238	1	2	12771,0653
58,5658089	0	0	7771,35914	58,5658089	0	0	7771,35914	58,5658089	0	0	7771,35914
52,2906567	0	0	4875,80108	52,2906567	0	0	4875,80108	52,2906567	0	0	4875,80108
48,2562268	0	0	3014,18472	48,2562268	0	0	3014,18472	48,2562268	0	0	3014,18472
45,1975615	-1	2	2602,81769	47,3647265	0	0	2602,81769	47,3647265	-1	2	4102,81769
45,3238422	-1	2	2661,0877	47,4910072	-1	2	3661,0877	49,6581723	-1	2	5161,0877
46,0368032	-1	2	2990,07094	48,2039682	-1	2	3990,07094	50,3711333	-1	2	5490,07094
49,7509603	-1	2	4703,90308	51,9181253	-1	2	5703,90308	54,0852904	-1	2	7203,90308
54,0573607	-1	2	6691,0154	56,2245257	-1	2	7691,0154	58,3916908	-1	2	9191,0154
57,996161	-1	2	8508,50519	60,1633261	-1	2	9508,50519	62,3304911	-1	2	11008,5052
57,7925051	-1	2	8414,53178	59,9596702	-1	2	9414,53178	62,1268352	-1	2	10914,5318

Figure 19. Output results file

To enhance the usability of the whole optimization algorithm, a user-friendly interface has been developed for the prediction of prices and energy storage system optimization strategy. The user interface included features are:

- Data selectors: These buttons allow the user to conveniently select .CSV files containing the historical and future data required for the simulation.

- Output path selector: A button that enables the user to specify the folder where the output results .CSV file will be stored.

- Input parameters form: a various input fields where users can enter the necessary input parameters such as capacity (MW), cycle number and cycle length (h).

- Execution button: A button that initializes the running of the simulation. When clicked, the entered data is collected, and the complete code is executed.

- Dialog Box: An area where messages and execution progress and results are displayed.

It is worth noting that the user interface program connects with the previously exposed codes (the optimization, the cycle count, and the execution codes) to perform the simulation and display the simulation results in the interface window.

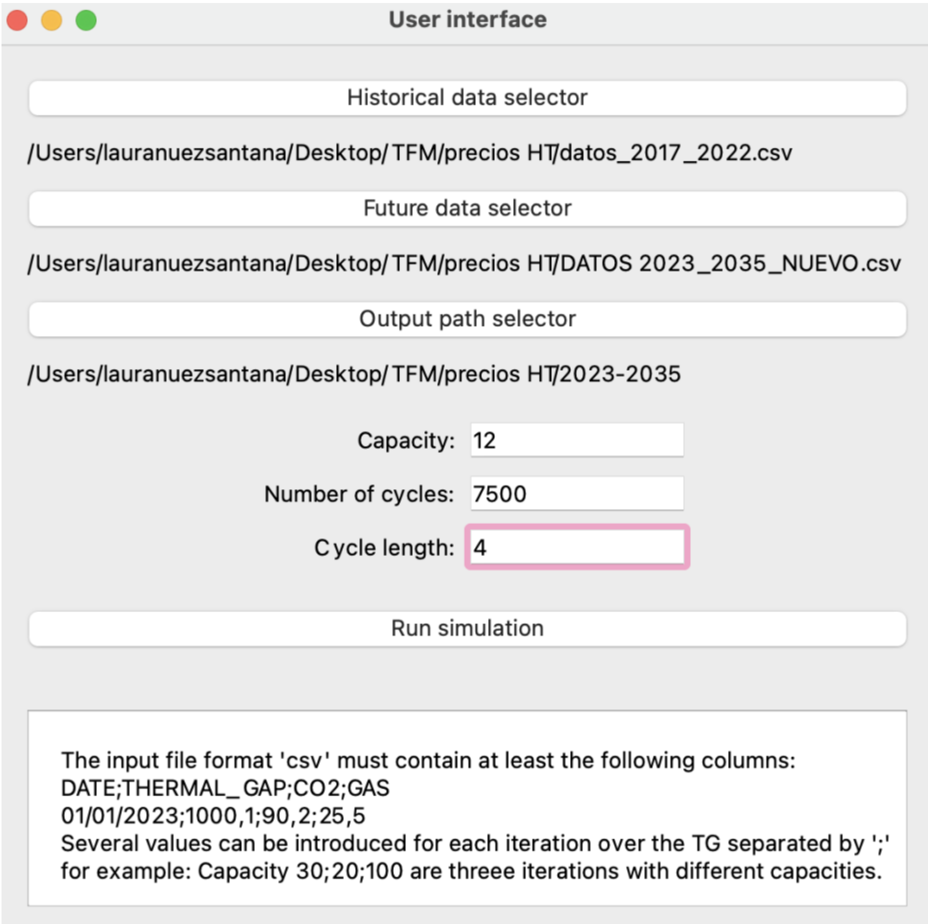

Figure 20. User interface window

6 RESULTS AND OBSERVATIONS

Following the previous theoretical framework and current situation explanations surrounding the energy storage systems, as well as the mathematical and optimization methodology employed, this section proceeds to obtain the quantitative and qualitative results derived. These results enable the study to conduct a profitability analysis and assess the behavioral impact expected in the short and medium term resulting from the introduction of new ESS in the day-ahead electricity market.

In the upcoming sections, several energy storage cases after being executed by the algorithm are going to be studied. As point of departure the definition of two base cases, one for the battery energy storage system and one for the pumped hydro storage system is taken. Each base case is independently analyzed and afterwards a set of alternative cases (different cycle lengths) for each of the technologies is going to be explored and compared among them to define the optimal technology strategy.

Once the better technical strategy has been identified for each ESS respectively, a scene based on the target scenario set by the INECP will be executed and its results examined afterwards.

6.1 Economic analysis

After obtaining the results of the optimal buying and selling actions using the presented model, for each of the afterwards explained systems, the subsequent step is to carry out a comprehensive financial analysis to find out which is the most suitable ESS to invest in, considering the different technologies and its energy capacity.

To accomplish this, a financial assessment is provided, exposing the different cases economic returns. For this financial analysis two economic indicators have been identified as decision-making parameters of economic viability: net present value and internal rate of return. These economic indexes stand out as the most widely used indicators to assess the financial viability of an energy storage system, among the reviewed related literature.

The NPV allows to obtain an estimation of the value that the capital invested is going to generate at the end of its life taking into consideration the effect of time in money valuation, with the interest rate. A project investment's is economically viable when the net present value is positive.

The expression for this indicator in this study is represented as (RotellaJunior, et al., 2021), (Lorenzi, et al., 2019):

$$NPV = -INV + \sum_{j=1}^{n} \frac{CF_j}{(1+i)^j}$$

Where the different factors are:

INV = Investment cost or initial period cash flow.

$CF_j =$ Cash flow in period j, consisting of the revenues generated in the sale of energy, the expenditures coming from the electricity purchase and the operation and maintenance costs.

$i =$ Interest or discount rate.

Similarly, IRR is another criterion employed in viability examinations that finds the discount rate that forces the NPV of the project to be equal to zero. This indicator defines the minimum accepted rate of return of the initial investment. Thus, the IRR is expressed as (Yianni, et al., 2018):

$$0 = -INV + \sum_{j=1}^{n} \frac{CF_j}{(1+IRR)^j}$$

The maximized annual net revenue is calculated using the optimized results of the algorithm as follows:

$$REV_{max}(€) = \sum_{i=1}^{8760} p_i * x_i * \eta * C_{inst}$$

The parameters in this expression are:

p_i = represents the electricity price series resulting from the prediction model, at ith hour of each day (€/MWh)

x_i = the vector that stores the buy/no action/sell (-1,0,1) energy operations resulting from the optimization code (positions_b_s)

η = energy efficiency for the energy discharge and charge process

C_{inst} = initial storage capacity (MWh)

The total lifetime cost of an energy storage system is generally composed of two elements, represented by the expression:

$$C_{TOT} = C_{INV} + C_{O\&M}$$

In this equation, C_{TOT} represent the overall cost of the energy storage system. C_{INV} is the capital invested in building the energy storage system and the $C_{O\&M}$ denotes the expenses in operation and maintenance incurred over the system's lifetime. (Feng, et al., 2022)**,** (Connolly, et al., 2011)

6.2 Battery energy storage system base case

The first BESS case to be carried out is a lithium-ion battery, with a cycle length of 4 hours and its behavior is studied between the years 2023 – 2035. The specific values of the technical and economic characteristics chosen for the case were previously exposed in chapter *5.1.1 Techno-economic parameters*.

For the financial analysis (in all cases) the electricity price series used is the resulting predicted prices (p_i) from the forecasting model for every hour of the years 2023 until 2025.

All input parameters defined for this base case are shown in the table below:

BASE CASE DATA	
Installed Capacity (MW)	12
Cycle Length (h)	4
Number of Cycles	7500
η	0,94
C_{INV} (€/MW)	1.724.000,00
$C_{O\&M}$ ($\%C_{INV}$)	1%
i	7,05
Time horizon	2023 – 2035

Table 4. BESS base case parameters

Entering the above-shown technical parameters in the interface and using the output results, the economic parameters, and the expressions of the financial indicators explained in the previous section, the annual and total revenues obtained by the battery throughout its lifetime are computed. For every hour the income from selling energy and the expenses from buying are calculated, obtaining from this the net revenues.

REVENUES (€)	
2023	387.361,13 €
2024	408.528,66 €
2025	399.760,21 €
2026	447.823,38 €
2027	470.015,11 €
2028	493.167,63 €
2029	484.474,00 €
2030	514.157,04 €
2031	541.699,56 €
2032	559.019,32 €
2033	523.383,53 €
2034	573.435,63 €
2035	543.521,21 €
Total	**6.346.346,42 €**

Table 5. Net annual revenues from 2023-2035 (BESS base case)

At first glance, it is observed in *Table 5*, that there is a linear increasing trend during the examined period, as expected. Revenues gradually increase from 2023 onwards, reaching their peak in year 2034. From this year on, economic benefits slightly decrease but remain at significant levels, which may be due to a flattening of the electricity prices profile during these final years of the selected period. In total, over the analyzed period, around 6,4 M€ are obtained from the optimization of price arbitrage by this BESS.

The increasing linear trend in earnings are attributed to the fast-growing penetration of renewable energy resources into the wholesale electricity market. As exposed in previous sections, the more renewable generation increases, the bigger need there is of managing the variability and intermittent nature related to this type of clean electricity generation. This linear upward trend in revenues and thus in the captured spread implies that the battery's capacity is greatly valued and used in the day-ahead electricity market.

From the annual income data and considering the initial capital costs and operation and maintenance costs incurred in the first period, the net cash flow is calculated as follows:

CASH FLOWS	
2023	- 20.505.381,10 €
2024	408.528,66 €
2025	399.760,21 €
2026	447.823,38 €
2027	470.015,11 €
2028	493.167,63 €
2029	484.474,00 €
2030	514.157,04 €
2031	541.699,56 €
2032	559.019,32 €
2033	523.383,53 €
2034	573.435,63 €
2035	543.521,21 €
NPV	-16.667.367,32 €
IRR	-14,78%

Table 6. Cash flows from 2023-2035 (BESS base case)

After the initial cash outflow in 2023, representing the total incurred costs by the implementation of the battery system, from this year onwards increasing positive cash flows are observed. However, the net present value of this cash flows, using an interest rate of 7,05%, is -16,7 M€. This negative value suggests that the project's profitability is lower than the required rate of return. The internal rate of return is calculated as -14,78%, this means that if the storage system project's cash flows are discounted at this rate, the present value of the inflows would precisely compensate the present value of the cash outflows.

Considering these two financial indicators, this BESS project would not be viable since the system does not generate sufficient profits, from the participation in the wholesale electricity market, to cover the costs and provide the minimum return on investment.

6.3 BESS sensitivity analysis

In this next section, a sensitivity analysis of the battery energy storage systems will be performed by assessing two alternative cases with different cycle lengths. The base case in our analysis has a cycle duration of 4 hours and it was found not financially viable. Thus, this sensitivity analysis aims to evaluate how variations in key parameters can impact the financial performance of the BESS in the electricity wholesale market.

As mentioned, in these cases the focus is on the cycle length as a critical factor influencing the system's revenue generation, as well as the investment costs of the system.

ALTERNATIVE CASE DATA		
Installed Capacity (MW)	19	8
Cycle Length (h)	2	6
Number of Cycles	7500	7500
η	0,92	0,94
C_{INV} (€/MW)	1.050.000,00	2.440.000,00
$C_{O\&M}$ ($\%C_{INV}$)	1%	1%
i	7,05	7,05
Time horizon	2023 – 2035	2023 – 2035

Table 7. BESS alternative cases parameters

In the 2-hour scenario, the performance of the battery in the electricity market is assessed to examine the fluctuations in revenues, net present value and other financial metrics. This alternative case provides valuable information about the potential benefits or drawbacks of investing in ESS with shorter cycle lengths, and thus less storage capacity.

Conversely, the 6-hour case will help us understand the trade-off related to longer cycle lengths and their effect on the overall financial viability of the BESS.

It is worth noting that in these battery storage systems, as the cycle length increases, the cost per megawatt (€/MW) also increases. The cases have been designed such that for the same investment cost of approximately 20 M€, the installed capacity of the battery is going to be adjusted accordingly in each scenario. By adapting this technical parameter to the given capital cost, the economic implications of various cycle lengths can be assessed while keeping a consistent investment level. This configuration will later provide crucial information for decision-making and determining the optimal configuration of the ESS based on the financial viability.

REVENUES (€)	**2 h**	**6 h**
2023	301.948,61 €	329.335,69 €
2024	319.660,49 €	346.119,57 €
2025	336.745,53 €	204.150,59 €
2026	359.693,09 €	302.258,35 €
2027	407.337,73 €	411.359,97 €
2028	415.276,86 €	437.678,26 €
2029	439.766,01 €	477.208,66 €
2030	438.120,74 €	487.241,49 €
2031	472.094,05 €	497.576,62 €
2032	482.229,04 €	489.229,24 €
2033	422.221,49 €	475.526,70 €
2034	472.184,64 €	517.808,22 €
2035	477.358,24 €	505.908,31 €
Total	**5.344.636,54 €**	**5.481.401,67 €**

Table 8. Net annual revenues from 2023-2035 (BESS 2h, 6h cases)

Based on the provided result from the algorithm, an analysis about the annual revenues for both cases has been carried out in *Table 8*, presented above.

Comparing the revenue figures, it can be observed that the cycle length of 2-hour results in a slightly lower total revenue compared to the longer 6-hour cycle length. It is noticeable in both cases that revenues increase gradually over the selected period as it was expected due to the reasons exposed in the base case scenario.

Also, examining the figures in detail, an unexpected decrease in revenues in the 6-hour case in the year 2025 is observed. The longer cycle length of 6 hours means that the battery is charged and discharged less frequently compared to the 2-hour case. From the forecasted prices results, we are aware that there is a high peak of electricity prices in that particular year, in this scenario the 6-hour battery may not capture as many spreads as it would with a shorter cycle length. In a high-price scenario, shorter cycle lengths allow the BESS to take advantage more frequently of price variations and capture more benefits from buying at lower prices and selling at higher prices. However, with a longer cycle length, the battery has less opportunities to participate in the market and may miss out on capturing the peak prices. These behaviors are exposed in the next graph, where also the upward trend in revenues generated of all battery configurations.

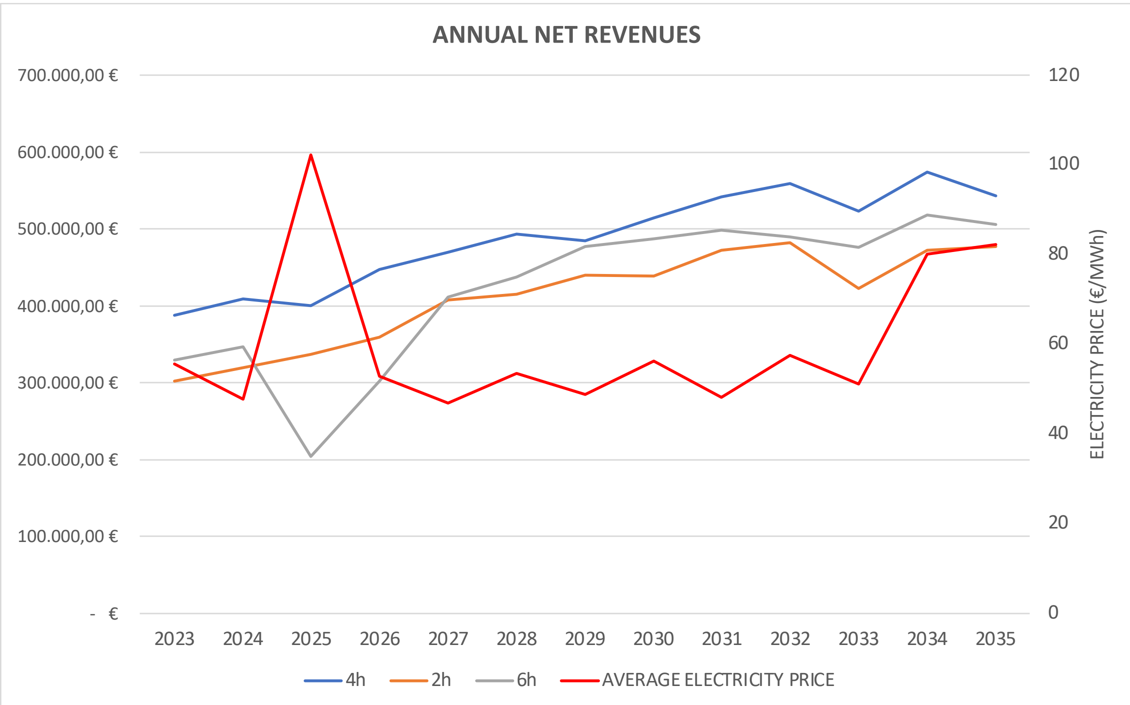

Figure 21. Comparison of net annual revenues (all BESS cases)

Subsequently, the cash flows corresponding to each scenario are calculated and showed in the following table:

CASH FLOWS	2 h	6 h
2023	-19.697.529,52 €	-19.385.864,31 €
2024	319.660,49 €	346.119,57 €
2025	336.745,53 €	204.150,59 €
2026	359.693,09 €	302.258,35 €
2027	407.337,73 €	411.359,97 €
2028	415.276,86 €	437.678,26 €
2029	439.766,01 €	477.208,66 €
2030	438.120,74 €	487.241,49 €
2031	472.094,05 €	497.576,62 €
2032	482.229,04 €	489.229,24 €
2033	422.221,49 €	475.526,70 €
2034	472.184,64 €	517.808,22 €
2035	477.358,24 €	505.908,31 €
VNP	-16.459.605,48 €	-16.131.671,19 €
IRR	-15,98%	-15,33%

Table 9. Cash flows from 2023-2035 (BESS 2h, 6h cases)

Looking into the cash flow figures of both cases, the cycle length of 2 hours and 6 hours, both still obtain in a negative net present value after the entire period. The same can be observed in the internal rate of return figures, indicating that these projects are still not financially viable. Given that the 6-hour battery, presents a higher net revenue value, their financial indicators are slightly better, however still referring to an unviable project.

The final comparison between the financial situation of the 2-hour,4-hour and 6-hour cases, the 4-hour configuration presents a relatively better outcome compared to the two other cases. While none of the configurations show a viable economic analysis, the 4-hour case demonstrates a higher total average revenue of nearly 600.000 € annually, in contrast to 400.000 € in both the 2 and 6-hour configurations. This can be evidently seen in the *Figure 22*:

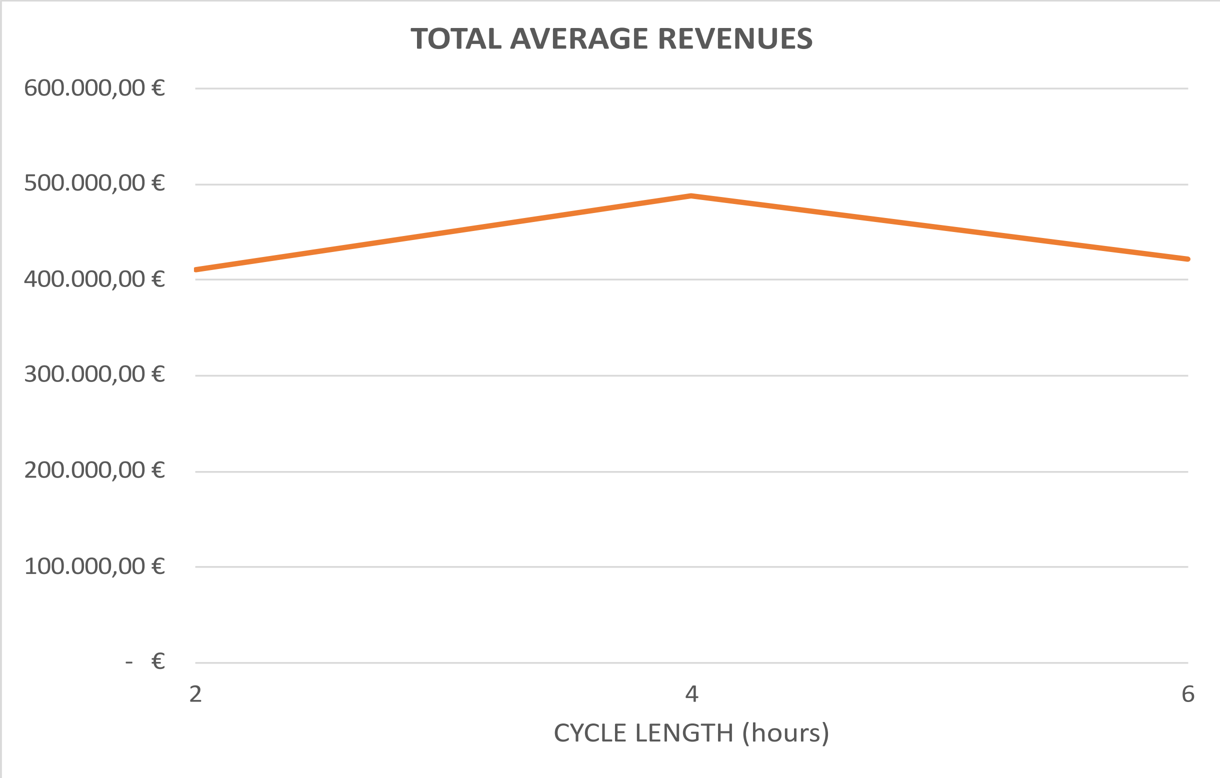

Figure 22. Comparison of average revenues (all BESS cases)

Considering the financial viability and profitability, although the 4-hour case still results in a loss of money, it is the scenario that incurs in the least amount of loss compared to the other two cases. Therefore, in terms of optimizing the economic performance, the 4-hour case can be considered the most favorable alternative among the three.

To conclude with the sensitivity analysis, a final BESS scenario has been proposed, selecting the 4-hour configuration given the conclusions obtained from the previous analysis and extending the useful lifetime of the system up to 2043.

The selected period for the previous simulations corresponds to the expected useful life of the battery, which is typically around 10-12 years. The objective is to maximize the utilization of the battery by performing approximately 2 cycles per day. This level of utilization ensures efficient use of the battery's capacity and provides the desired operational benefits.

However, it is important to note that batteries have the potential to last up to 20 years or even longer. In cases where longevity is a priority and minimizing degradation is a key consideration, the battery's functioning can be optimized by executing fewer cycles per day. This approach allows for reduced stress on the battery, leading to less deterioration over time. By adjusting the operational strategy to perform only a daily cycle or even less, the battery's lifespan can be extended while maintaining its performance and capacity.

To explore the potential for a better financial viability, this final case has been proposed. This strategy aims to find whether adopting a longer time horizon and adjusting the operating performance of the BESS can lead to a more favorable and sustainable financial situation.

LAST CASE DATA	
Installed Capacity (MW)	12
Cycle Length (h)	4
Number of Cycles	7500
η	0,94
C_{INV} (€/MW)	1.724.000,00
$C_{O\&M}$ ($\%C_{INV}$)	1%
i	7,05
Time horizon	2023 – 2043

Table 10. BESS 2023-2043 case parameters

The change was introduced by extending the input variable values (thermal gap, gas, and carbon prices) entered in the algorithm to perform the prediction of electricity prices up to 2043 and run the optimization model over this new period. As in the previous cases, the net annual revenues generated the purchase and sale of energy were computed and exposed in the next chart:

REVENUES (€)			
2023	274.201,02 €	**2034**	409.060,18 €
2024	331.038,86 €	**2035**	380.553,14 €
2025	159.424,11 €	**2036**	389.839,43 €
2026	261.987,55 €	**2037**	409.456,73 €
2027	368.844,21 €	**2038**	434.333,52 €
2028	401.080,88 €	**2039**	417.511,62 €
2029	349.422,78 €	**2040**	408.340,68 €
2030	400.162,79 €	**2041**	418.018,50 €
2031	394.746,73 €	**2042**	461.537,95 €
2032	394.746,73 €	**2043**	397.812,04 €
2033	415.225,06 €	**Total**	**7.877.344,51 €**

Table 11. Net annual revenues from 2023-2043 (BESS 4h case)

The analysis of the extended time horizon revealed that the battery energy storage system was able to capture additional revenue in the added years. However, it is noteworthy that despite the extension of eight years, the average total revenues per year showed a decrease, given that in the 2023-2035 period the peak revenues are around 550.000 € while in this 2023-2043 horizon the peak revenue does not excess the 460.000 €. The total revenue over the extended period amounted to 7.877.344,51€, compared to the approximately 6.400.000 € earned in the initial 12-year scenario. This finding suggests that while the longer time horizon allowed for some additional revenue opportunities, it may not do significantly enhance the overall financial viability of the BESS project.

In this next cash flow analysis, we will discover if the assumptions we have made from the revenue's examination is fulfilled.

CASH FLOWS			
2023	- 21.099.601,07	**2034**	415.225,06
2024	274.201,02	**2035**	409.060,18
2025	331.038,86	**2036**	380.553,14
2026	159.424,11	**2037**	389.839,43
2027	261.987,55	**2038**	409.456,73
2028	368.844,21	**2039**	434.333,52
2029	401.080,88	**2040**	417.511,62
2030	349.422,78	**2041**	408.340,68
2031	400.162,79	**2042**	418.018,50
2032	394.746,73	**2043**	461.537,95
2033	394.746,73		
	NPV		- 17.372.702,85
	IRR		-7,9%

Table 12. Cash flows from 2023-2043 (BESS 4h case)

As it was supposed, the cash flows assessment for the extended time horizon also shows that both the NPV for the project and the IRR are negative, indicating that the project does not yield a positive return on capital.

It its noticeable that the IRR for the 20-year period appears more favorable, against the -14,78% from the 12-year period, thanks to the longer period and the potential for higher total cash flow. However, at the same time, this last scenario results in a worse NPV meaning that the additional revenues earned during the extra years are not sufficient to offset the costs.

These results confirm that both scenarios; base case and the extended period case, do not demonstrate financial viability for the battery energy storage project. As it has been observed, in all cases proposed the financial analysis has demonstrated the poor economic viability of the performance of a battery in the electricity wholesale market, since in none of the configurations does not even recover their costs, let alone generating extra benefits.

6.4 Small pumped hydro storage base case

This section aims to analyze the revenue generation of a pure pumped hydro storage system through its participation in the wholesale electricity market.

As similarly to the battery cases earlier exposed, the financial viability of this technology's projects will be assessed by examining its revenues generation over a specific time horizon. The objective is to understand how the system can capture revenue by efficiently utilizing its energy storage capacity and optimizing its operation in response to price fluctuations in the wholesale electricity market.

The first PHS case to be performed is system, considering a cycle length of 7 hours and the chosen time horizon is between the years 2023 – 2035, for the results to be able to be compared later with the BESS scenarios. As it was mentioned in section *6.2*, the values of the technical and economic characteristics chosen for the case were earlier explained in chapter *5.1.1 Techno-economic parameters*.

PHS BASE CASE DATA	
Installed Capacity (MW)	34
Cycle Length (h)	7
Number of Cycles	2500
η	0,75
C_{INV} (€/MW)	600.000,00
$C_{O\&M}$ (%C_{INV})	1,4% /year
i	6
Time horizon	2023 – 2035

Table 13. PHS base case parameters

The annual revenues generated by this system that reflect the dynamic nature of the wholesale electricity market are exposed in the below table:

REVENUES (€)	
2023	639.465,63 €
2024	664.612,79 €
2025	218.559,61 €
2026	469.631,69 €
2027	722.544,85 €
2028	720.431,23 €
2029	903.198,44 €
2030	796.198,63 €
2031	734.998,03 €
2032	851.851,62 €
2033	835.215,03 €
2034	897.222,26 €
2035	967.713,06 €
Total	**9.421.642,87 €**

Table 14. Net annual revenues from 2023-2035 (PHS base case)

In the early years, the revenues gradually increase, with notable growth observed from 2023 to 2027. This indicates that the system successfully captures opportunities during periods of high electricity demand and corresponding price variations. These years demonstrate the system's ability to provide valuable energy storage services and contribute to the overall stability of the electricity grid.

As we move to the later years, the revenues show a relatively stable trend, with some fluctuations. This suggests that the system maintains its revenue generation capabilities and continues to participate actively in the wholesale electricity market. However, to prove its long-term viability and profitability of the PHS system, an analysis of the project’s cash flows needs to be carried out to provide valuable insight into the financial performance of this technology.

CASH FLOWS	
2023	- 23.187.734,37 €
2024	664.612,79 €
2025	218.559,61 €
2026	469.631,69 €
2027	722.544,85 €
2028	720.431,23 €
2029	903.198,44 €
2030	796.198,63 €
2031	734.998,03 €
2032	851.851,62 €
2033	835.215,03 €
2034	897.222,26 €
2035	967.713,06 €
NPV	-17.309.698,46 €
IRR	-11,61%

Table 15. Cash flows from 2023-2035 (PHS base case)

The net present value of the cash flows is -17,3 M€, using a discount rate of 6%. The negative NPV suggests that, considering the initial investment costs and the subsequent cash flows, the financial performance of the pumped hydro storage system is not financially viable in the analyzed period.

On the other hand, the internal rate of return is also determined to be negative around a -12%, indicating as well that the economic analysis performed to this storage system is not favorable.

After finding these unfavorable results, as it happened in the battery system cases, further considerations and adjustments may be needed to obtain an improved financial viability and try to achieve a positive return on investment.

6.5 Small PHS sensitivity analysis

In this new section, as it was similarly done with the BESS technology, a sensitivity analysis will be conducted to evaluate the financial performance of the pumped hydro storage system under various cycle lengths. The assessment will consider three alternative cases with cycle lengths of 12, 24, and 50 hours respectively.

One of the major strengths of PHS systems is their flexibility to adjust the duration of the cycles depending on the specific operational requirements. This enables the simulation of longer cycle lengths, which can have a potential impact in the economic viability of the system. Unlike battery energy storage systems, where the duration of the storage capacity affects the investment costs, in the case of PHS, the infrastructure and installed capacity remain the same regardless of the cycle length. In the table below, all input parameters for these three alternative PHS cases are exposed:

ALTERNATIVE CASES DATA	**1**	**2**	**3**
Installed Capacity (MW)	34	34	34
Cycle Length (h)	12	24	50
Number of Cycles	2000	1000	500
η	0,75	0,75	0,75
C_{INV} (€/MW)	600.000,00	600.000,00	600.000,00
$C_{O\&M}$ ($\%C_{INV}$)	1,4% /year	1,4% /year	1,4% /year
i	6	6	6
Time horizon	2023 – 2035	2023 – 2035	2023 – 2035

Table 16. PHS alternative cases parameters

It should be mentioned that to ensure comparability and facilitate decision-making for any potential agent or investor, the investment cost for all four cases, including the base case, is set at approximately 20 M€. This enables the focus to be on the critical factor, the cycle length, on the economic performance while maintaining the invested capital. This insights into how the system's revenue creations are affected by the longer duration of the storage cycles, will provide valuable information for decision-makers regarding the optimal cycle length for maximizing revenue potential.

Following the same procedure employed in the previous cases, by examining and treating the results from the optimization algorithm, the annual revenues generated by each cycle length are calculated and compare among them.

REVENUES (€)	12 h	24 h	50 h
2023	527.909,78 €	890.375,78 €	182.139,57 €
2024	476.813,49 €	786.833,13 €	337.316,63 €
2025	688.896,93 €	214.073,07 €	82.362,85 €
2026	711.936,18 €	540.914,58 €	- €
2027	757.286,06 €	1.057.197,08 €	350.660,61 €
2028	735.783,10 €	843.262,11 €	204.163,11 €
2029	1.153.043,02 €	804.580,73 €	577.559,33 €
2030	1.081.410,36 €	945.837,58 €	234.810,72 €
2031	1.216.564,64 €	1.037.479,67 €	427.979,99 €
2032	1.201.354,83 €	1.143.517,10 €	166.967,95 €
2033	1.239.559,27 €	770.793,26 €	231.670,58 €
2034	1.227.098,39 €	1.054.938,60 €	377.384,45 €
2035	1.119.475,22 €	915.320,05 €	323.736,43 €
Total	**12.137.131,26 €**	**11.005.122,73 €**	**3.496.752,21 €**

Table 17. Net annual revenues from 2023-2035 (PHS alternative cases)

Comparing the revenue figures above, significant variations in the revenue generation among the different configurations can be observed. The 12-hour cycle length generated the highest total revenue at the end to the period, followed by the 24-hour cycle length and finally the 50-hour generating the lowest total revenue value. Providing a more detailed insight among the different cases the 12-hour configuration revenues show an overall upward trend in revenue over the analyzed period. Like the 12-hour cycle, although there are fluctuations in revenue from year to year, there is a slight increase in earning over the entire period. However, the 50-hour cycle length exhibits huge fluctuations, and no apparent trend seems to be followed even obtaining year 2026 as an empty year, where the algorithm given the electricity price profile and the limitation of the number of cycles decided to carry out no action at all during that year.

This revenue analysis may indicate that the 12-hour cycle length allows for more frequent energy storage and discharge, capturing market opportunities and maximizing revenue potential. While, the 24-hour cycle length shows relatively stable or slightly increasing revenue over the years, the growth rate is not as significant as the 12-hour cycle length. The 50-hour cycle length demonstrates a less favorable revenue trend, with relatively lower economic benefit and a limited ability to capture market opportunities due to less frequent energy storage and release.

Additionally, it is essential to study other financial aspects, as the computation of the NPV and subsequently the internal rate of return for each cycle length, computation that is shown in the upcoming table:

CASH FLOWS	12 h	24 h	50 h
2023	- 23.299.290,22 €	- 22.936.824,22 €	- 23.645.060,43 €
2024	476.813,49 €	786.833,13 €	337.316,63 €
2025	688.896,93 €	214.073,07 €	82.362,85 €
2026	711.936,18 €	540.914,58 €	- €
2027	757.286,06 €	1.057.197,08 €	350.660,61 €
2028	735.783,10 €	843.262,11 €	204.163,11 €
2029	1.153.043,02 €	804.580,73 €	577.559,33 €
2030	1.081.410,36 €	945.837,58 €	234.810,72 €
2031	1.216.564,64 €	1.037.479,67 €	427.979,99 €
2032	1.201.354,83 €	1.143.517,10 €	166.967,95 €
2033	1.239.559,27 €	770.793,26 €	231.670,58 €
2034	1.227.098,39 €	1.054.938,60 €	377.384,45 €
2035	1.119.475,22 €	915.320,05 €	323.736,43 €
NPV	-15.587.587,89 €	-16.117.279,91 €	-21.403.496,71 €
IRR	-8,6%	-10,17%	-21,3%

Table 18. Cash flows from 2023-2035 (PHS 12h, 24h, 50h cases)

Surprisingly, we encounter the same situation that in the BESS section where neither of the alternatives provide a financially viable outcome for the analyzed period. Based on these financial indexes, as stated previously, the 12-hour cycle length appears to be the most financially viable option among the three alternatives. It shows a relatively improved NPV and a more favorable than the other two options.

Finally, a global evaluation is performed between the financial situations of the 7-hour, 12-hour, 24-hour and 50-hour cases. It reveals that the 12-hour configuration presents a relatively better outcome compared to the other configurations. In the next graph the comparison between average annual revenues of the four cases can be clearly distinguished.

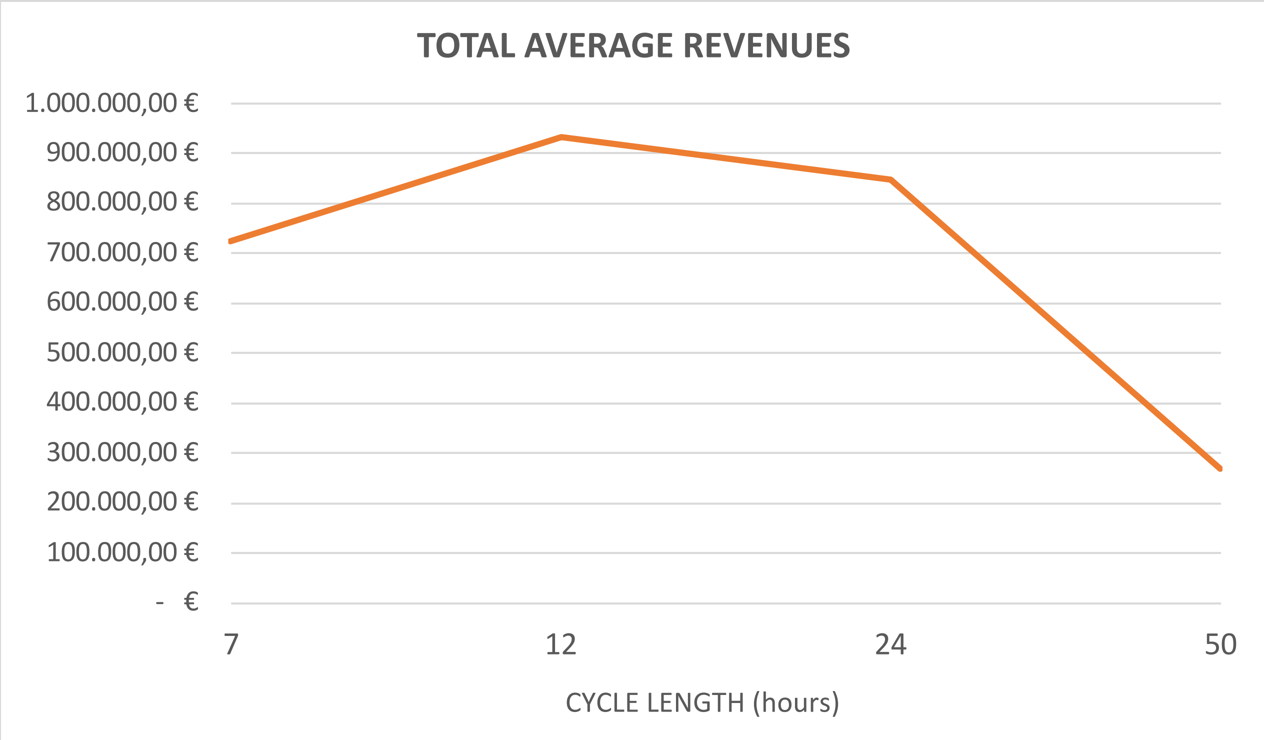

Figure 23. Comparison of average revenues (all PHS cases)

The 12-hour case demonstrates a higher total average revenue of more than 900.000 € annually, compared to approximately 800.000 € in both the 24-hour and 7-hour cases, and less than 300.000 € in the 50-hour configuration. The financial indicators NPV and IRR also show better values for the 12-hour case compared to the chosen base case of the 7-hour configuration.

This comparison shows that having the longest cycle length configuration is not necessarily better from a financial perspective. It is essential to carefully consider the balance between cycle length and revenue generation potential.

However, it is important to emphasize that even though the 12-hour case appears more favorable in the chosen time horizon (2023-2035), all cases still demonstrate financial unviability.

This indicates that additional considerations and potential improvements are necessary to achieve a financially sustainable pumped hydro storage system.

Another significant advantage that the pumped hydro storage system offers over the batteries is its extended useful lifetime. The PHS system can operate for 40 or 50 years, and with proper maintenance and occasional equipment replacement, its operational lifespan can be further extended. In contrast, the BESS has a limited lifetime due to the degradation of its battery components over time.

The extended lifetime of the PHS system allows for a longer recovery period for the initial investment costs. With more time available, the PHS system has a better opportunity to generate sufficient revenues and become a financially viable project. This expanded time horizon provides a greater chance for the PHS system to recoup its costs and potentially achieve profitability.

ALTERNATIVE CASES DATA	**1**
Installed Capacity (MW)	34
Cycle Length (h)	12
Number of Cycles	6000
η	0,75
C_{INV} (€/MW)	600.000,00
$C_{O\&M}$ ($\%C_{INV}$)	1,4% /year
i	6
Time horizon	2023 – 2043

Table 19. PHS 2023-2043 case parameters

In the above-presented case, the time horizon has been extended until the year 2043, taking advantage of the long lifetime of the PHS system. This extended timeframe allows for a more comprehensive analysis of the financial viability of the project, considering both short-term and long-term revenue generation potential.

12h REVENUES (€)			
2023	942.644,39 €	**2034**	1.711.861,57 €
2024	806.915,46 €	**2035**	1.601.634,75 €
2025	1.025.863,40 €	**2036**	1.554.824,45 €
2026	1.060.575,17 €	**2037**	1.619.705,99 €
2027	1.186.171,88 €	**2038**	1.736.171,44 €
2028	1.299.281,20 €	**2039**	1.636.322,56 €
2029	1.487.928,31 €	**2040**	1.774.544,52 €
2030	1.447.228,75 €	**2041**	1.822.713,70 €
2031	1.629.606,65 €	**2042**	1.629.922,67 €
2032	1.629.606,65 €	**2043**	1.784.596,57 €
2033	1.520.746,52 €	**Total**	**30.908.866,62 €**

Table 20. Net annual revenues from 2023-2043 (PHS 12h case)

The 20-year period revenues for the pumped hydro storage project show a consistent and increasing trend over the years. The revenues gradually increase from 942.644,39 € in 2023 to a peak of almost 1.800.000 M€ in 2043. This indicates a positive revenue growth pattern throughout the extended time horizon.

The increasing trend in revenues demonstrates the long-term potential and financial viability of the 12-hour configuration. It indicates that over the extended period, the PHS system becomes increasingly effective in leveraging its energy storage capabilities to capture additional revenue and contribute to the overall stability and efficiency of the electricity market. It's important to note that the total revenue for the extended period in the 12-hour PHS configuration amounts to 31 M€, indicating a significant revenue potential over the extended time horizon. This reinforces the notion that the longer lifespan of the PHS system allows for a more sustainable and financially viable project.

The cash flows for the 12-hour cycle length case over the 20-year period show a significant improvement compared to the initial base case, represented in *Table 21*:

12h CASH FLOWS			
2023	- 25.169.355,61 €	**2034**	1.711.861,57 €
2024	806.915,46 €	**2035**	1.601.634,75 €
2025	1.025.863,40 €	**2036**	1.554.824,45 €
2026	1.060.575,17 €	**2037**	1.619.705,99 €
2027	1.186.171,88 €	**2038**	1.736.171,44 €
2028	1.299.281,20 €	**2039**	1.636.322,56 €
2029	1.487.928,31 €	**2040**	1.774.544,52 €
2030	1.447.228,75 €	**2041**	1.822.713,70 €
2031	1.629.606,65 €	**2042**	1.629.922,67 €
2032	1.629.606,65 €	**2043**	1.784.596,57 €
2033	1.520.746,52 €		
NPV		- 8.942.146,25 €	
IRR		1,6%	

Table 21. Cash flows from 2023-2043 (PHS 12h case)

This economic analysis shows a still negative net present value. Although the NPV is negative, it is significantly improved compared to the shorter time horizon. This indicates that the extended period allows the PHS system to better recover the initial costs and reduce the overall negative financial impact.

For the first time in all studied cases, including the BESS scenarios, the internal rate of return is 1,6%, indicating a positive rate on return on the investment over the extended time-horizon. This further supports the improved financial viability of the 12-hour PHS configuration. By the year 2043, the project has already recovered around a 60% of its incurred costs over the only 30% recovered in the 2023–2035-time horizon.

Cash flow analysis demonstrates that extending the time horizon of the 12-hour PHS configuration results in more positive cash flows and improved financial indicators. While the system is still not financially viable in absolute terms, the extended period allows for better revenue generation and a more favorable financial outlook.

Following the positive outcome of the financial analysis for the 12-hour PHS configuration and considering the long remaining useful lifetime of the pumped storage system, it is reasonable to explore an extended time horizon for the analysis. Therefore, the final scenario for this technology would involve extending the period up to the year 2050. This extension would require obtaining and incorporating additional input data for electricity prices into the prediction model.

LAST CASE DATA	
Installed Capacity (MW)	34
Cycle Length (h)	12
Number of Cycles	12.000
η	0,75
C_{INV} (€/MW)	600.000,00
$C_{O\&M}$ (%C_{INV})	1,4% /year
i	6
Time horizon	2023 – 2050

Table 22. PHS 2023-2050 case parameters

The extended time horizon analysis for the pumped storage system reveals the revenues generated over the years from 2023 to 2050. The annual revenues exhibit fluctuations and variations across different years, showed in the following table:

REVENUES (€)			
2023	1.109.606,86 €	**2037**	1.842.866,79 €
2024	1.112.021,57 €	**2038**	1.940.427,57 €
2025	1.258.528,61 €	**2039**	1.823.140,70 €
2026	1.290.162,68 €	**2040**	1.948.771,55 €
2027	1.384.513,46 €	**2041**	1.962.358,95 €
2028	1.491.335,97 €	**2042**	1.864.715,63 €
2029	1.692.131,24 €	**2043**	1.949.266,81 €
2030	1.642.801,80 €	**2044**	1.990.677,67 €
2031	1.747.761,64 €	**2045**	1.946.777,46 €
2032	1.768.580,57 €	**2046**	2.100.918,08 €
2033	1.722.768,60 €	**2047**	2.030.301,44 €
2034	1.861.707,28 €	**2048**	2.046.891,85 €
2035	1.804.467,52 €	**2049**	2.113.929,68 €
2036	1.772.691,58 €	**2050**	2.047.369,74 €
Total		**49.267.493,31 €**	

Table 23. Net annual revenues from 2023-2050 (PHS 12h case)

Starting from the initial years, the revenues gradually increase and reach higher levels in the later years. For example, in the early years, such as 2023 and 2024, the revenues are around 1,1 million euros. As we progress towards the later years, the revenues continue to rise steadily. In the middle years, there might be some fluctuations where the revenues slightly decrease or increase, but overall, the trend remains upward reaching towards the end of the analyzed period the 2 M€ in the final years, such as 2048, 2049, and 2050.

This increasing trend in revenues over the years is attributed to several factors, but mainly such to the growth in electricity demand and the increasing rapid expansion of renewable energy sources.

CASH FLOWS			
2023	-25.287.993,14 €	**2037**	1.842.866,79 €
2024	1.112.021,57 €	**2038**	1.940.427,57 €
2025	1.258.528,61 €	**2039**	1.823.140,70 €
2026	1.290.162,68 €	**2040**	1.948.771,55 €
2027	1.384.513,46 €	**2041**	1.962.358,95 €
2028	1.491.335,97 €	**2042**	1.864.715,63 €
2029	1.692.131,24 €	**2043**	1.949.266,81 €
2030	1.642.801,80 €	**2044**	1.990.677,67 €
2031	1.747.761,64 €	**2045**	1.946.777,46 €
2032	1.768.580,57 €	**2046**	2.100.918,08 €
2033	1.722.768,60 €	**2047**	2.030.301,44 €
2034	1.861.707,28 €	**2048**	2.046.891,85 €
2035	1.804.467,52 €	**2049**	2.113.929,68 €
2036	1.772.691,58 €	**2050**	2.047.369,74 €
NPV		-3.203.931,42 €	
IRR		5%	

Table 24. Cash flows from 2023-2050 (PHS 12h case)

Based on the cash flows table above provided for the extended period from 2023 to 2050, it can be observed that the pumped storage system generates negative cash flows in the initial years but gradually turns positive as the project progresses.

The negative net present value of -3 M€ suggests that the project's cash inflows are not sufficient to cover the initial investment and operational costs, considering a discount rate of 6%. However, it is important to note that the PHS project has a long useful lifetime, and the analysis only covers a period of 27 years. Based on the calculations, it is estimated that approximately 84% of the costs would be recovered within the first 27 years, considering the imposed interest rate. This indicates that the project is on track to fully recover its costs and even generate a return on investment over its extended useful lifetime.

Considering that the project has not yet reached its full useful lifetime, it is reasonable to expect that over the course of approximately 30 years, the project would have fully recovered its costs and earned a return on investment. This suggests that the project has the potential to become financially viable in the long run.

6.6 Comparisons

After computing the individual analysis of the different BESS and PHS cases, this section provides a comparison between the results for the two different energy storage technologies. These two technologies have distinct characteristics, and analyzing their performance can provide insights into their effectiveness and economic feasibility.

Figure 24 shows the annual average peak-valley price difference captured by the three BESS cases.

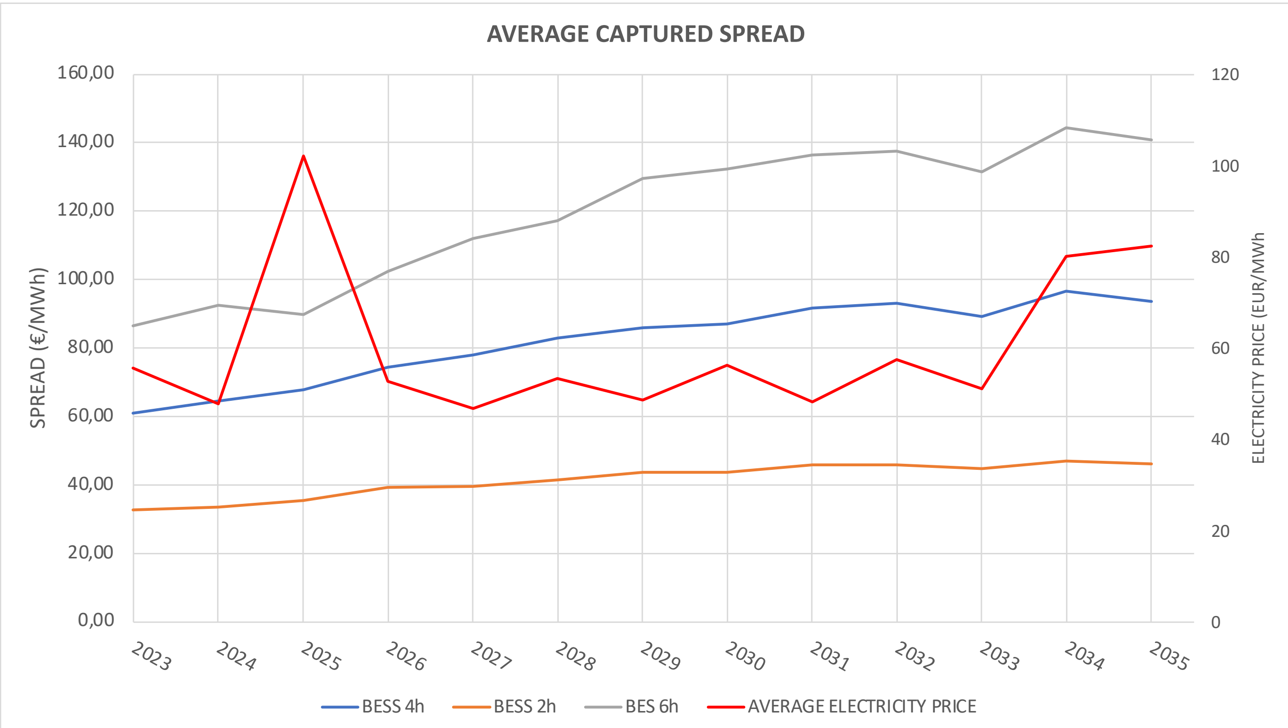

Figure 24. Annual average captured spread of BESS cases

For the battery scenarios, as it happened with the annual net revenues the annual captured spread follows an evident upwards linear trend. The increase in captured spread over the years can be attributed to the influx of renewable energy sources, such as solar and wind power. The high penetration of renewable energy in the electricity system has resulted in surplus electricity supply during periods of high renewable generation.

By participating in the market, the storage system can help balance the supply and demand of electricity, reducing the curtailment of renewable energy and optimizing the utilization of renewable resources. This ability of the storage technologies to participate in the market and reduce curtailment can contribute to an increase in the captured spread. As the BESS can buy electricity from the market at lower prices during periods of surplus supply and sell it at higher prices during periods of higher demand, the spread between buying and selling prices increases.

In the following figure the same graph is exposed to show the price difference captured by the different pumped hydro storage system scenarios.

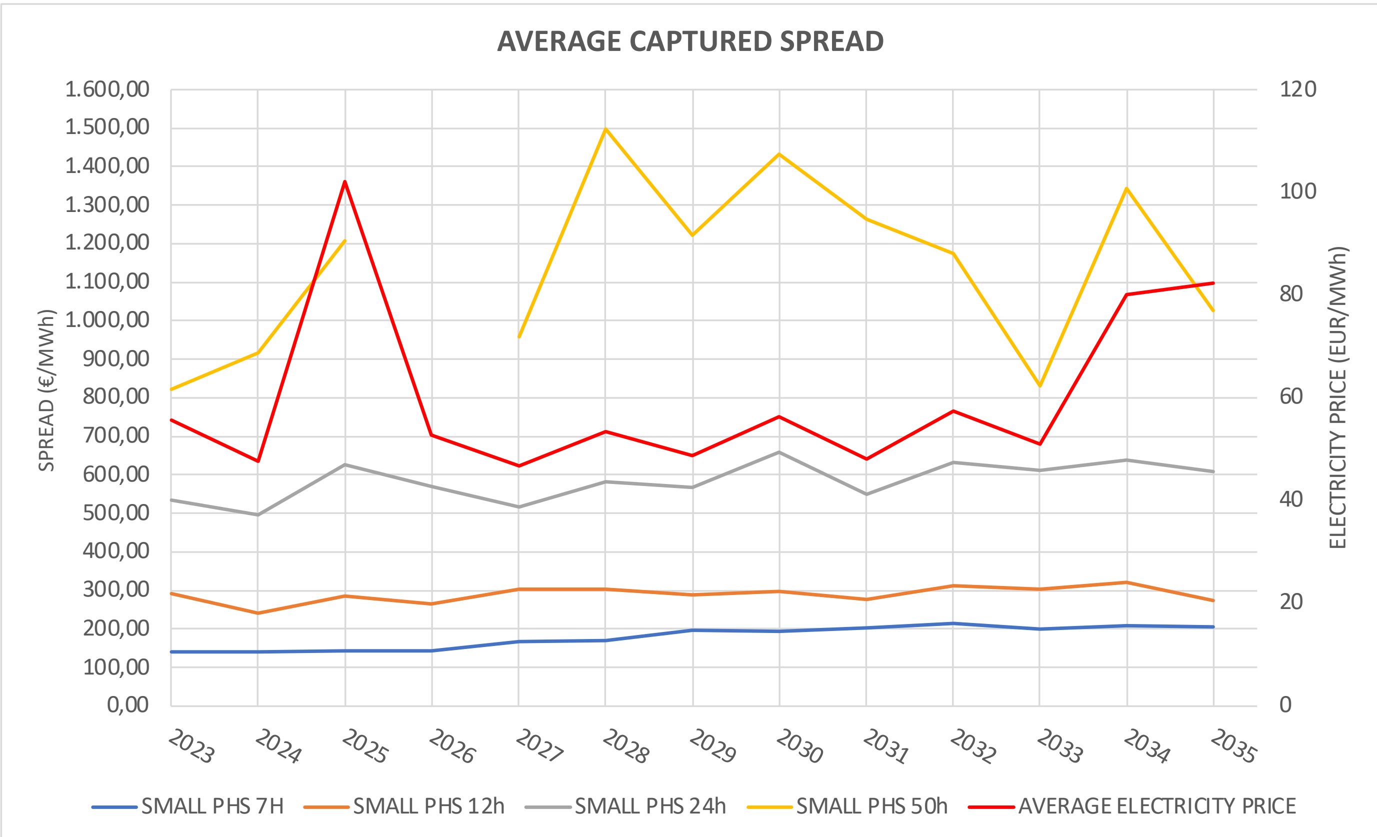

Figure 25. Annual average captured spread of PHS cases

In the shorter cycle length cases, there may be a slight increasing linear trend in the captured spread over the years, as it was observed in the battery's scenarios. However, in the longer cycle length cases, the trend may not follow a linear pattern. The captured spread in these cases is influenced by the number of cycles and the profile of electricity prices. As the cycle length increases, the frequency of participating in the market decreases, leading to fewer opportunities to capture the spread even in some cases obtaining years with no action at all, observed in 2026 in the 50-hour PHS configuration.

What it is observed in both figures, is that it seems that in both technologies the longer the cycle length, the higher the captured spread. However, in the previously conducted financial analysis it was observed that the longest cycle length scenario, was not necessarily the most profitable one and the more suitable to be financially viable.

The trade-off between cycle length and captured spreads should be carefully considered when evaluating the financial viability of energy storage systems. While a longer cycle length may result in higher captured spreads per transaction, it may also lead to fewer overall transactions and subsequently to lower net annual revenues and on the contrary, a shorter cycle length allows for more frequent participation in the market even though the captured spread per cycle may be lower.

Lastly, a global comparison is shown in *Figure 26* based on the results obtained from the individual financial analysis to each one of the battery and hydro scenarios.

The figure clearly highlights the differences in financial viability among the various energy storage scenarios. Despite none of the cases showing a strong return on investment, it is evident that the 12-hour pumped storage system has the highest potential for reaching financial viability in the future. In this specific period, it has been able to recover a significant portion, more than a 30 % of its costs compared to the other scenarios.

Contrary to the assumption that longer cycle lengths always lead to better outcomes, the comparison shows that the 50-hour pumped storage system has the lowest recovery rate among all the storage options, even all the battery scenarios. This finding supports the notion that longer cycle lengths do not always guarantee improved financial performance.

It is evident that the 4-hour battery storage system does not achieve a high recovery rate, recovering less than 20% of the incurred costs although it was found the best case from the battery's scenarios. In contrast, several cases of the pumped storage system, including the 12-hour and other configurations, have achieved a higher recovery rate, exceeding 25% of the incurred costs.

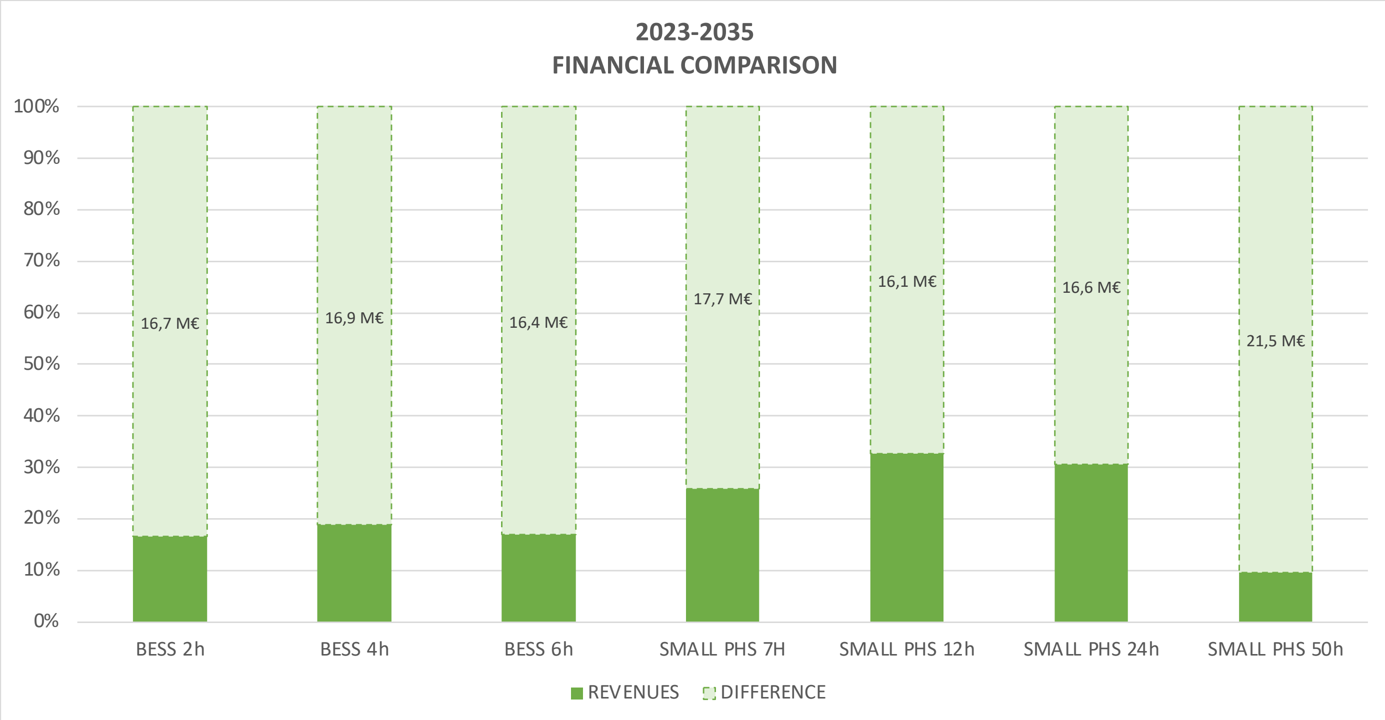

Figure 26. Global financial comparison from 2023-2035 for all ESS cases

6.7 INECP scenario

The National Energy and Climate Plan sets forth a target scenario for energy storage, aiming to add an additional capacity of 6 GW by 2030. This capacity will be divided between 3,5 GW of pumped hydro storage and 2,5 GW of battery energy storage. (Ministry for Ecological Transition and the Demographic Challenge, 2020)

In this section, the implications of this storage scenario on the wholesale market prices and the evolution of the thermal gap curve will be analyzed. By understanding the potential impact of increased energy storage capacity, we can gain insights into the changing dynamics of the energy sector and the role of storage technologies in facilitating a more efficient and sustainable energy system.

To assess the impact of the target energy storage capacity proposed in the INECP, an iterative strategy has been deployed. This configuration introduces the additional storage capacity in different iterations, allowing for the study of its impact on various aspects such as the revenues earned by each iteration of storage introduced and the evolution of the thermal gap and prices, according to them.

By incorporating the target capacity in a phased manner, the algorithm enables an in-depth analysis of the changing dynamics in the energy market as more and larger storage systems are deployed. This approach allows to study the incremental effects of increased storage capacity on key variables and indicators, providing valuable insights into the potential benefits and challenges of the proposed storage scenario.

The precise configuration and operation of the storage technologies chose to be introduced using an iterative procedure, is based on the analysis carried out in the previous section where the most financially viable BESS and PHS configurations were identified.

ITERATION	**0**	**1**	**2**	**3**	**4**
TECHNOLOGY	PHS	PHS	PHS	BESS	BESS
CAPACITY (MW)	1000	1000	1500	1000	1500
NUMBER OF CYCLES	6000	6000	6000	7500	7500
CYCLE LENGTH (h)	12	12	12	4	4

Table 25. INECP target scenario iterative strategy

To comprehensively analyze the INECP target scenario, a detailed financial analysis is conducted for each individual iteration. The analysis begins by calculating the annual net revenue for each iteration, followed by the computation of financial indicators as utilized in the previous cases. It should be noted that based on the outcomes obtained from the individual scenarios, a specific time horizon from 2023 to 2043 has been chosen to evaluate the performance of this configuration over the years. This time horizon assumes a progressive introduction of all renewable capacity starting from the year 2023.

REVENUES (€)	0 (PHS)	1 (PHS)	2 (PHS)	3 (BESS)	4 (BESS)
2023	27.724.835,09 €	18.146.996,95 €	21.672.681,51 €	18.332.415,45 €	16.060.285,45 €
2024	23.732.807,61 €	16.378.011,58 €	21.771.634,33 €	22.660.119,40 €	29.123.376,71 €
2025	30.172.452,85 €	22.303.386,85 €	10.767.195,60 €	13.040.865,02 €	7.380.780,82 €
2026	31.193.387,46 €	20.085.257,43 €	7.846.479,49 €	17.661.882,56 €	18.168.033,05 €
2027	34.887.408,23 €	25.655.028,18 €	27.724.799,85 €	30.205.462,42 €	33.238.318,28 €
2028	38.214.153,04 €	24.658.260,13 €	27.984.914,43 €	28.529.575,28 €	33.477.440,80 €
2029	43.762.597,23 €	33.210.590,73 €	36.278.758,87 €	27.707.601,18 €	39.380.741,69 €
2030	42.565.551,49 €	34.029.465,96 €	38.107.241,08 €	29.732.625,37 €	38.817.467,21 €
2031	47.929.607,45 €	37.534.983,30 €	40.373.404,13 €	29.905.034,50 €	38.863.875,46 €
2032	45.473.040,63 €	35.233.086,94 €	35.966.071,98 €	27.667.389,91 €	42.990.453,68 €
2033	44.727.838,87 €	34.140.883,58 €	36.962.226,64 €	29.735.157,48 €	30.955.377,68 €
2034	50.348.869,80 €	37.447.570,52 €	32.185.669,73 €	29.688.197,19 €	37.421.681,83 €
2035	47.106.904,50 €	35.938.707,09 €	43.530.911,46 €	31.565.236,80 €	46.687.996,83 €
2036	45.730.130,99 €	35.464.688,16 €	41.860.396,53 €	32.089.600,42 €	25.414.761,13 €
2037	47.638.411,48 €	35.776.621,86 €	43.781.210,17 €	31.515.241,90 €	39.453.399,56 €
2038	51.063.865,88 €	41.179.164,44 €	51.035.287,54 €	32.159.315,16 €	45.883.985,06 €
2039	48.127.134,09 €	34.438.800,11 €	39.528.386,84 €	31.728.646,32 €	34.481.030,26 €
2040	52.192.485,75 €	36.793.693,65 €	47.234.248,44 €	36.773.013,13 €	44.549.925,46 €
2041	53.609.226,53 €	42.165.706,28 €	44.926.644,26 €	33.402.383,44 €	42.255.114,75 €
2042	47.938.902,03 €	38.164.127,09 €	46.096.150,67 €	33.930.491,02 €	39.769.916,03 €
2043	52.488.134,46 €	37.633.326,84 €	46.468.450,37 €	35.197.934,28 €	44.234.989,04 €
Total	**906.627.745,47 €**	**676.378.357,65 €**	**742.102.763,92 €**	**603.228.188,22 €**	**728.608.950,79 €**

Table 26. Net annual revenues from 2023-2043 (INECP scenario)

Upon conducting a preliminary examination of the total revenues per iteration in the INECP target scenario, it became evident that in order to facilitate a fair and equal analysis of the revenues obtained in each iteration, a dimensionless comparative measure is required. This measure will allow for a standardized evaluation of revenues across different capacities, enabling meaningful comparisons between iterations.

By employing a dimensionless comparative metric (€/MW), we can effectively assess and compare the revenue performance of each iteration, irrespective of the varying storage capacities involved.

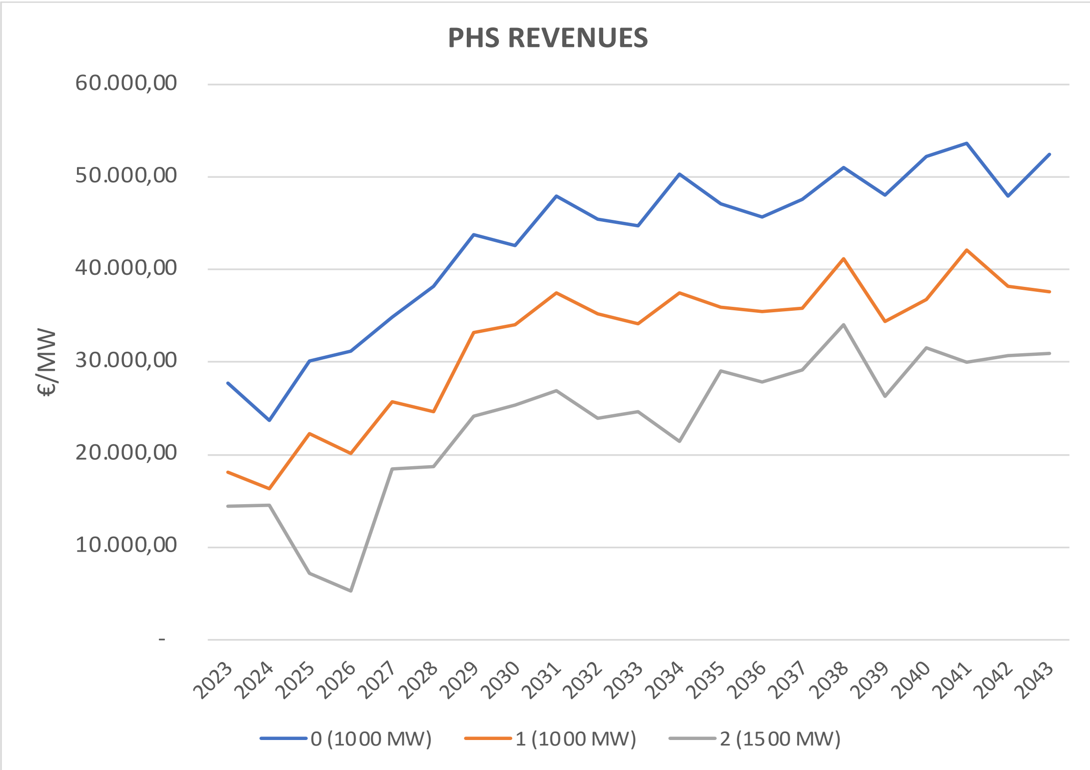

Figure 28. Net annual revenues from 2023-2043 of INECP scenario (PHS)

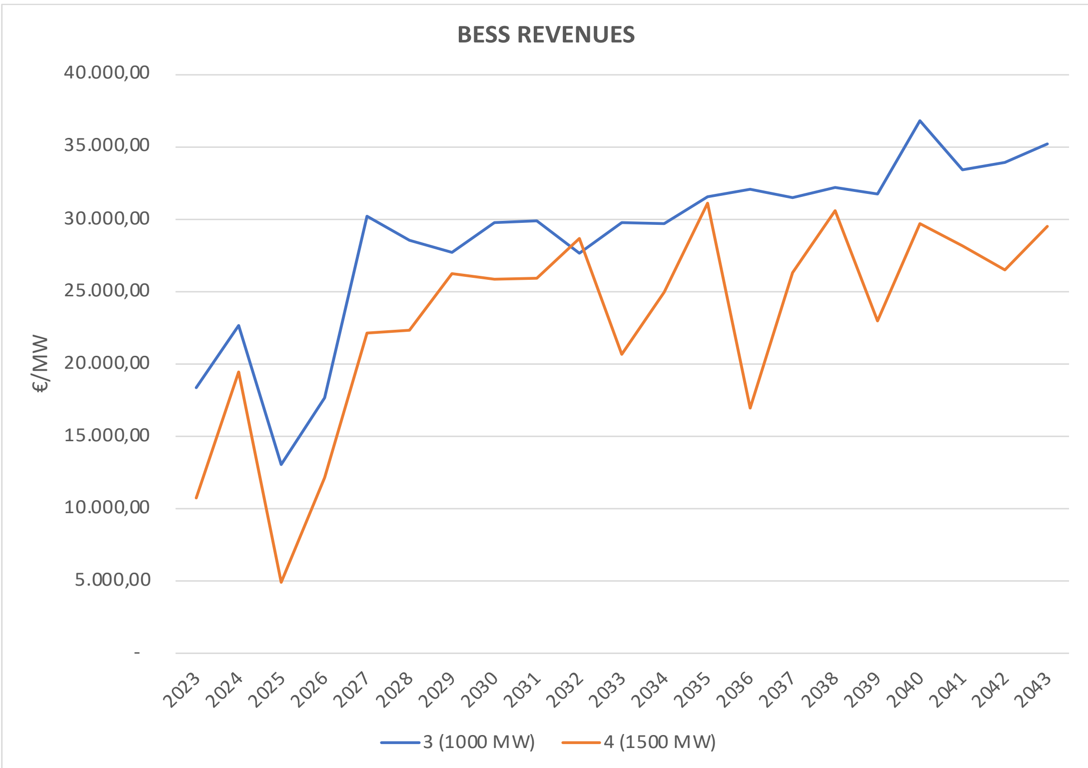

Figure 27. Net annual revenues from 2023-2043 of INECP scenario (BESS)

The two above graphs clearly depict the net annual revenue in euros per megawatt for the different iterations of pumped hydro storage and the last two iterations of battery energy storage systems. A notable observation is the decrease in revenue captured by the systems as more storage capacity is introduced. The figures lead us to the concept of revenue cannibalization, whereby the addition of more storage capacity leads to a reduction in the revenue potential for each unit of capacity. As the market becomes saturated with storage systems, the competition for capturing the available revenue increases, resulting in lower revenue per unit of capacity.

Upon closer examination, it is evident that there is an overall upward trend in the revenues earned across all iterations as the years progress, as it was observed in the previous individual cases. This increasing trend shows the potential for storage systems to capture more revenue over time. However, it is important to note that the two last iterations, which represent the BESS projects, exhibit a less consistent and more fluctuating pattern in their revenue trends compared to the pumped hydro storage iterations.

These fluctuations can be attributed to several factors, including the impact of storage capacity introduction on market prices and the subsequent reduction in spread. With more storage capacity available, there may be fewer and less predictable opportunities to generate revenue, leading to irregular fluctuations in the revenue trends.

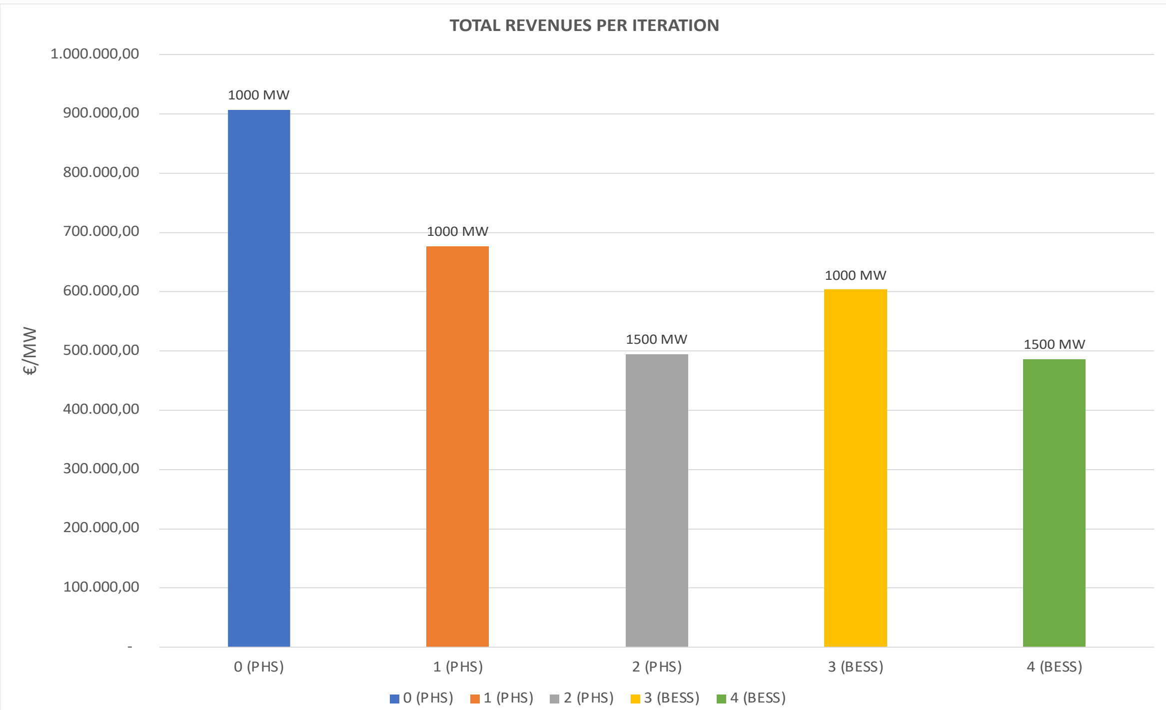

Figure 29. Total revenues per iteration

In the *Figure 29*, all iteration's revenue has been put together and analyzed. It is evident the expected reduction in total benefits as iterations progress. Nevertheless, a discrepancy is identified regarding the higher revenues generated by the 4^{th} iteration compared to the 3^{rd} iteration. This inconsistency can indeed be attributed to several factors, including the cycle length and efficiency of the technologies.

The 12-hour PHS 3^{rd} iteration may not capture as much revenue at that specific point, as it requires longer periods to fully utilize its storage capacity. On the other hand, the 4-hour BESS 4^{th} iteration, with its smaller cycle length and potentially higher participation frequency, may have more opportunities to capture revenues, especially during periods of price volatility. In addition to this, the higher roundtrip efficiency of batteries compared to PHS can contribute to a more effective utilization of stored energy, further enhancing revenue generation potential.

However, it is crucial to note that despite the potentially higher revenues observed in the BESS iteration, the financial viability of the battery energy storage system still needs to be carefully assessed. The higher costs associated with BESS technologies compared to PHS systems could significantly impact the overall profitability and feasibility of the project.

The analysis of financial indicators, performed in *Table 27* will provide valuable insights for policymakers, stakeholders, and decision-makers involved in shaping and implementing the target scenario.

CASH FLOWS	0 (PHS)	1 (PHS)	2 (PHS)	3 (BESS)	4 (BESS)
2023	-740.275.164,91 €	-749.853.003,05 €	-1.130.327.318,49 €	-1.718.867.584,55 €	-2.589.739.714,55 €
2024	23.732.807,61 €	16.378.011,58 €	21.771.634,33 €	22.660.119,40 €	29.123.376,71 €
2025	30.172.452,85 €	22.303.386,85 €	10.767.195,60 €	13.040.865,02 €	7.380.780,82 €
2026	31.193.387,46 €	20.085.257,43 €	7.846.479,49 €	17.661.882,56 €	18.168.033,05 €
2027	34.887.408,23 €	25.655.028,18 €	27.724.799,85 €	30.205.462,42 €	33.238.318,28 €
2028	38.214.153,04 €	24.658.260,13 €	27.984.914,43 €	28.529.575,28 €	33.477.440,80 €
2029	43.762.597,23 €	33.210.590,73 €	36.278.758,87 €	27.707.601,18 €	39.380.741,69 €
2030	42.565.551,49 €	34.029.465,96 €	38.107.241,08 €	29.732.625,37 €	38.817.467,21 €
2031	47.929.607,45 €	37.534.983,30 €	40.373.404,13 €	29.905.034,50 €	38.863.875,46 €
2032	45.473.040,63 €	35.233.086,94 €	35.966.071,98 €	27.667.389,91 €	42.990.453,68 €
2033	44.727.838,87 €	34.140.883,58 €	36.962.226,64 €	29.735.157,48 €	30.955.377,68 €
2034	50.348.869,80 €	37.447.570,52 €	32.185.669,73 €	29.688.197,19 €	37.421.681,83 €
2035	47.106.904,50 €	35.938.707,09 €	43.530.911,46 €	31.565.236,80 €	46.687.996,83 €
2036	45.730.130,99 €	35.464.688,16 €	41.860.396,53 €	32.089.600,42 €	25.414.761,13 €
2037	47.638.411,48 €	35.776.621,86 €	43.781.210,17 €	31.515.241,90 €	39.453.399,56 €
2038	51.063.865,88 €	41.179.164,44 €	51.035.287,54 €	32.159.315,16 €	45.883.985,06 €
2039	48.127.134,09 €	34.438.800,11 €	39.528.386,84 €	31.728.646,32 €	34.481.030,26 €
2040	52.192.485,75 €	36.793.693,65 €	47.234.248,44 €	36.773.013,13 €	44.549.925,46 €
2041	53.609.226,53 €	42.165.706,28 €	44.926.644,26 €	33.402.383,44 €	42.255.114,75 €
2042	47.938.902,03 €	38.164.127,09 €	46.096.150,67 €	33.930.491,02 €	39.769.916,03 €
2043	52.488.134,46 €	37.633.326,84 €	46.468.450,37 €	35.197.934,28 €	44.234.989,04 €
NPV	- 264.458.339,46 €	- 395.866.466,88 €	-755.127.897,24 €	-1.429.141.523,78 €	-2.239.709.381,31 €
IRR	1,5%	-1,1%	-3,5%	-8,2%	-9,5%

Table 27. Cash flows from 2023-2043 (INECP scenario)

Examining the economic assessment the only iteration that appear to have started recovering its incurred costs although still below the imposed interest rate, is the first 1000 MW iteration of the 12-hour PHS configuration. This initial iteration, has recoverd up to this point in time a 60% of its costs. After this, as the iterations progress and more storage capacity is introduced, several factors that contribute to the worsening of the financial indicators.

One key factor is the decrease in revenues over time. As more storage capacity is added to the market, the supply of storage resources increases, leading to increased competition. This competition can drive down the wholesale market prices and reduce the opportunities for revenue generation.

In the case of the 2nd and 3rd iterations, although it captures a significant amount of revenue, recovering a 45% and a bit more than a 30% of their incurred costs respectively, they still faces challenges in terms of financial viability.

On the other hand, although the 4th iteration (BESS) captures higher revenues compared to the 3rd iteration, the higher costs associated with battery energy storage systems offset the revenue gains. The higher costs are be attributed to the technology development and infrastructure required for battery storage. As a result, the financial viability of the BESS system is still compromised, reflected in the negative NPV and lower IRR.

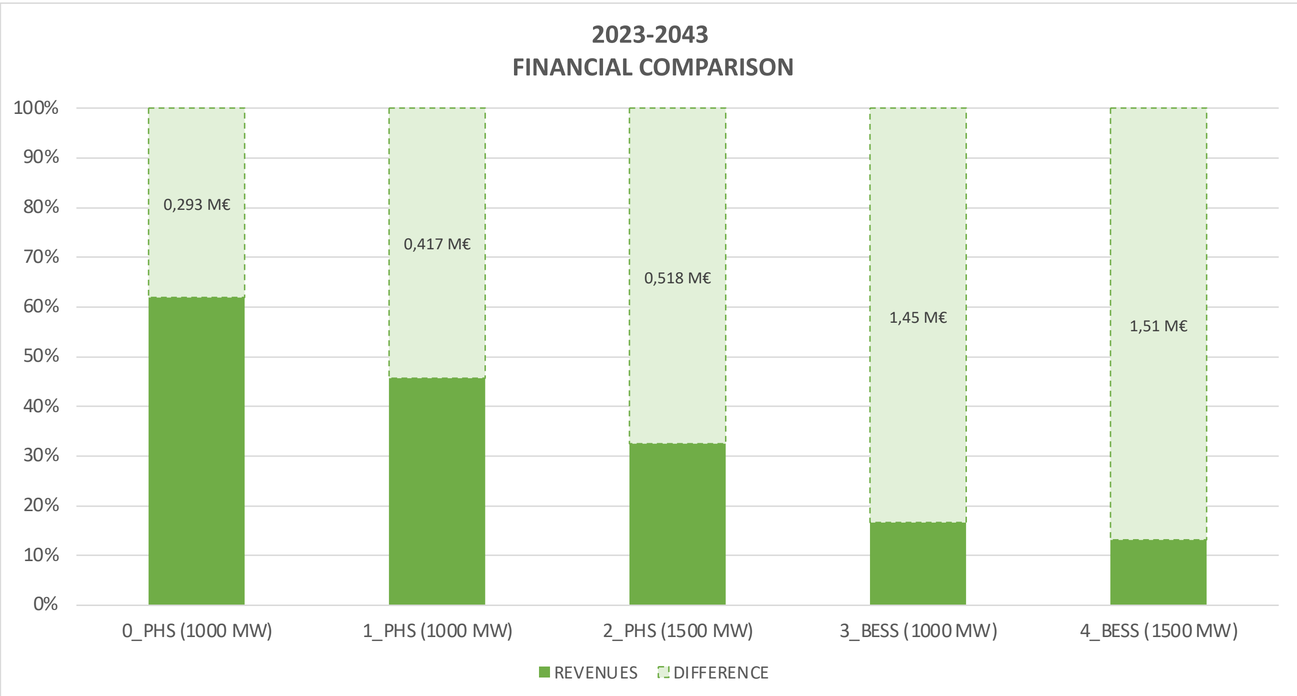

Figure 30. Global financial comparison from 2023-2043 (INECP scenario)

In addition to the financial aspects, the interesting focus of simulating the INECP target scenario employing an iterative strategy is to study the evolution of the energy mix, more specifically the thermal gap, as well as the evolution of the wholesale electricity market prices as the penetration of energy storage capacity in the market grows.

The graph showing the evolution of the thermal gap for the year 2030, as the iterations (in different colors) progress provides insights into the impact of storage capacity on the balance between electricity supply and demand. As more storage capacity is introduced, it can contribute to a more balanced and reliable energy system by absorbing excess electricity during periods of high generation and supplying electricity during peak demand, thus the expectation is that the thermal gap decreases over time.

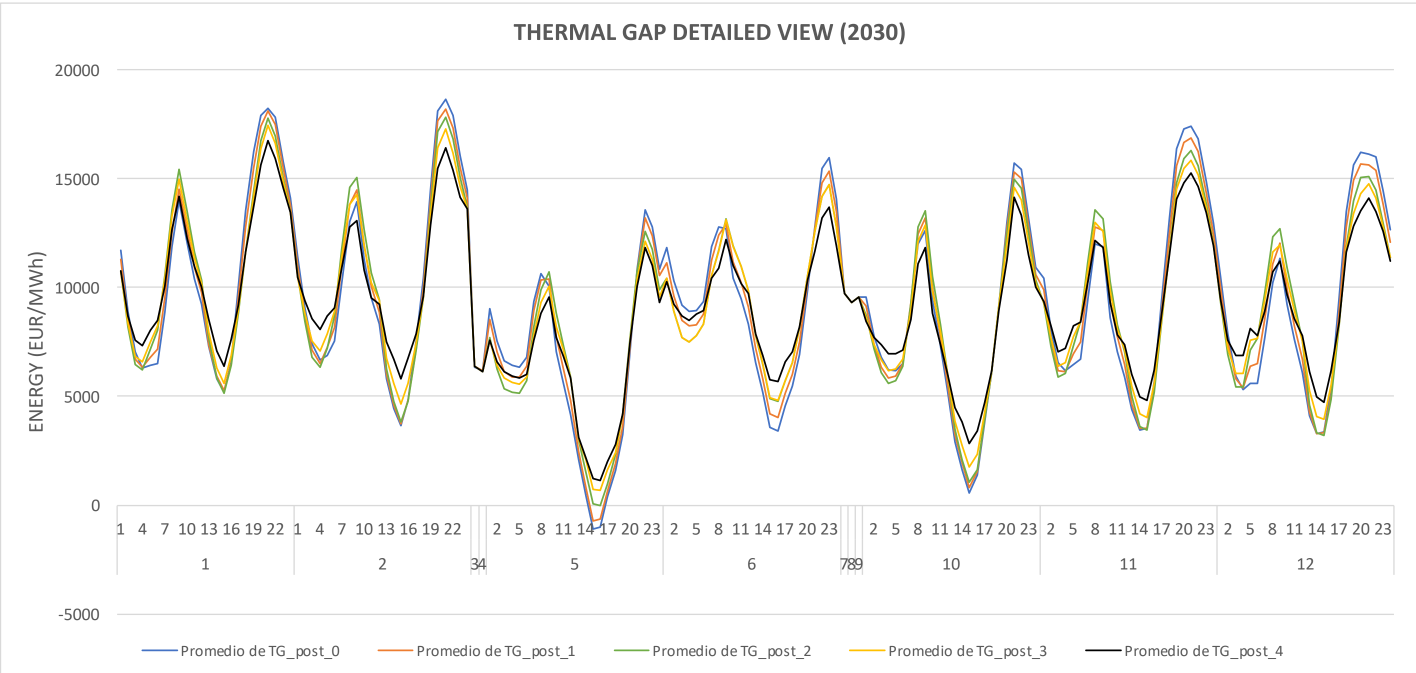

Figure 31. Detailed thermal gap evolution for year 2030

This has led to an initial thermal gap (blue curve) that occasionally dips into negative values, indicating an excess of renewable energy generation. In such cases, the grid may not have enough demand to accommodate all the renewable energy being produced, resulting in renewable curtailment. Thus, it can be understood that negative values of the thermal gap mean renewable energy curtailment. However, as energy storage systems are progressively introduced, this issue is alleviated. The energy storage systems capture the surplus energy during periods of low demand and store it for later use when demand is higher, evolving up to a final iteration thermal gap where all values are positive.

On the other hand, during periods of low electricity demand, when there is excess generation from renewable sources, the storage systems can store the surplus electricity. This leads to an increase in valley values of the thermal gap, as the stored electricity is utilized to fill the gap between renewable generation and lower demand. By doing so, it helps to avoid curtailment of renewable energy and makes better use of the available excess generation.

In *Figure 35*, the same representation as before including the evolution of the electricity prices is exposed. To simplify the display of the results only the curves involving the initial (light blue and yellow) and last iterations (black and orange) have been represented.

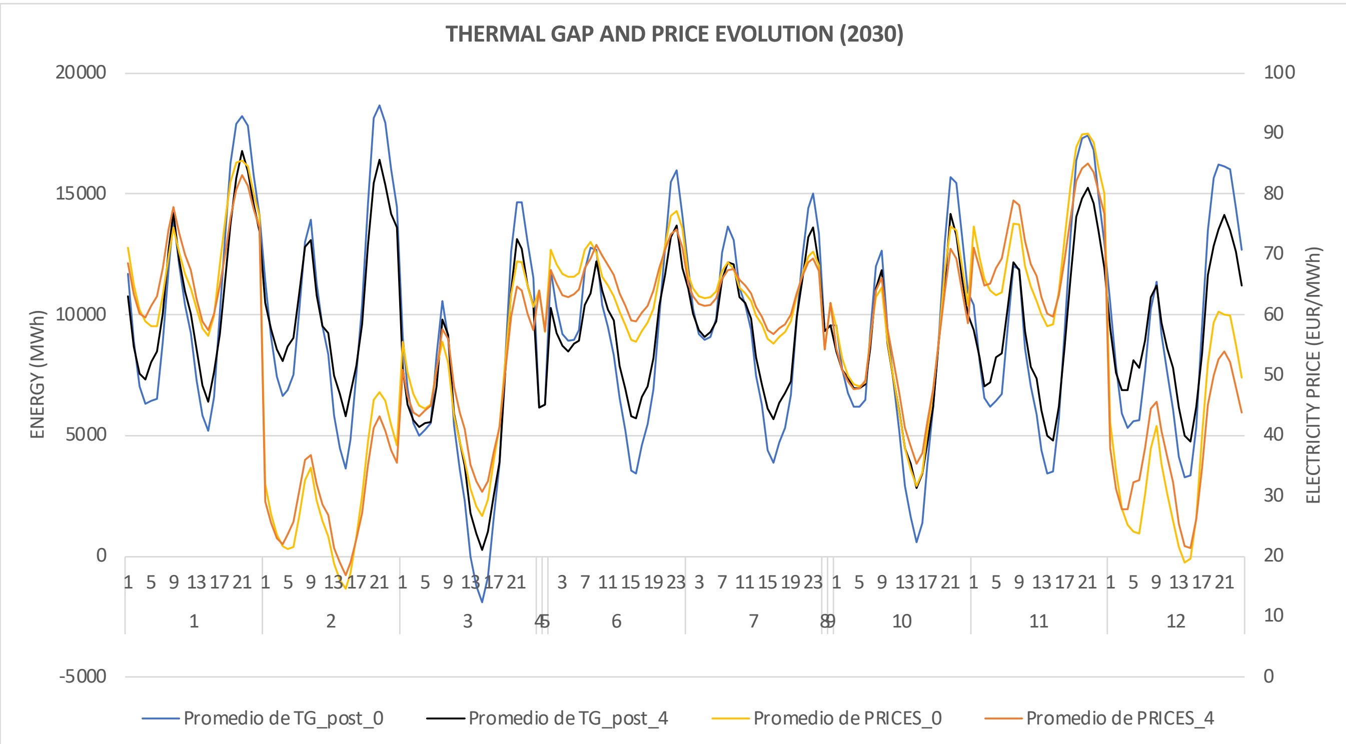

Figure 32. Detailed thermal gap and electricity price evolution for year 2030

As observed in the graphs, the presence of energy storage systems helps reduce peak prices by storing excess energy during low-demand periods and releasing it during high-demand periods. This effectively smooths out the price spikes that occur during periods of high electricity demand.

However, a notable consequence of increased storage penetration is the rise in baseload prices, as indicated by the transition from the yellow to the orange curve. This is because as more storage capacity is deployed, the systems are increasingly utilized to capture excess energy during periods of low demand, which leads to a flattening effect on prices during these times. As a result, the prices during low-demand periods tend to increase, approaching the level of baseload prices.

In years with exceptionally high electricity prices, such as in 2025, energy storage systems can play a more active role by capitalizing on these high prices. They achieve this by charging during low-price periods and discharging during high-price periods to maximize their revenue potential. However, during these high-price periods, the storage systems may opt to perform only discharging actions due to the continued relatively high prices compared to low-price months. Consequently, the storage systems may find it more profitable to discharge electricity during these high-price periods rather than charging during low-price periods. This strategic approach allows the energy storage systems to optimize their earnings by leveraging the price fluctuations in the electricity market.

Given the decarbonization policies and the net-zero target, as years go by the penetration of renewables will increase aiming for a 100% renewable energy mix in the midterm future. The effect of these objectives in the thermal gap was exposed in year 2030, but in the next year represented in *Figure 36*, 2043, the impact is even higher as we observe more frequent and steep periods where the thermal gap is negative. More and larger energy storage systems help reduce the frequency of curtailments in the electricity grid in these scenarios.

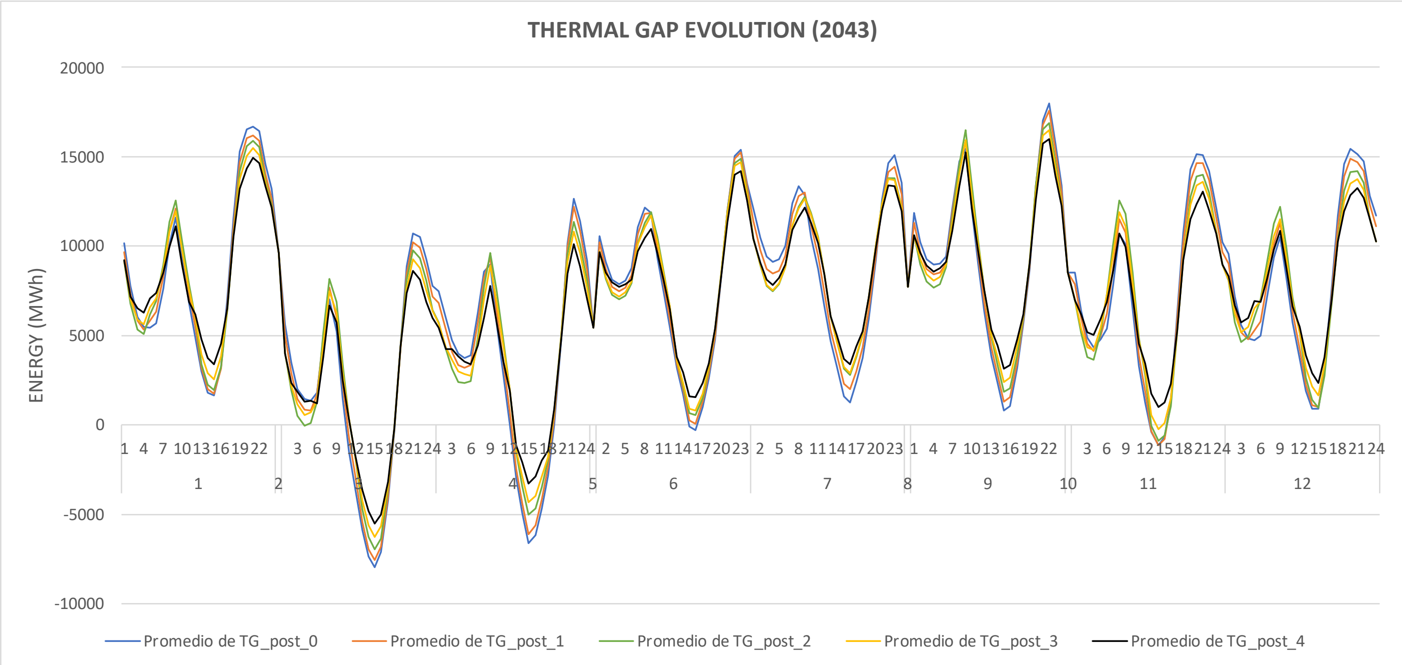

Figure 33. Detailed thermal gap evolution for year 2043

Curtailment occurs when there is an excess of electricity supply, particularly from renewable energy sources, leading to a waste of energy and lost revenue for renewable energy producers. By the curtailed renewable energy during low-demand periods and releasing it when demand is higher, energy storage systems can effectively reduce curtailment, in the hours with a negative thermal gap. This means that more of the renewable energy generated can be utilized and sold, leading to higher revenues for renewable energy producers and less missing money.

However, there is a possibility that as more energy storage is introduced and curtailment decreases, there may be a potential reduction in the need for as much installed renewable energy capacity. This could lead to decreased incentives for investing in new renewable energy projects, as the demand for additional renewable capacity might decrease. As a result, renewable energy producers might face reduced incentives to invest in new projects or expand their existing capacity.

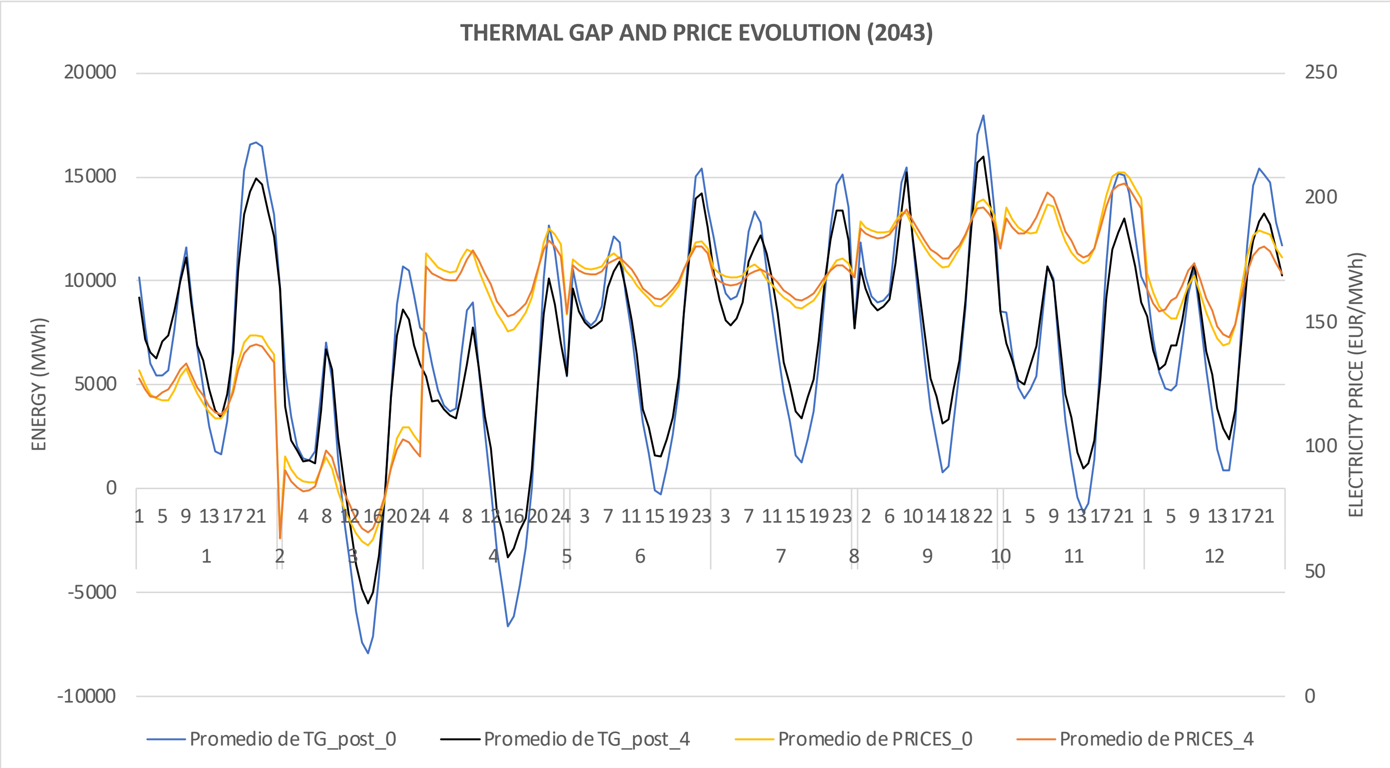

Figure 34. Detailed thermal gap and price evolution for year 2043

By observing this above-figure it is again confirmed that as increasing energy storage is introduced into the market and used for peak-shaving purposes, the spread between buying at low prices and selling at high prices decreases.

As the price difference between peak and off-peak periods becomes less pronounced, the revenue potential for new storage investments also decreases. At a certain point, the diminishing returns on additional storage capacity may make it less financially attractive for investors to continue expanding storage installations. Additionally, as the market becomes saturated with energy storage resources, competition among storage operators increases, further driving down the revenue potential. This could potentially happen there is a point in time where the storage capacity greatly exceeds the demand for peak-shaving and arbitrage services. (AFRY, 2020)

7 CONCLUSIONS

After conducting a comprehensive analysis of the current state of energy storage technologies, the energy transition initiatives in Spain and Europe, the major challenges posed by the journey towards the net-zero target, the evaluation of an MLMR prediction model for electricity prices, and the development of an optimization and financial model for energy storage projects utilizing lithium-ion batteries and pumped hydro storage technologies, this chapter will present and discuss the final conclusions drawn from the entire thesis.

7.1 THESIS CONCLUSIONS

Our exhaustive analysis revealed that both pumped storage and battery energy storage systems have unique advantages and challenges, making them suitable for different applications in the evolving energy landscape.

PHS systems have demonstrated impressive capabilities in handling very high cycle numbers, making them highly viable energy storage system technologies. Even without considering additional revenue streams generated through electricity generation in mixed pumped systems and water inflows, this study focuses solely on the price arbitrage activity. The results show that PHS installations remain financially viable due to their long operational lifetime, enabling them to fully recover their initial costs and even generate additional profits over time. The combination of high cycle numbers and the revenue earned from price arbitrage alone validates pumped hydro storage as a robust and reliable ESS technology.

On the other hand, battery energy storage systems offer excellent modularity and efficiency, making them crucial elements for achieving the ambitious 2030 targets set in the European “Fit for 55" proposal and in the Spanish Integrated National Energy and Climate Plan. With an increasing share of renewable energy sources in the energy mix, BESS plays a vital role in addressing key challenges such as avoiding RES curtailment, improving grid stability, and providing flexibility to the electricity system.

However, despite their significance, the main challenge observed for batteries lies in their relatively higher investment costs compared to other technologies. To fully capitalize on the potential benefits of BESS and maximize their role in the energy transition, it is essential to address these cost-related barriers. Several factors contribute to the higher investment costs of BESS. Firstly, the cost of battery technology itself remains a significant component of the overall investment. While there have been notable cost reductions in lithium-ion batteries, further research and development are necessary to explore new battery chemistries and materials, improved manufacturing processes, and enhanced system designs that can lower costs without compromising performance and safety. Continued research and innovation in BESS are vital to uncovering innovative solutions that can reduce costs.

Also, achieving economies of scale will be instrumental in driving down battery storage systems costs. As deployments of BESS increase, the rising demand and manufacturing efficiencies will lead to cost reductions, making them more cost-competitive with other already-competitive energy storage technologies, such as PHS, as it has been proven in our study.

It is evident that batteries are necessary to achieve the ambitious energy transition objectives. However, in the present scenario, battery storage systems are unlikely to be profitable without incentives on the wholesale market, especially when considering only the revenues generated through price arbitrage. To unlock the full potential of BESS and encourage their widespread adoption, government incentives or significant reductions in BESS investment costs are crucial. Incentives can act as catalysts to enhance the competitiveness of BESS, making them as financially viable as PHS. Moreover, a new regulatory framework must be put in place to organize storage incentives and to create a level playing field for different storage technologies.

An important observation made, thanks to the analysis of the INECP scenario, is that in this future context of high targets for renewable energy penetration in a relatively low time period, energy storage emerges as a vital solution to avoid renewable curtailments. The introduction of energy storage systems also, reduces the need for costly grid infrastructure expansions to accommodate the increasing penetration of renewables. Grid-scale storage can act as a buffer, mitigating the variability of renewable energy sources and enhancing grid stability. This ability to smooth out fluctuations in energy generation ensures a seamless integration of renewable energy into the grid.

However, this INECP scenario also enables to explore the phenomenon of revenue cannibalization that introduces the critical need for understanding the impact of storage capacity expansion in the energy sector. As storage capacity increases, there is a clear trend of decreasing net annual revenue in euros per megawatt observed, this highlights the challenges that arise when scaling up storage without considering market dynamics and revenue optimization strategies. This insight underscores the importance of carefully managing storage growth to achieve optimal financial outcomes, Decision-makers and stakeholders must recognize the significance of implementing effective market mechanisms, pricing strategies, and operational optimizations to maximize revenue potential and ensure the financial sustainability of storage projects in a competitive market environment.

Extensive research has demonstrated the necessity for a well-defined national regulatory framework that effectively incentivizes energy storage, with a particular focus on BESS. it is crucial to create a regulatory environment that provides stability and certainty to investors and stakeholders. By doing so, it will instill confidence and drive interest in the deployment of energy storage solutions, especially BESS.

Incentives play a pivotal role in attracting investments and fostering the growth of energy storage. By offering financial incentives, tax benefits, or other supportive mechanisms, governments can encourage more significant participation in the storage market. These incentives will act as key drivers for both research and development efforts, as well as large-scale deployment of BESS projects.

Moreover, clearly defined regulatory aspects will help create a level playing field for energy storage technologies. Uniform standards and guidelines ensure that storage projects are treated fairly and equally in the market, regardless of their technology type or size. This equity will boost competition and innovation, ultimately leading to cost reductions and improved performance of BESS.

7.2 FUTURE WORK

The findings and conclusions drawn from this thesis provide valuable insights into the role of energy storage technologies, particularly pumped hydro storage, and battery energy storage systems, in the energy transition. As we look towards the future, several key areas deserve further attention and research to accelerate the deployment and optimization of energy storage solutions in the evolving energy landscape.

These aspects pave the way for the continuation of several lines of research, including but not limited to the following:

- **Policy and regulatory framework:** A robust and comprehensive national regulatory framework is necessary to incentivize energy storage deployment, particularly BESS. Researchers and policymakers should prioritize creating and exploring new supportive policies, incentives, and guidelines that encourage investments in storage projects and level the playing field for different storage technologies. Clear regulations will foster investor confidence and accelerate the integration of energy storage into the energy system.

- **Optimization of BESS for ancillary services:** Further research in this area could expand the operation of BESS in ancillary services. While this study focused primarily on the price arbitrage activity of energy storage systems, BESS has the potential to provide valuable ancillary services to the grid. Ancillary services refer to the support functions that help maintain the stability, reliability, and security of the electricity grid. These services include frequency regulation, voltage control, reactive power support, and grid balancing, among others. BESS, with their fast response times and high efficiency, are well-suited to provide these essential services.

- **Hydrogen:** Hydrogen Energy Storage Systems (HESS) are gaining momentum as a promising and cost-effective solution for storing renewable energy, facilitating energy transportation, and supporting a transition to a low-carbon energy system. The concept of a hydrogen economy is becoming increasingly compelling in various sectors, including electricity generation, transportation, and industrial processes. The utilization of hydrogen as an energy carrier offers the potential to store excess renewable energy, enabling its use during periods of high demand or when renewable generation is low. (Arsad, et al., 2022)

As the hydrogen economy continues to garner interest and support from researchers, international organizations, and businesses, there is a growing need for optimization studies like those conducted for pumped hydro storage and battery energy storage systems. An optimization study specific to HESS technology would be an exciting and valuable future guideline to explore.

8 BIBLIOGRAPHY

Acosta, S., 2023. *El nuevo PNIEC 2023-2030, al completo.* [En línea] Available at: https://elperiodicodelaenergia.com/el-nuevo-pniec-2023-2030-al-completo/
[Último acceso: July 2023].

AFRY, 2020. *Energy Storage.* Madrid, s.n.

Aguas del Júcar S.A., 2007. *INFORME DE VIABILIDAD DE LA " INFRAESTRUCTURA PARA EL APROVECHAMIENTO HIDROELÉCTRICO EN EL EMBALSE DE CORTES II",* Valencia: Ministerio de Medio Ambiente.

Alvarez, G. E., 2020. Operation of pumped storage hydropower plants through optimization for power systems. *Energy,* Volumen 202, pp. 1-13.

Andrey, C., Barberi, P. & Nuffel, L., 2020. *Study on energy storage : contribution to the security of the electricity supply in Europe,* Luxembourg: Publications Office.

Arsad, A. et al., 2022. Hydrogen energy storage integrated hybrid renewable energy systems: A review analysis for future research directions. *International Journal of Hydrogen Energy,* 47(39), pp. 17285-17312.

Augustine, C. & Blair, N., 2021. *Energy Storage Futures Study: Storage Technology Modeling Input Data Report,* Golden: National Renewable Energy Laboratory.

Böckers, V., Haucap, J. & Heimeshoff, U., 2013. *Benefits of an integrated European electricity market: the role of competition* , Brussels: European Added Value Unit.

Balietti, A. C., 2016. Trader types and volatility of emission allowance prices. Evidence from EU ETS Phase I. *Energy Policy,* Volume 98, pp. 607-620.

Barberi, P., Fournié, L. & Boßmann, T., 2018. *Effect of high shares of renewables on power systems,* Brussels: European Commission.

Baumgarte, F., Glenk, G. & Rieger, A., 2020. Business Models and Profitability for Energy Storage. *iScience,* 23 October, Volumen 23, pp. 1-12.

Beuse, M., Steffen, B., Dirksmeier, M. & S. Schmidt, T., 2021. Comparing CO2 emissions impacts of electricity storage across applications and energy systems. *Joule,* 5(6), pp. 1501-1520.

Brozyna, J., Strielkowski, W. & Zpevák, A., 2023. Evaluating the Chances of Implementing the "Fit for 55" Green Transition Package in the V4 Countries. *Energies,* 16(2764).

Carbajo, A., 2007. LOS MERCADOS ELÉCTRICOS Y LOS SERVICIOS DE AJUSTE DEL SISTEMA. *Economía Industrial,* Issue 364, pp. 55-62.

Castro, A., 2006. *Minicentrales hidroeléctricas,* Madrid: Instituto para la Diversificación y Ahorro de la Energía.

CEOE, 2022. *Claves del Paquete "Fit For 55" de la Comisión Europea,* s.l.: CEOE: Industria, Energía, Medio Ambiente y Clima.

Chandreyee, B. & Velten, E., 2014. *"The EU Emissions Trading System: Regulating the Environment in the EU".* [Online] Available at: http://climatepolicyinfohub.eu/eu-emissions-trading-system-introduction [Accessed 2023].

CNMC, 2018. *PROPUESTA DE METODOLOGÍA DE CÁLCULO DE LA TASA DE RETRIBUCIÓN FINANCIERA DE LA ACTIVIDAD DE PRODUCCIÓN DE ENERGÍA ELÉCTRICA A PARTIR DE FUENTES DE ENERGÍA RENOVABLES, COGENERACIÓN Y RESIDUOS PARA EL SEGUNDO PERIODO REGULATORIO 2020-2025,* s.l.: Comisión Nacional de los Mercados y la Competencia.

Connolly, D. y otros, 2011. Practical operation strategies for pumped hydroelectric energy storage (PHES) utilising electricity price arbitrage. *Energy Policy,* 39(7), pp. 4189-4196.

Council of the European Union, 2023. *Fit for 55.* [En línea] Available at: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

Cuthbertsom, A., 2020. *POWER PRICE CANNIBALISATION – HOW IS IT AFFECTING YOUR RENEWABLES PROJECTS?.* [Online] Available at: https://www.bdo.global/en-gb/blogs/valuations-blog/june-en/power-price-cannibalisation-%e2%80%93-how-is-it-affecting-your-renewables-projects [Accessed February 2023].

Deloitte, 2022. *"Fit for 55" package: EU legislative action for the climate.* [En línea] Available at: https://www2.deloitte.com/lt/en/pages/consulting/topics/Fit-for-55-package.html

Directorate General for Energy, 2020. *Study on energy storage – Contribution to the security of the electricity supply in Europe,* Brussels: European Commission.

DNV & smartEN, 2022. *Demand-side flexibility in the EU: Quantification of benefits in 2030,* Bruselas: DNV.

DOE, 2023. *Global Energy Storage Database.* [Online] Available at: https://gesdb.sandia.gov/statistics.html [Accessed June 2023].

EnergySage, 2019. *Environmental impacts of hydropower.* [Online] Available at: https://www.energysage.com/about-clean-energy/hydropower/environmental-impacts-hydropower/#:~:text=Constructing%20large%20storage%20or%20pumped,important%20migration%20routes%20for%20fish. [Accessed June 2023].

Enseñat y Berea, F. J., 2021. *El almacenamiento hidráulico en centrales reversibles.* Madrid, s.n.

entso-e, 2023. *Single Day-ahead Coupling (SDAC).* [En línea] Available at: https://www.entsoe.eu/network_codes/cacm/implementation/sdac/#market-information
[Último acceso: June 2023].

ESAE, 2021. *Energy Storage Technology Descriptions.* [Online] Available at: https://ease-storage.eu/energy-storage/technologies/
[Accessed June 2023].

European Comission, 2019. *Implementation of the Strategic Action Plan on Batteries: Building a Strategic Battery Value Chain in Europe,* Brussels: Publications Office.

European Commission, 2021. *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS.* Brussels, s.n.

European Commission, 2023. *EU Emissions Trading System (EU ETS).* [Online] Available at: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en
[Accessed June 2023].

Feng, L. y otros, 2022. Optimization analysis of energy storage application based on electricity price arbitrage and ancillary services. *Journal of Energy Storage,* 55(105508), pp. 1-10.

ICAP, 2022. *International Carbon Action Partnership.* [Online] Available at: https://icapcarbonaction.com/es/ets_system/43
[Accessed June 2023].

IEA, 2022. *Data and Statistics.* [En línea] Available at: https://www.iea.org/data-and-statistics/charts/annual-grid-scale-battery-storage-additions-2017-2022

IEA, 2022. *Grid-Scale Storage,* Paris: IEA.

Instituto para la Diversificación y Ahorro de la Energía, 2006. *Minicentrales hidroeléctricas,* Madrid: IDAE.

IRENA, 2017. *Electricity Storage and Renewables: Costs and Markets to 2030,* Abu Dhabi: International Renewable Energy Agency.

IRENA, 2017. *Electricity Storage and Renewables: Costs and Markets to 2030,* Abu Dhabi: International Renewable Energy Agency.

IRENA, 2020. *Electricity Storage Valuation Framework: Assessing system value and ensuring project viability,* Abu Dhabi: International Renewable Energy Agency.

IRENA, 2022. *Renewable Power Generation Costs in 2021,* Abu Dhabi: International Renewable Energy Agency.

Jülch, V., 2016. Comparison of electricity storage options using levelized cost of storage (LCOS) method. *Applied Energy,* Volumen 183, pp. 1594-1606.

Kasuya, E., 2019. On the use of r and r squared in correlation and regression. *Ecological Research,* 34(1), pp. 234-235.

Kumar, A., 2020. Assessment of energy storage technologies: A review. *Energy Conversion and Management,* 223(113295).

Lam, L. H., Ilea, V. & Bovo, C., 2018. European day-ahead electricity market coupling: Discussion, modeling, and case study. *Electric Power Systems Research,* Volumen 155, pp. 80-92.

LAZARD, 2021. *Levelized Cost Of Storage Analysis - Version 7.0,* s.l.: Lazard and Roland Berger.

Lorenzi, G., da Silva Vieira, R., Santos Silva, C. A. & Martin, A., 2019. Techno-economic analysis of utility-scale energy storage in island settings. *Journal of Energy Storage,* Volume 21, pp. 691-705.

López de la Nieta Polonio, C., 2022. *Ánalisis de los precios en el mercado diario eléctrico español.* Madrid: Escuela Técnica Superior de Ingeniero Industriales (UPM).

MARINO, M. D., ARANGO, A., LOTERO, L. & JIMENEZ, M., 2021. Modelos de series temporales para pronóstico de la demanda eléctrica del sector de explotación de minas y canteras en Colombia. *EIA,* 18(35), pp. 77-99.

Memmel, E. y otros, 2021. Forecast of Renewable Curtailment in Distribution Grids Considering Uncertainties. *IEEE Access,* Volumen 9, pp. 60828-60840.

MIBGAS, 2023. *MIBGAS Spot.* [Online] Available at: https://www.mibgas.es/en/mainmenu/mibgas-spot?menu=1&parent=8#10 [Accessed June 2023].

Ministry for Ecological Transition and the Demographic Challenge, 2020. *DRAFT OF THE INTEGRATED NATIONAL ENERGY AND CLIMATE PLAN 2021-2030,* s.l.: s.n.

Ministry for Ecological Transition and the Demographic Challenge, 2023. *DRAFT OF THE INTEGRATED NATIONAL ENERGY AND CLIMATE PLAN 2023-2030,* s.l.: s.n.

Navalés, B., 2021. *Ciclo de conferencias sobre Almacenamiento de Energía Almacenamiento Eléctrico con Bombeo Hidráulico.* s.l., s.n.

Navarro Uriel, M., 2012. *ANÁLISIS DE VIABILIDAD DE LOS BOMBEOS REVERSIBLES.* Zaragoza: Universidad de Zaragoza.

Nguyen, T.-T., Martin, V., Malmquist, A. & A.S. Silva, C., 2017. A review on technology maturity of small scale energy storage technologies. *Renewable Energy and Enviromental Sustainability,* 2(36).

Olabi, A. y otros, 2021. Critical review of energy storage systems. *Energy,* 214(118987).

OMIE, 2022. *Informe Anual 2022 ESP,* s.l.: OMIE.

Pacce, M., Sánchez, Isabel & Suárez-Varela, M., 2021. *EL PAPEL DEL COSTE DE LOS DERECHOS DE EMISIÓN DE CO2 Y DEL ENCARECIMIENTO DEL GAS EN LA*

EVOLUCIÓN RECIENTE DE LOS PRECIOS MINORISTAS DE LA ELECTRICIDAD EN ESPAÑA, Madrid: Banco de España.

Pacce, M., Sánchez, I. & Suárez-Varela, M., 2021. *RECENT DEVELOPMENTS IN SPANISH RETAIL ELECTRICITY PRICES: THE ROLE PLAYED BY THE COST OF CO2 EMISSION ALLOWANCES AND HIGHER GAS PRICES,* Madrid: Documentos Ocasionales (BANCO DE ESPAÑA).

PwC España, 2021. *El papel del almacenamiento en la Transición Energética,* s.l.: Fundación Naturgy.

Ramasamy, V., Feldman, D., Desai, J. & Margolis, R., 2021. *U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021,* Golden: National Renewable Energy Laboratory.

Red Eléctrica de España, 2023. *REData.* [Online] Available at: https://www.ree.es/en/datos/generation/installed-capacity [Accessed July 2023].

REE, 2009. *Equivalent hours" in the context of a hydro plant refers to the number of hours during which the plant would generate an amount of energy equal to its rated output over a given period of time. In other words, it is a measure of how many hours per year the,* s.l.: Red Eléctrica de España.

Rogel-Salazar, J. & Sapsford, N., 2013. *Seasonal Effects in Natural Gas Prices and the Impact of the Economic Recession,* Hatfield: s.n.

RotellaJunior, P. y otros, 2021. Economic Analysis of the Investments in Battery Energy Storage Systems: Review and Current Perspectives. *Energies,* 14(2503).

Schönheit, D. y otros, 2021. Toward a fundamental understanding of flow-based market coupling for cross-border electricity trading. *Advances in Applied Energy,* 2(100027).

TESLA, 2023. *Megapack: Massive Energy Storage.* [En línea] Available at: https://www.tesla.com/megapack/design

Tiseo, I., 2023. *Emissions Statistics.* [En línea] Available at: https://www.statista.com/statistics/450017/co2-emissions-europe-eurasia/ [Último acceso: July 2023].

United States of America Department of Energy, 2011. *Energy Storage Program Planning Document,* s.l.: Office of Electricity.

Uyanık, G. K. & Güler, N., 2013. A Study on Multiple Linear Regression Analysis. *Procedia - Social and Behavioral Sciences,* Volume 106, pp. 234-240.

Van Hoof, S., 2021. *European Commission launches proposals to reach 55% emissions reduction by 2030.* [En línea] [Último acceso: July 2023].

Viadero, R., Rehbein, M. & Singh, A., 2017. *Hydropower on the Mississippi River.* Illinois, s.n.

Yianni, C., Efthymiou, V. & Georghiou, G. E., 2018. Economic Viability of Battery Energy Storage for the Provision of Frequency Regulation Service. *Journal of Power Technologies*, 98(5), pp. 403-407.

Zhang, X. y otros, 2021. Arbitrage analysis for different energy storage technologies and strategies. *Energy Reports*, Volumen 7, pp. 8198-8206.

Zhang, X. y otros, 2021. Arbitrage analysis for different energy storage technologies and strategies. *Energy Reports*, Volumen 7, pp. 8198-8206.