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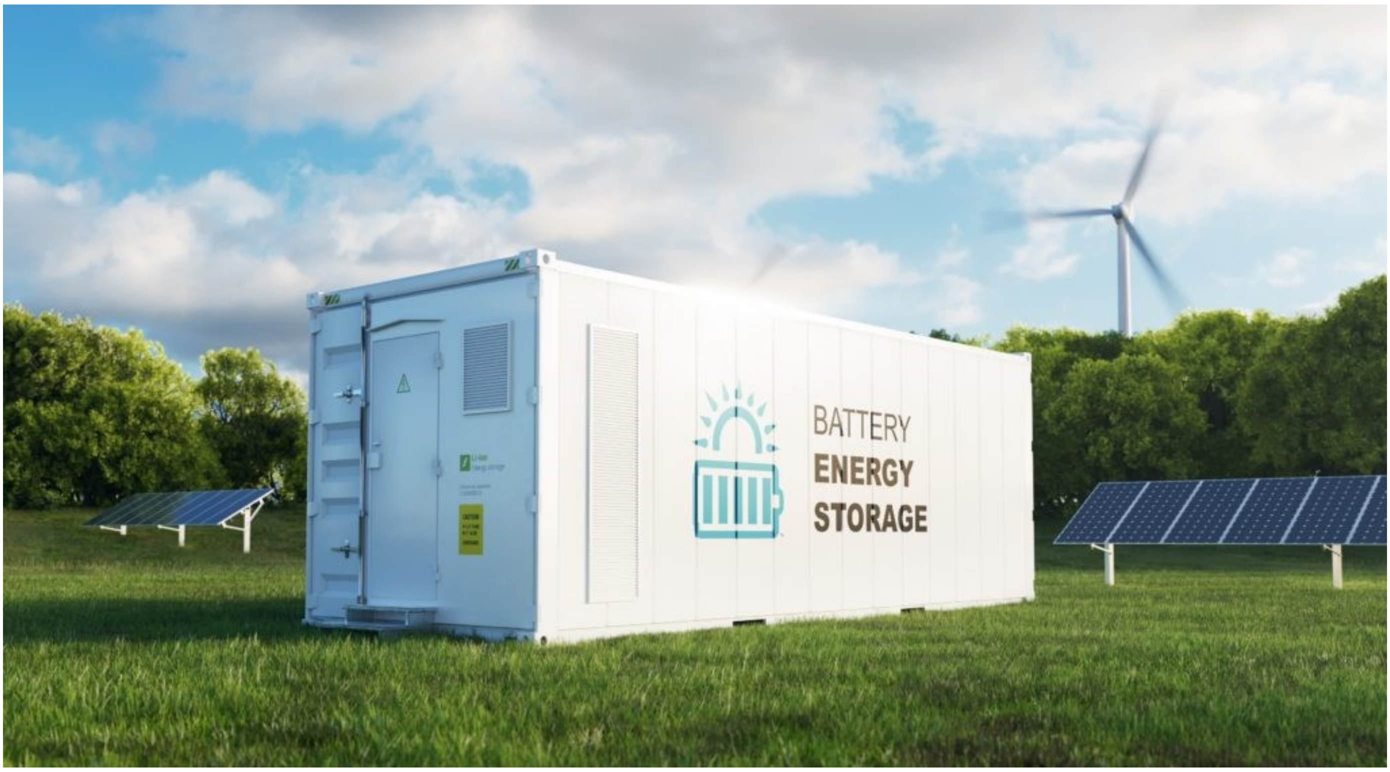
Techno-economic analysis of utility scale BESS projects

ADITYA



KTH Industrial Engineering and Management	**Master of Science Thesis TRITA-ITM-EX 2024:521** **Techno-economic analysis of utility scale BESS projects**	
	Aditya	
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Abstract

Battery Energy Storage Systems are being projected as a key instrument for energy transition particularly within the context of the European Union's energy transition goals. The study focuses on Spain as a key market, exploring the integration of BESS with renewable sources such as solar and wind to enhance grid stability and optimize energy usage. Through market research, data exploration, and optimization modelling, the study examines the economic viability of BESS under various operational scenarios and project parameters.

The findings indicate that co-located BESS can significantly improve the economic performance of renewable energy installations by enabling energy arbitrage, frequency regulation, and peak shaving, thereby enhancing revenue streams while reducing operational costs. The research highlights the technological synergies of BESS, such as shared infrastructure and reduced transmission losses, which contribute to overall grid stability and reliability.

However, the study also identifies challenges, including high capital costs, evolving technology standards, and market sensitivity to electricity prices and regulatory changes. These factors necessitate careful planning and consideration in the deployment of BESS projects. The analysis suggests that, despite these challenges, the integration of BESS with renewable energy projects offers substantial opportunities for enhancing efficiency and profitability, particularly in markets with high electricity price volatility and robust ancillary service markets.

The study also explores stand-alone use cases of BESS as a cost saving approach for data centres and any other large electrical load centres. The economic viability of BESS projects for these use cases was discussed and the results provide a framework for project developers to identify and develop BESS projects for their specific requirements.

Keywords: BESS, Energy arbitrage, Frequency regulation, Peak shaving, Co-located BESS, Hybrid PPAs, Spanish electricity market, Optimization, Modelling, Linear Programming, Datacentres, Solar + BESS, Python

FOREWORD

This master's thesis represents the completion of a challenging yet rewarding journey, during which I have received invaluable support and guidance from many people. I would like to express my gratitude to my thesis supervisor, Farzin Golzar, whose expertise and insightful feedback have been instrumental in shaping this project. I am also thankful to my family and friends for their support and for providing a healthy environment.

I would like to extend my heartfelt gratitude to Frank Gielen for suggesting the idea for this thesis and for his invaluable guidance in helping me identify the key areas to focus on within the scope of this project. I am also thankful to Johan Karlsson at Repono for providing essential data and practical information about the project and discussions with him helped me shape my project. Additionally, I wish to express my sincere appreciation to Sara Hermansson and Johan Söderbom for their unwavering support and supervision throughout the project. Their insightful discussions helped me to simplify and better understand this complex topic, while their constant course correction helped me stay on track.

Thank you all for your invaluable contributions. Your support and encouragement have been vital in achieving this milestone.

ADITYA

Stockholm, August 2024

NOMENCLATURE

Here are the Notations and Abbreviations that are used in this Master thesis.

Abbreviations

BESS	Battery Energy Storage Systems
PV	Photovoltaic
PPA	Power Purchase Agreement
IPP	Independent Power Producer
Li-ion	Lithium Ion
MW	Megawatt
MWh	Megawatt hour
mFRR	Manual Frequency Restoration Reserve
aFRR	Automatic Frequency Restoration Reserve
OMIE	Operator of the Iberian Energy Market
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
P/C	Profit to Cost ratio
RES	Renewable Energy Source
SOC	State of Charge
UPS	Uninterruptible Power Supply
ROI	Return on Investment
CRAC	Computer Room Air Conditioning
CRAH	Computer Room Air Handler

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1 INTRODUCTION

This chapter describes the background, the purpose, the limitations and the methods used in the presented project.

Battery Energy Storage Systems are set to play a pivotal role in the European Union's energy landscape as the continent accelerates its shift toward renewable energy. The European Green Deal, with its goal of achieving carbon neutrality by 2050, has spurred significant investments in renewable energy sources such as solar and wind. However, the intermittent nature of these sources necessitates robust energy storage solutions to maintain grid stability, ensure supply-demand balance, and optimize energy use. By 2030, the EU aims to have around 200 gigawatts (GW) of renewable energy storage capacity (Comission, n.d.), with BESS expected to account for a substantial share of this capacity, reflecting its critical role in the energy transition.

Within this broader European context, Spain stands out as a key market for BESS deployment. The country is committed to a significant energy transition, aiming to generate 74% of its electricity from renewable sources by 2030 (European Investment Bank, n.d.), as outlined in its National Energy and Climate Plan (NECP). This transition is essential for meeting Spain's long-term goal of carbon neutrality by 2050. As of 2021, Spain had approximately 64 GW of installed renewable energy capacity (Red Eléctrica, n.d.), predominantly from solar and wind power. However, the variability of these renewable sources presents challenges for grid stability, making the adoption of BESS technology increasingly crucial.

Spain's NECP includes a target of installing 20 GW of storage capacity by 2030 (Renewables Now, n.d.), underscoring the anticipated growth of BESS in the Spanish electricity market. At the end of 2021, Spain's total energy storage capacity, including pumped hydro, was around 8.3 GW (Renewables Now, n.d.), indicating substantial room for expansion in BESS. The Spanish government has recognized the importance of energy storage in achieving its energy goals and has introduced various incentives, such as subsidies, tax benefits, and streamlined permitting processes, to encourage BESS deployment.

The methodology for this project involved a comprehensive approach to evaluate the potential and implementation of BESS co-located with solar PV plants. Initially, a detailed Spanish electricity market review was performed to understand the scope of BESS and its role in energy transition. Following this, data was collected from a variety of sources to inform the creation of an optimization algorithm. This algorithm was designed to determine the optimal operating behaviour of BESS for electricity arbitrage within the Spanish spot market. Additionally, the project included an analysis of a specific use case for BESS in data centres, examining both business and operational perspectives.

Some of the data utilized in the optimization process were simulated, and the model was intentionally simplified, focusing on a single revenue stream and assuming ideal battery characteristics. It is important to note that the scope of this project is limited to Spain, and all analyses conducted pertain specifically to the Spanish electricity market.

2 PROBLEM STATEMENT AND OBJECTIVES

The rapid integration of renewable energy sources in Europe, particularly in Spain, has created a growing demand for reliable energy storage solutions to manage the variability and intermittency of solar and wind power. BESS has emerged as a critical component of the energy transition, enabling the storage of excess energy and ensuring grid stability. However, the deployment and commercialization of BESS faces significant challenges, particularly in the structuring of PPAs and contracts between power producers, storage operators, and industrial consumers.

2.1 Problem Statement

One of the primary difficulties lies in the complexity of PPAs and contracts involving BESS. Unlike traditional energy contracts, where the power output is relatively predictable, the involvement of storage systems introduces additional layers of uncertainty and risk. These include the variability of renewable energy generation, the timing of energy storage and discharge, and the potential for fluctuating market prices. As a result, power producers and industrial consumers face challenges in agreeing on terms that fairly allocate risks and benefits, leading to delays and complications in finalizing contracts.

Furthermore, for BESS project developers, finding optimal project parameters—such as the size, location, and operational strategy of BESS co-located with renewable power plants—is a complex task. These parameters must be carefully calibrated to maximize the financial and operational efficiency of the project, taking into account factors like energy demand patterns, grid conditions, and regulatory requirements. The lack of standardized models or clear guidelines for these decisions further complicates the planning and development process, potentially leading to suboptimal investments.

In addition to traditional applications, BESS is increasingly being considered for new use cases, such as supporting data centres. Data centres require highly reliable and uninterrupted power supplies, which can be challenging to achieve solely through renewable energy sources due to their intermittent nature. BESS can provide the necessary backup and load-balancing capabilities, but the unique energy needs and operational demands of data centres require tailored storage solutions. This adds another layer of complexity to the design and implementation of BESS projects, as developers must account for the specific requirements of these new use cases.

2.2 Objective

The primary objective of this research is to address the challenges associated with the deployment and commercialization of BESS in the Spanish electricity market. Specifically, the research aims to:

- Develop Strategies for Streamlining PPA and Contract Negotiations: Propose methodologies and frameworks to simplify and optimize the structuring of Power Purchase Agreements and contracts between power producers, BESS operators, and industrial consumers. This includes researching about various agreements already being used in the market between different stakeholders.

- Optimize Project Parameters for BESS Co-Located with Renewable Power Plants: Identify and analyse key factors that influence the optimal sizing, location, and operational strategy of BESS systems co-located with solar and wind power plants. The research will provide guidelines and decision-making tools for developers to maximize the financial viability and grid benefits of such projects.

- Explore BESS Applications for New Use Cases Such as Data Centres: Investigate the potential of BESS to support emerging use cases, particularly in providing reliable and efficient power supply to data centres. The research will focus on developing tailored storage solutions that meet the specific energy needs of these facilities while also contributing to grid stability and renewable energy utilization.

By addressing these objectives, the research aims to enhance the commercial viability and operational efficiency of BESS projects in Spain, thereby supporting the broader goals of the country's energy transition and decarbonization efforts.

3 MARKET RESEARCH

This section explores the electricity market landscape for BESS with a focus on their application in co-location setups and their role in the evolving electricity markets of Spain. It further mentions the technical aspects of BESS and how important they are in the decision-making process of project development. Finally, an in-depth research on various types of PPAs and contracts between storage operators and IPPs is also presented.

3.1 Spain Market – Electricity generation mix forecast

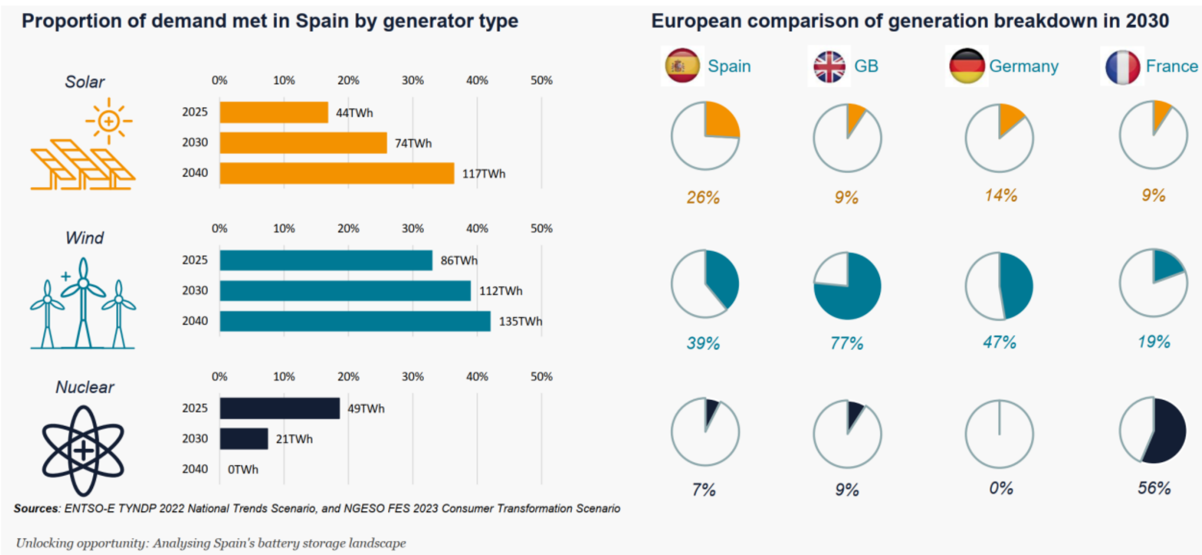

Figure 1. Electricity generation mix in European countries and forecast until 2030

Spain's low carbon energy transition will be more influenced by solar compared to other countries in Europe as can be seen in Figure 1. Spain is uniquely positioned within Europe due to its strong solar energy resources, making solar power a cornerstone of its renewable energy strategy. The country's geographical location offers abundant sunshine, leading to a significant share of its renewable energy capacity being derived from solar power. By 2030, Spain aims to have a large portion of its electricity generation coming from renewable sources, with solar energy playing a central role.

However, solar energy generation is inherently intermittent, with production peaking during daylight hours and dropping sharply at night. This creates a challenge for maintaining a stable and continuous energy supply. BESS is ideally suited to address this challenge by storing excess energy generated during peak solar production hours and discharging it when solar output decreases. The ability of BESS to provide this intraday balancing makes it a crucial component of Spain's energy infrastructure, particularly as the country increases its reliance on solar energy. This dependency on solar power creates a continuous and predictable demand for energy storage solutions, making the Spanish market particularly attractive for BESS investments.

In Spain, over 50% of excess renewable energy occurs in periods where there is continuous excess for less than 12 hours i.e. a battery that chooses to charge on this energy would be able to discharge within 12 hours (LCP Delta, 2023). This would allow BESS to charge and discharge within a day.

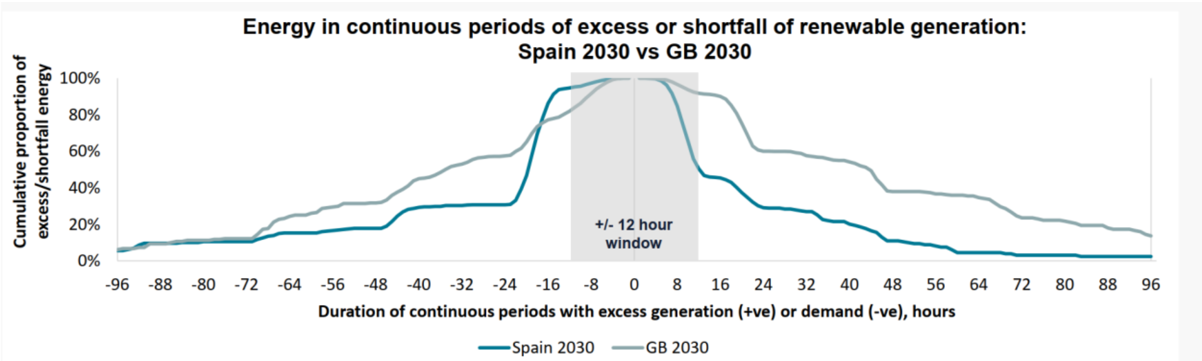

Figure 2. 2030 forecast of excess generation or demand hours in Spain vs England

3.2 BESS Operation Scenario

When analysing the operation of BESS, it is important to consider different scenarios for their charge-discharge cycles based on the balance between renewable energy generation and electricity demand. Here are the three key scenarios:

1. Excess Renewable Generation Over a Full Day

In this scenario, the grid experiences a surplus of renewable energy throughout the entire day. This situation typically occurs in regions with a high penetration of renewable sources, such as solar and wind, especially during seasons or weather conditions that favour maximum output. When there is an excess of renewable energy generation that consistently meets or exceeds demand for an entire day, the BESS may remain fully charged and unable to discharge any stored energy back into the grid. The grid's energy needs are met entirely by renewables, leaving no opportunity for the BESS to provide its services. This scenario can be less favourable for BESS operators because there is limited or no opportunity to capitalize on price differentials by discharging stored energy. The absence of demand fluctuations means that energy prices remain low, reducing the profitability of storage operations.

2. Demand Exceeds Renewable Generation

This scenario occurs when the energy demand is higher than the available renewable generation throughout the day. It can occur commonly during times of the year when renewable output is lower, such as cloudy days for solar or calm days for wind. In this case, BESS might not get an opportunity to charge throughout the day. The grid relies heavily on conventional generation sources, and any available renewable energy is immediately consumed by demand, leaving no surplus for the BESS to store. Like the first scenario, this situation can also be economically challenging for BESS operators. The inability to charge means that the storage remains underutilized, and there are limited opportunities to benefit from price arbitrage or grid services.

3. Ideal Case – Mixed Excess and Shortfall Within the Same Day

The ideal scenario for BESS operation occurs when there is a mix of excess and shortfall in renewable generation within the same day. This situation is characterized by periods when renewable generation exceeds demand, followed by periods when demand exceeds generation. During periods of excess renewable generation, the BESS can charge by storing surplus energy. Later, when the demand surpasses renewable generation, the BESS can discharge the stored energy to meet the shortfall. This operation enables the BESS to actively participate in grid balancing, ensuring stability and reliability. This scenario creates price differentials throughout the day, with lower prices during periods of excess generation (when the BESS charges) and higher prices during periods of shortfall (when the BESS discharges). This price volatility is essential for making BESS operations profitable, as it allows operators to buy low and sell high, capitalizing on energy arbitrage and grid services.

By 2030, it is estimated that BESS in Spain will experience over 300 days annually where they can engage in both charging and discharging cycles within the same day (LCP Delta, 2023). This estimate is based on the anticipated growth in renewable energy capacity, particularly solar and wind, and the corresponding fluctuations in generation and demand. With more than 300 days of viable charge-discharge opportunities, BESS in Spain will be able to consistently exploit price differentials, contributing to grid stability and enhancing profitability. The frequent occurrence of such ideal scenarios suggests a robust market environment for energy storage, driven by the dynamics of renewable energy and demand patterns.

For investors and grid operators, this projection underscores the strategic importance of BESS in the future energy landscape. The ability to efficiently manage energy storage will be key to integrating more renewable energy, reducing reliance on fossil fuels, and ensuring a reliable and economically viable energy supply.

3.3 Level of Interconnection with Spain

Spain's electricity market is relatively isolated from the broader European grid due to limited interconnection capacity with neighbouring countries like France, Portugal, and Morocco. This isolation results in a more self-contained energy market where supply and demand imbalances cannot be easily mitigated by importing or exporting electricity.

The limited interconnection increases the importance of domestic energy storage solutions like BESS. Without the ability to rely on neighbouring countries for balancing supply and demand, Spain must develop its own capacity to store excess renewable energy and release it when needed. This creates a unique opportunity for BESS to play a critical role in ensuring grid stability and reliability within the Spanish market.

Furthermore, the lack of extensive interconnection reduces competition from cross-border energy storage solutions, allowing Spanish BESS projects to operate more independently and potentially secure higher returns. As a result, investors in Spain's BESS market may face less competition and enjoy more favourable market conditions compared to other European markets with greater interconnection capacity.

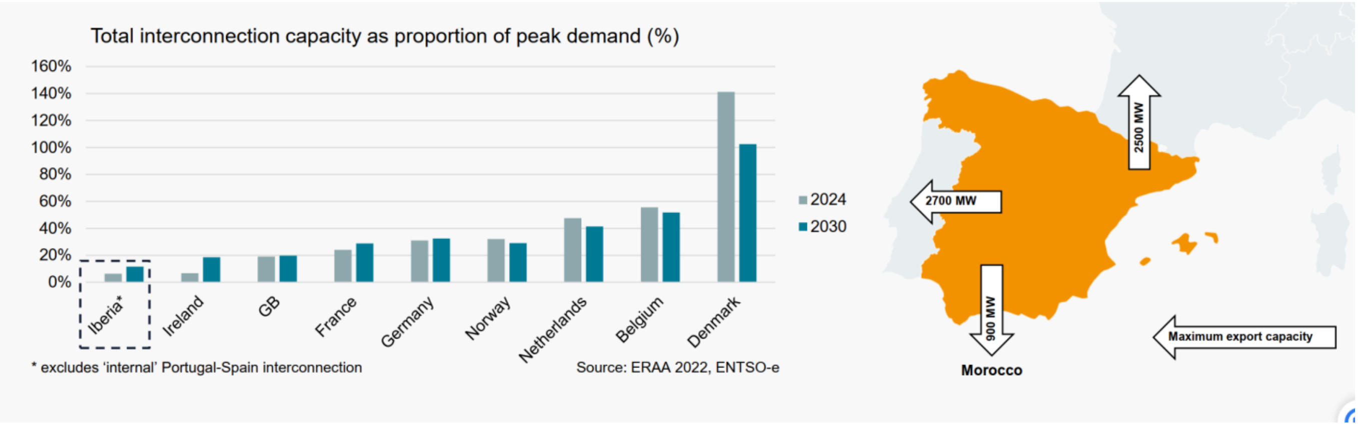

Figure 3. Chart showing limited interconnection capacity of Iberian region vs other EU countries

Iberia region has relatively low level of interconnection as can be seen in the figure 3 chart above (LCP Delta, 2023). Spanish storage faces limited competition from cross-border flexibility. Increasing energy storage will also reduce imports of electricity.

3.4 Electricity market and revenue stacking

Spain's electricity market has been characterized by significant price volatility, especially in recent years. Factors such as fluctuations in gas prices, changes in demand patterns, and the increasing penetration of renewable energy sources contribute to this volatility. For instance, during periods of high renewable energy generation, electricity prices can plummet due to oversupply, while during low generation periods, prices can spike sharply.

This price volatility presents a lucrative opportunity for BESS. Energy storage systems can be charged when electricity prices are low (usually during periods of high renewable output) and discharged when prices are high (during periods of low renewable output or peak demand). This arbitrage opportunity allows BESS operators to maximize revenue by buying low and selling high, capitalizing on the price differentials in the market.

Moreover, as Spain continues to increase its share of renewable energy, this price volatility is expected to persist or even intensify as can be seen in figure 4 (LCP Delta, 2023), further enhancing the potential revenue streams for BESS projects. The ability of BESS to respond quickly to market signals and provide services such as frequency regulation and reserve power also creates additional revenue opportunities, making BESS a versatile and financially attractive investment in Spain's electricity market.

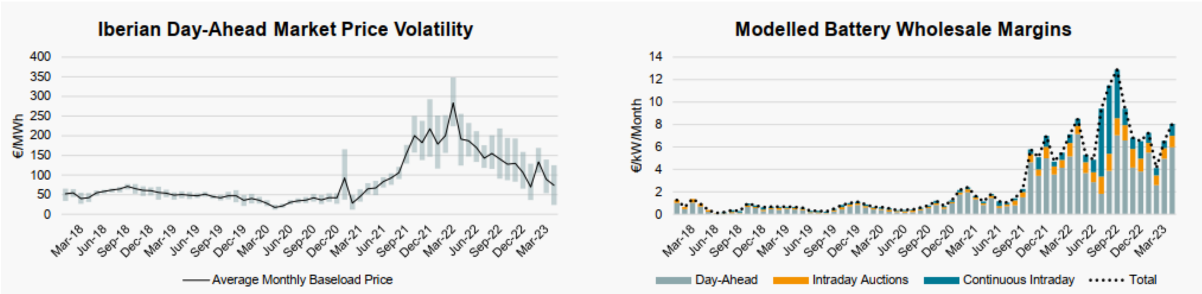

Figure 4. Electricity price volatility and wholesale margins modelled for BESS

Over the recent years, wholesale price spreads in the energy market have increased significantly. In a study by LCP Delta, a modelled 50MW, 2-hour battery with a roundtrip efficiency of 87%, trading in the Iberian market, could have captured an average margin of €7.04/kW/month from September 2021 to December 2022, with a peak margin of €12.87/kW/month in September 2022 (LCP Delta, 2023). Before 2021, lower price volatility meant fewer periods of high price spreads, limiting the potential for batteries to achieve substantial energy margins.

To understand the potential revenue streams for BESS in the electricity market, it is important to explore the different market categories where BESS can operate and the concept of "revenue stacking." Revenue stacking refers to the practice of leveraging multiple revenue streams from various markets and services to maximize the financial returns of a BESS project. Here is a more detailed look at each option available in Spain:

1. Wholesale Electricity Market

The wholesale electricity market in Spain is managed by OMIE (Operador del Mercado Ibérico de Energía), and it offers several opportunities for BESS to generate revenue:

- Day-Ahead Market: This is the primary market where electricity for the next day is traded. BESS operators can participate by bidding to sell or buy electricity based on price predictions and expected demand. For instance, BESS can charge during periods of low prices (usually during times of excess renewable generation) and discharge during peak periods when prices are higher. This allows operators to capitalize on price differentials.
- Intraday Market: This market allows trading closer to the delivery time, providing opportunities for BESS to adjust their positions based on more accurate short-term forecasts of demand and generation. The flexibility of BESS makes it particularly

well-suited to participate in intraday markets, where rapid response times can optimize revenue.

2. Ancillary Services Market

Ancillary services are crucial for maintaining grid stability and reliability. BESS can provide several key services in this market like frequency regulation:

- Primary Frequency Control (FCR): Immediate response to frequency deviations, usually handled by automatic systems within the BESS.
- Secondary Frequency Control (aFRR): Automatic Frequency Restoration Reserve involves adjusting power output in real-time to correct frequency deviations over a span of minutes.
- Tertiary Frequency Control (mFRR): Manual Frequency Restoration Reserve, where BESS can be dispatched to provide additional balancing services as needed, usually within a 15-minute response time.

3. Capacity Market

The capacity market is designed to ensure there is enough generation capacity available to meet peak demand, even during periods of low renewable output. BESS can contribute by providing firm capacity that can be dispatched when needed:

- Future Market Uncertainty: Although a capacity market represents a potential revenue stream for BESS in Spain, its implementation has faced delays. The market is intended to compensate generators and storage operators for being available to supply power during peak periods or in times of grid stress. BESS could receive payments for their capacity, whether or not they are actively discharging energy.
- Long-Term Contracts: In the capacity market, BESS operators might secure long-term contracts that provide stable revenue streams, helping to de-risk investments. These contracts are typically awarded through auctions, where operators bid to provide a specified amount of capacity.

4. Renewable Energy Support

BESS can be integrated with renewable energy projects to optimize their output. For example:

- Solar + Storage: Pairing solar PV with BESS allows excess solar energy generated during the day to be stored and used during the evening peak, discharging to supply the peak in demand.
- Wind + Storage: Similarly, wind energy, which can be intermittent, benefits from BESS by storing energy generated during high-wind periods and discharging it during cut-offs.

Given the variety of market categories and services available, BESS operators often adopt a revenue stacking strategy to maximize their returns. This involves combining multiple revenue streams, such as participating in the wholesale market while also providing ancillary services and balancing functions. By diversifying income sources, BESS projects can enhance financial stability and improve overall project economics.

Revenue stacking is particularly important in markets like Spain, where individual revenue streams may not be sufficient to justify the investment in BESS. By tapping into multiple markets and services, operators can optimize their assets, ensure higher utilization rates, and enhance the return on investment.

3.5 BESS Project parameters

When developing a BESS project, there are several critical technical and financial considerations that project developers must account for to ensure optimal performance, longevity, and economic viability. Below is a detailed overview of key technical aspects that should be factored into the planning and execution of a BESS project:

1. BESS Technology – Type of Battery

The choice of battery technology is fundamental to the design and performance of a BESS. Each battery type has distinct characteristics that influence its suitability for specific applications, cost, and operational life. According to a survey by Pexapark in which 408 project developers with BESS in their portfolio participated (Pexapark, 2022), the most commonly used battery technologies in BESS projects are:

- Lithium-Ion Batteries (44.6%): Lithium-ion batteries are the most widely used technology in BESS due to their high energy density, efficiency, and low self-discharge rate. They are scalable, making them suitable for both small-scale and utility-scale applications. These batteries are ideal for applications requiring quick response times, such as frequency regulation, peak shaving, and energy arbitrage, and are also used in residential and commercial energy storage systems. Their advantages include high efficiency (typically over 90%), mature technology, and decreasing costs due to economies of scale. However, they have a limited cycle life compared to some alternatives, are sensitive to temperature variations, and pose risks associated with thermal runaway.

- Flow Batteries (22.5%): Flow batteries, such as vanadium redox flow batteries, store energy in liquid electrolytes held in external tanks, allowing for the decoupling of energy storage capacity from power output capability. They are well-suited for long-duration storage applications, where energy needs to be stored and released over extended periods, such as renewable energy integration, load shifting, and backup power. Their advantages include a longer cycle life, lower degradation over time, and the ability to scale energy capacity independently of power. However, they have a lower energy density compared to lithium-ion batteries, higher initial capital expenditures (CAPEX), and a more complex system design due to the need for pumps and large storage tanks.

2. Co-location coupling set-up

- In a Hybrid AC Coupled setup, two assets—generation and storage—each have their own inverters but share a single grid connection. These co-located assets are managed as a unified hybrid resource at the point of interconnection (POI), optimizing the overall efficiency of the site. This configuration is particularly advantageous for projects that prioritize the integrated management of both generation and storage resources, ensuring streamlined and effective operations.
- In an AC Coupled setup, two assets—each with its own inverter—share a single grid connection but are managed independently. This configuration offers significant flexibility, allowing each asset to operate and generate revenue separately. It is popular among investors because it reduces risk through the separation of business models for generation and storage, enabling each to be financed individually. Additionally, this setup allows for different ownership of the assets, with shared grid connection arrangements that can maximize overall revenue.

- In a Hybrid DC Coupled setup, two assets share a single inverter and one grid connection, making it the most technically efficient configuration for a site. This setup is both cost-effective and efficient, as it simplifies the electrical infrastructure, reducing complexity. However, the shared inverter can limit the operational independence of the assets, which might be a disadvantage in certain market conditions where flexibility is crucial.

3. Capacity– Energy vs. Power

The capacity of a BESS is defined by its energy (kWh or MWh) and power (kW or MW) capabilities.

Energy capacity refers to the total amount of energy the battery can store and deliver over time. This is critical for applications that require sustained energy output over several hours, such as load shifting or providing backup power. Flow batteries are typically more appropriate for these systems due to their ability to store large amounts of energy for extended periods.

Power capacity is the maximum rate at which the battery can discharge. This is important for applications requiring rapid discharge, such as frequency regulation. Lithium-ion batteries are well-suited for these applications due to their ability to quickly deliver high power.

4. Charge/discharge cycles (Impact on Battery Health)

The number of charge-discharge cycles a battery can undergo before its capacity significantly degrades is a critical factor in determining its lifespan and overall cost-effectiveness:

Different battery technologies have varying cycle lives. Lithium-ion batteries typically have a cycle life of around 3,000 to 5,000 cycles, depending on the specific chemistry and usage profile. Flow batteries can achieve up to 10,000 cycles or more due to their less stressful charge-discharge mechanism. Operating batteries at a lower depth of discharge can extend their lifespan but may reduce the available capacity for use. Lifecycle of battery is directly associated with CAPEX and OPEX of a project. As battery degrades, its storage capacity is lost gradually. The replacement of battery is included in the OPEX of the project.

3.6 Economic Considerations: CAPEX and OPEX

When planning a BESS project, both CAPEX and OPEX must be carefully evaluated. CAPEX includes initial costs such as the purchase and installation of batteries, inverters, power conversion systems, housing, and supporting infrastructure. Generally, lithium-ion batteries have lower upfront costs compared to flow batteries, though flow batteries offer longer life and lower degradation rates. OPEX involves ongoing costs like maintenance, operation, cooling/heating systems, and potential replacements of battery cells or components over the project's life. While flow batteries may have higher initial CAPEX due to their complex systems, they benefit from lower long-term costs due to less frequent replacements. A detailed cost-benefit analysis is essential to determine the most cost-effective technology and configuration, considering system efficiency and specific use cases.

Lithium-ion batteries typically offer higher efficiencies, which can offset their higher degradation rates. System-level considerations such as temperature management, state of charge management, system availability, and safety features are crucial for ensuring the reliability, safety, and performance of a BESS project. Effective thermal management and sophisticated control systems help maintain optimal battery health and prevent issues like thermal runaway, particularly in lithium-ion batteries. By carefully considering these technical aspects and their implications for CAPEX, OPEX, efficiency, and longevity, developers can design BESS projects that are both economically viable and technically robust, meeting operational demands and safety standards in today's energy markets.

In the following figure 5, the comparison between different storage technologies like BESS and hydropower is done based on CAPEX sensitivity. It can be seen that 2-hour BESS appears to be least CAPEX intensive.

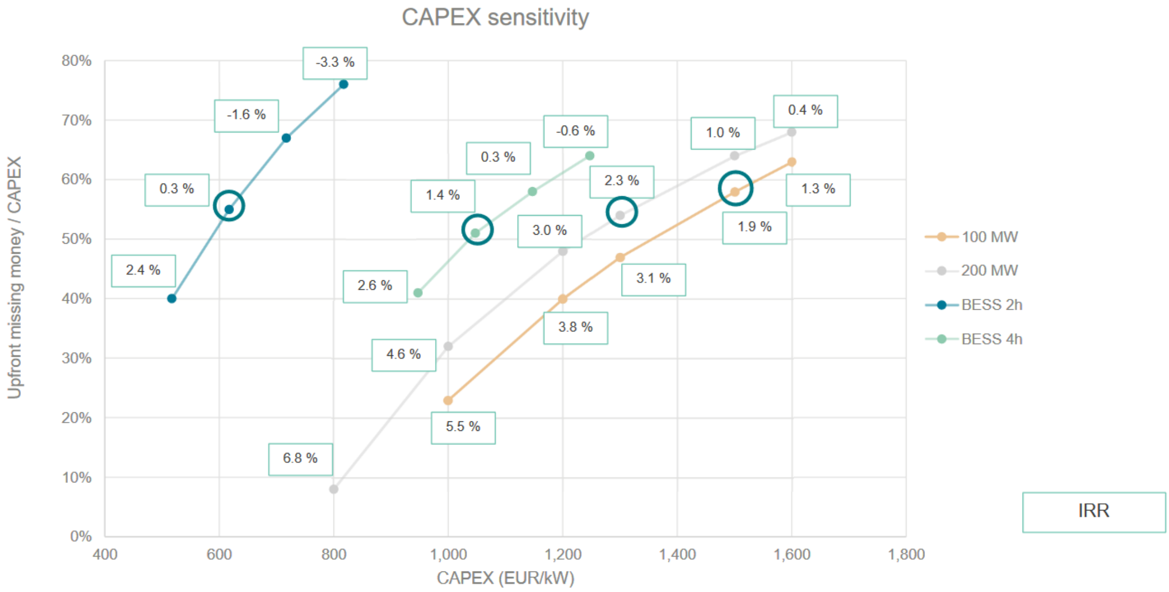

Figure 5. Pumped hydro vs BESS – compared by Association of Energy storage in Spain

In the Pexapark survey, the project developers responded about importance of various factors in the selection of technologies for co-located BESS projects. The following figure 6 shows the weightage of each factor.

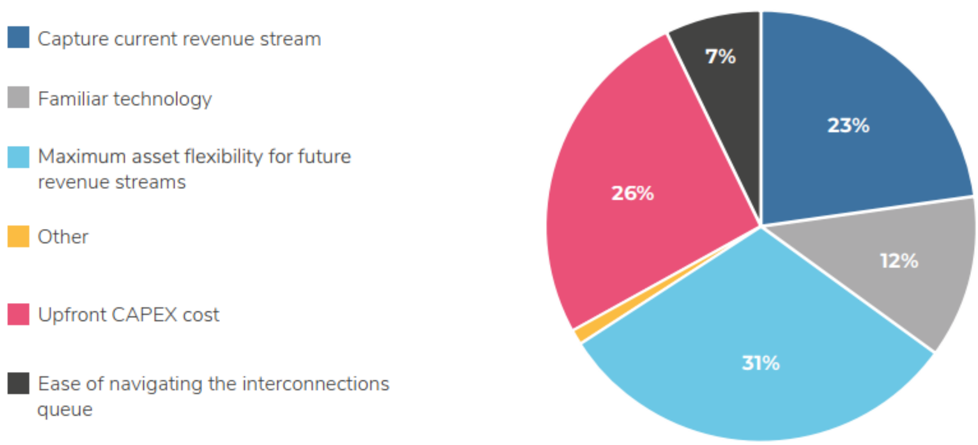

Figure 6. Important factors for selecting co-located BESS projects

3.7 Types of BESS projects

Co-located and standalone BESS projects represent two primary approaches to deploying battery energy storage systems, each with its unique advantages and challenges. Co-located BESS projects are installed alongside renewable energy generation facilities, such as solar or wind farms. This setup allows for better utilization of the generated energy by storing excess power during periods of high generation and discharging it during low generation or high demand periods. Co-located systems benefit from shared infrastructure, such as land and grid connection points, reducing overall project costs and enhancing the economic viability of renewable energy projects through improved capacity factors and reduced curtailment. On the other hand, standalone BESS projects are deployed independently of any specific generation source and can be strategically located across the grid to provide services like frequency regulation, peak shaving, and grid stability. These projects offer greater operational flexibility, as they are not tied to the variable output of a renewable plant and can respond to market signals or grid needs independently. While standalone BESS projects may have higher upfront costs due to the need for dedicated infrastructure, they play a critical role in enhancing grid reliability and supporting the integration of higher levels of renewable energy into the grid. The scope of this project includes co-located BESS projects.

Co-located BESS projects integrate battery storage directly with renewable energy generation assets, such as solar or wind farms, sharing the same site and grid connection. This approach offers several advantages, but it also introduces complexities that must be carefully managed.

3.7.1 Advantages of Co-locating BESS

Co-locating BESS with renewable energy plants offers several key advantages that can significantly enhance the economic viability and operational efficiency of energy projects.

- Cost Reductions (CAPEX and OPEX) - By integrating BESS with existing renewable energy infrastructure, projects can achieve notable cost savings. Sharing grid connections with the renewable power plant helps to significantly reduce both capital expenditures (CAPEX) and operational expenditures (OPEX), as the need for additional grid connections is minimized, lowering overall project costs. Furthermore, co-locating on the same site reduces site-related expenses such as rent and overheads, contributing to further OPEX reductions. Additionally, the cost savings from charging the BESS directly from on-site renewable generation due to removal of taxes makes the charging cost cheaper. As an estimate, the charging cost could reduce to around one-third to that of the market price of electricity.
- Optimized Grid Connection Utilization - Co-located BESS projects make more efficient use of existing grid connections, which are often a bottleneck in project development. This optimized usage can expedite grid connections for BESS, reducing administrative delays and maximizing the utility of grid infrastructure. By integrating BESS into an existing renewable energy site, developers can fully capitalize on the available grid connections, enhancing the overall effectiveness of the project.
- Charging Advantages - Co-located BESS can take advantage of power that would otherwise be curtailed, storing energy during periods of low grid demand or high renewable generation when market prices are less favourable. This capability also helps manage the "duck curve" effect, where solar generation leads to negative pricing during midday. By storing energy when prices are low and discharging it during peak demand, co-located BESS can optimize revenue and ensure a more balanced energy supply.

- Risk Reduction - Combining technologies like solar with BESS diversifies the energy mix and reduces overall project risk. This technological diversification provides multiple revenue streams and helps balance the inherent variability of renewable energy generation, making the project more resilient and financially stable.

3.7.2 Complications in Co-location

- Value Erosion and BESS Sizing - The need to share grid connections between the RES and the BESS can lead to constrained access, particularly during periods when the RES asset is exporting power. This can erode the value of the BESS by limiting its ability to operate optimally. Calculating the revenue impact of these constraints is crucial for optimizing the BESS sizing relative to the connection, ensuring that the shared connection does not significantly diminish the BESS's profitability. The BESS must be sized carefully to minimize the value impact of the shared connection. Oversizing can lead to underutilization, while undersizing may result in lost opportunities for energy storage and discharge.
- Increased Project Complexity - Co-located projects often require complex grid-sharing agreements between the renewable plant and the BESS. These agreements can add layers of complexity to the project, necessitating careful negotiation and consideration of grid connection rights, usage, and potential constraints. Additionally, the BESS and the renewable energy plant may operate under different business models, which can create operational and financial challenges. For instance, while renewable generation typically operates under long-term fixed PPAs, the BESS may participate in various electricity markets. This divergence can lead to conflicts, particularly if the integration of a BESS interferes with existing PPAs or other contractual obligations.

3.7.3 Operating Scenario

A typical operating scenario for a co-located BESS with a solar PV plant might unfold in three main phases. The BESS dispatches stored energy to the grid during high-power price periods in the morning, before solar generation becomes available. As the day progresses and solar generation ramps up, power prices typically drop due to the increased supply. The BESS charges from the solar PV plant with cheap electricity or with excess solar generation that exceeds grid capacity and would otherwise be curtailed. As solar generation declines in the evening and demand for electricity peaks, the BESS discharges its stored energy during these periods of high-power prices, taking advantage of the increased demand.

As it can be seen in the figure 7, a co-located BESS was modelled in UK and the operational behaviour shows a predictable pattern of operation (Gresham House Asset Management, 2023). Solar generation is particularly attractive for co-location with BESS because it provides a highly predictable and reliable daily cycle based on location and time of year. This predictability offers the BESS two key opportunities each day to efficiently store and dispatch energy.

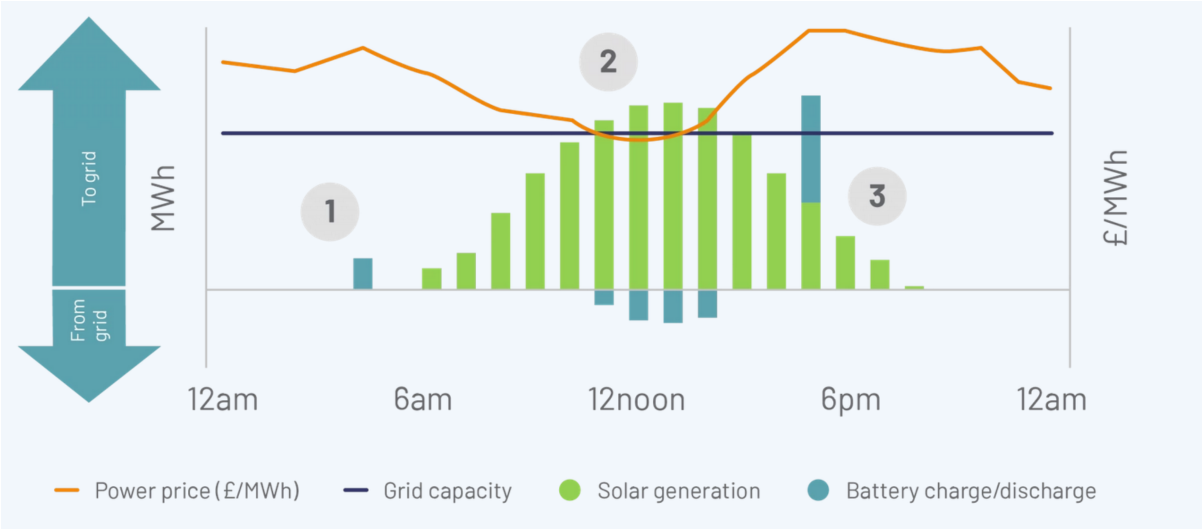

Figure 7. Battery cycle and solar generation profile for a collocated project in the UK

3.8 Hybrid PPAs for Co-located BESS Projects

In the context of renewable energy projects, particularly those involving solar and wind power, hybrid PPAs have emerged as innovative contractual structures that combine renewable energy generation with BESS. These agreements are designed to enhance the financial viability of renewable projects by integrating storage solutions that mitigate the intermittent nature of renewable energy sources. Some hybrid PPA options are as follows:

- Hybrid PPA Option I: Renewable PPA & Storage Capacity Agreement (CSA)/Optimization Agreement – This option involves two distinct contracts: one for the renewable energy generation and another for the storage asset. The Renewable PPA governs the energy generation, while the CSA or Optimization Agreement pertains to the storage asset. Despite the separation, there is potential for synergy between the two contracts. The storage asset can be utilized for grid services or energy arbitrage, optimizing overall revenue. This approach allows for flexible financing and risk management tailored to each asset. However, the challenge lies in ensuring that the contracts do not conflict, particularly if the generation asset's operations constrain the storage asset's ability to export energy.

- Hybrid PPA Option II: Shaped Renewable PPA – In this arrangement, both renewable generation and storage assets are covered under a single contract, forming a Hybrid Shaped Pay-as-Produced PPA. This model allows for variable pricing, where different rates are applied to each MWh of energy delivered, depending on the time of delivery. This setup enables the project to capture higher prices during peak demand periods when stored energy can be discharged to the grid, thus optimizing revenue. The integration of storage in this model supports better profile shaping, ensuring that energy is delivered when it is most valuable.

- Hybrid PPA Option III: Blended Renewable & Storage Premium PPA – This option combines renewable generation and storage assets into a single contract, offering a premium rate for all MWh delivered. The premium pricing reflects the added value provided by profile shaping, where the storage asset enhances the reliability and predictability of energy delivery, increasing the overall value of the generated energy. This structure is particularly appealing in markets where price cannibalization is a concern, as it ensures that the combined assets can command a higher price by delivering energy at optimal times.

In Spain, PPAs have long been the preferred model for securing long-term revenue for renewable energy projects. Despite the relative security offered by PPAs, the growing interest in merchant operations, where energy is sold directly on the spot market without a long-term contract, indicates a shift in investor risk appetite. Renovalia Energy's 79.2 MW solar park, launched in 2021, marked Spain's first utility-scale PV facility to sell its entire output on the spot market (PV Tech.org, 2019). Spain presents a unique landscape for hybrid PPAs and co-located BESS projects due to specific market dynamics and government support. Since 2021, solar asset capture prices in Spain have declined, prompting investors to seek physical hedges, such as hybrid PPAs, to preserve the value of the MWh produced. The Spanish government has bolstered this shift by providing significant grants, totalling €150 million in 2022, to support energy storage projects co-located with renewables (Solar Media Limited, 2023). This governmental support, coupled with growing concerns over price cannibalization, has significantly increased interest in hybrid setups, driving the adoption of these innovative contractual structures.

4 METHODOLOGY

The methodology for this project involved a structured approach to modelling the revenue potential of a solar PV plant with a co-located BESS in the Spanish electricity market. The primary objective was to maximize revenue by optimizing the interaction between solar generation and storage capabilities under various market conditions. The analysis was done on a duration of one year for the years 2020 and 2023. The key steps undertaken in the modelling process are detailed below:

4.1 Data Collection and Preparation

One of the most important aspects of modelling BESS operation was to collect quality data to work with. For this modelling, the following data was collected.

- Solar PV Plant Data – For co-located BESS with a renewable power plant, selecting a solar PV plant seemed a good choice considering its predictable pattern of electricity production and abundant solar resources available in Spain. The Nunez de Balboa PV plant in Badajoz, Spain, with an installed capacity of 500 MW, was selected as the case study. This plant is one of the largest in Europe, consisting of 1,430,000 photovoltaic panels with a planned annual electricity production of 832 GWh

(Iberdrola, n.d.). Detailed technical data such as installed capacity, connection capacity, type of PV panels, and inverter specifications were collected. Historical electricity production data for the PV plant was obtained for the years 2020 and 2023 using the Photovoltaic Geographical Information System (PVGIS) for 2020 and Renewables.ninja for 2023.

- Electricity Price Data – Hourly electricity prices for the years 2020 and 2023 were obtained from OMIE, the electricity market operator for the Iberian Peninsula. This data was essential for assessing the revenue potential based on market conditions.

A co-located BESS was modelled alongside a solar PV plant to evaluate its impact on overall revenue. The goal was to determine how storage could enhance revenue by optimizing the timing of electricity sales through price arbitrage. By analysing the sensitivity of revenue to various BESS parameters, the model aimed to identify the optimal settings for any specific project. The BESS's charge and discharge behaviour was optimized to maximize annual revenue, taking into account different market scenarios, including periods of high and low electricity prices, to identify the most profitable operational strategy.

One of the simplest ways to model this problem would be to use an Excel spreadsheet with its programming. This approach works well for smaller datasets, offering the advantage of simultaneous data visualization. However, for datasets with hourly granularity over an entire year, a more sophisticated method is necessary. In this case, mathematical optimization models coded in Python were utilized, providing significant advantages such as enhanced results, diverse visualization options, and the potential for further automation and standardization of the model to handle larger datasets.

The primary objective of the optimization model was to maximize the revenue generated by the BESS. The model was set up to identify the optimal charge/discharge schedule that would result in the highest possible revenue over the year. The model included constraints related to the technical specifications of the BESS, such as capacity limits, charge/discharge rates, and maximum discharge limit over 24 hours cycle.

The problem was modelled as a linear optimization problem, where the objective function and constraints were expressed as linear equations and inequalities. This approach was chosen due to the linear nature of the relationships between variables in the problem. The optimization problem was classified as a single-objective problem. An appropriate solver within Python capable of handling these characteristics was selected to execute the model.

From the results of the optimization model, the revenue generated by the PV plant and the BESS was analysed separately to differentiate between the contributions of solar generation and storage. This analysis could be used in the development of a new hybrid PPA structure that could effectively capture the value of both assets.

By following this structured methodology, the project aimed to develop a model that could be used to optimize the revenue of solar PV plants with co-located storage in Spain, while also exploring the potential for mutually beneficial PPA structures.

5 DATA EXPLORATION AND OPTIMIZATION MODEL

This section provides a detailed explanation of the data collection and model creation process. The data used in the model consisted of a combination of collected real-world data and simulated data.

5.1 Data collection and generation

In this subsection, the process of collection and generation of data is explained.

The solar PV plant selected for the model is Nunez de Balboa photovoltaic plant, Badajoz, Spain with an installed capacity of 500 MW. It is one of the biggest PV plants in Europe. The facility covers an area of 943 hectares and consists of 1,430,000 photovoltaic panels installed on 288,000 foundations with a total weight of more than 12 thousand tons. The planned annual electricity production is 832 GWh. In 2018 the specified inverter capacity was reduced to 391 MW while maintaining the 500 MW installed capacity of all photovoltaic panels (Iberdrola, n.d.).

According to the project, the solar power plant was to consist of 1,535,637 number of 325W polycrystalline silicon photovoltaic panels JA Solar or similar (Iberdrola, n.d.).

Figure 8. Núñez de Balboa solar PV plant

The following tables present the technical details of the selected PV plant, which are crucial in determining the appropriate parameters for the installation of the BESS project. These details help to ensure that the storage system is optimally designed to complement the PV plant's performance, maximizing efficiency and revenue generation.

Table 1. Technical specs of PV panels used in Núñez de Balboa plant

Technical specifications of PV panel	Indicators
Number of cells (polycrystalline)	72
Peak power, W	325
Estimated panel efficiency, %	16.5
No-load voltage, V	46.5
Maximum power point voltage, V	37.5
Maximum power point current, A	8.7
Short-circuit current, A	9.1
Temperature coefficient, % / ºC	0.1
Panel length, mm	1,965.00
Width, mm	991
Thickness, mm	45
Weight, kg	26

Table 2. Technical specs for the Núñez de Balboa plant

Technical specifications of the plant	Indicators
Number of 325 W photovoltaic panels	1,535,637
Number of strings of photovoltaic modules	52,953
Capacity of a set of modules (string), kW	9,425
Total installed capacity of the solar power plant, kW	499,082
Number of inverters 1580 kV / 680 V	273
Mounting structures for 87 PV modules	17,651
Total area of photovoltaic panels, m²	2,977,247
Connection capacity MW	391

Further, it is also important to understand how the produced electricity is evacuated from the plant for planning and optimization of BESS. In this case, Iberdrola, the owner of this solar PV plant, has negotiated private agreements with different companies to supply them with long term with 100 % renewable energy.

However, this is only a fraction of the produced electricity being used by the clients, while the rest of the electricity is sold to the grid in the spot market. Although specific data on the quantities of electricity sold to private clients and the grid was not available, this information is essential for determining the capacity of the solar PV plant connected to the grid that could be optimized by the BESS. Despite the lack of direct data, Iberdrola provided information on the reduction in CO_2 emissions for its clients due to their use of green energy. This data can be indirectly used to estimate the amount of renewable energy consumed by these clients from the solar plant. By applying the average CO_2 emission for the Spanish electricity mix in 2019 (0.19 t CO_2-eq/MWh of electricity) (Red Electrica, 2021), it is possible to calculate the amount of renewable energy utilized by private clients. This calculation helps to approximate the portion of the solar plant's output that is not directly available for BESS optimization, thereby informing the design and operation of the storage system.

The following equation shows the calculation for the used electricity.

$$Annual\ electricity\ used(MWh) = \frac{CO_2\ emissions\ reduced\ annually\ (tons)}{Avg\ electricity\ CO_2\ emission\ \left(\frac{\text{tons}}{\text{MWh}}\text{of electricity}\right)}$$

Moreover, 832 GWh of annual electricity generation was estimated for the PV plant by Iberdola (Iberdrola, n.d.). This corresponds to the plant capacity used by each client as shown in the following table 3 -

Table 3. Núñez de Balboa plant's customer electricity consumption details

Purchasers	Sector	Tons CO2 per year saved	Years contract	Annual energy estimate MWh	% of plant capacity
Kutxabank	Bank	15000	10	78947	9%
Euskaltel	Telecom	7740		40737	5%
Uvesko	Supermarket	26700		140526	17%

This shows that a total of around 31% of plant capacity is contracted with PPA with private parties, while the rest of the electricity generated is sold in the spot market. This is important information for BESS asset to be set up with optimal parameters.

For the optimization, the electricity generation output of the plant was needed. This data was not publicly available. Hence, Photovoltaic Geographical Information System - PVGIS was used. It provides information on solar radiation and photovoltaic system performance for any location in the world, developed by researchers at EC Joint Research Centre (European Comission, n.d.).

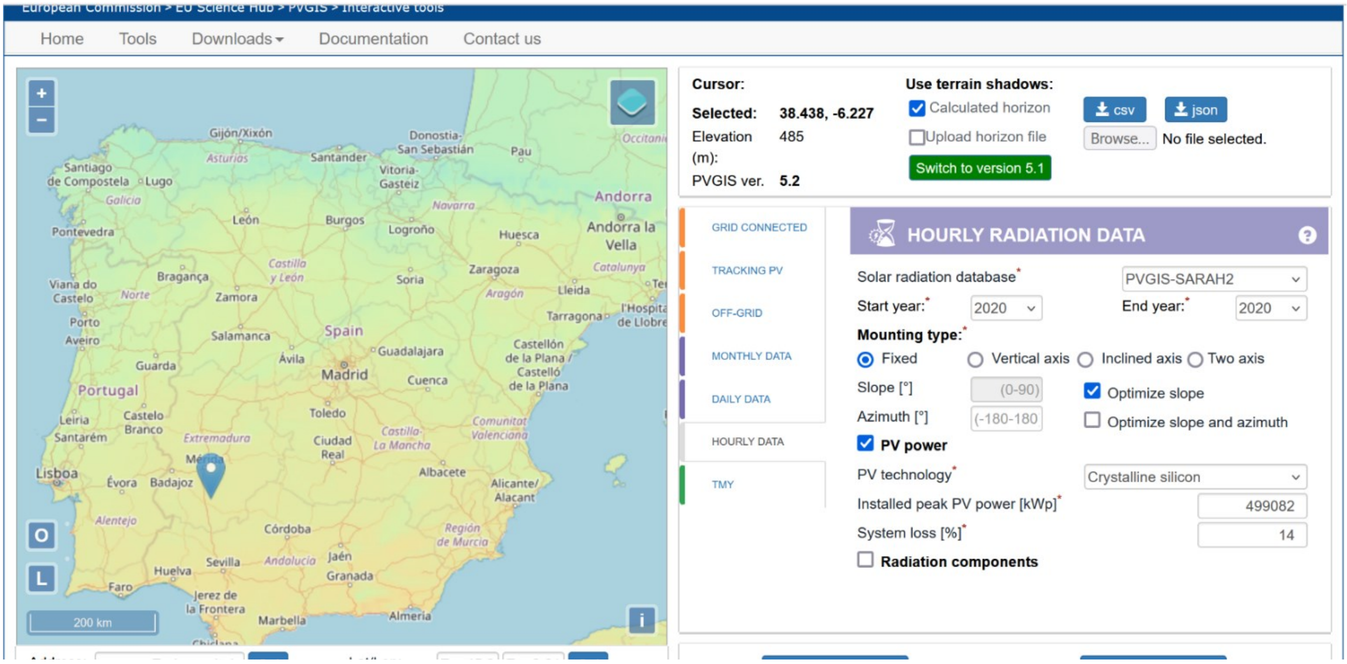

Figure 9. PVGIS interface showing customizable input fields to generate PV output data

This tool was used to generate the simulated PV output of the plant for the year 2020. Figure 9 shows the features and options available while generating the PV output simulation.

Since the PVGIS database does not have data available beyond 2020, another tool was employed to calculate the solar PV output for the year 2023. Renewables.ninja, an online tool developed by researchers at TU Delft and Imperial College London, was used for this purpose. Renewables.ninja is designed to simulate the energy output of renewable energy systems, such as solar PV and wind turbines, on a global scale. By utilizing high-resolution weather data, the tool enables users to generate precise estimates of electricity production based on specific geographic locations and system configurations. This tool provided the simulated electricity production data for the solar PV plant for the year 2023, ensuring the analysis remained up-to-date and accurate despite the limitations of the PVGIS database.

Since the solar PV plant electricity production data for years 2020 and 2023 was obtained, next step was to get the historical hourly electricity price from OMIE for the same years. OMIE is the nominated electricity market operator (NEMO) for managing the Iberian Peninsula's day-ahead and intraday electricity markets. This hourly granularity in price of electricity is used by the model to optimize the charge/discharge behaviour of the BESS.

5.2 Optimization model – BESS co-location

The goal of this optimization model was to maximize the revenue generated by co-locating a BESS asset with a power plant through energy arbitrage in the electricity market. The formation of the optimization model can be explained by understanding the different parts of the model.

Inputs

To start the optimization process, BESS parameters must be quantified, which would act as inputs for the model. Table 4 below shows the values of the inputs that have been selected for the model based on research and discussion with relevant stakeholders about average BESS size co-located with solar plants.

Table 4. Inputs for the optimization model

Parameters	Value
Max discharge power capacity (MW)	50
Max charge power capacity (MW)	50
Charge capacity (hours)	4
Discharge energy capacity (MWh)	200
Round-trip efficiency (%)	85%
Maximum daily discharged throughput (MWh)	200
Electricity price hourly (€/MWh)	Market data

Outputs

During the optimization process, the model output two BESS parameters for each hour of the data available. So, for each hour of the year, the model would find the optimum charge/discharge power and the resulting remaining capacity for the BESS. Table 5 shows these parameters.

Table 5. Optimization model hourly output parameter

Outputs (hourly)
Power output (MW)
Capacity remaining (MWh)

Once the optimization is done, the results can be output in the form of a spreadsheet for a detailed analysis. Additionally, the numbers can be summarized in the annual timescale, and it can be shown using the parameters mentioned in the tables 6 and 7.

Table 6. Optimization model summary outputs

Outputs (Summary)
Total annual revenue generation (€)
Total annual charging cost (€)
Total annual discharged throughput (MWh)

Table 7. Optimization model graphical outputs

Outputs (Graphical)
Plot showing the most profitable week (hourly dispatch vs hourly price)
Plot showing monthly profit

Assumptions

The optimization model for the co-located BESS is built on several key assumptions to ensure accurate and practical results. First, it is assumed that the BESS has 100% depth of discharge capabilities, meaning it can be fully discharged without any loss in efficiency or capacity. This assumption allows for maximizing the use of stored energy. Additionally, historical hourly electricity prices are utilized to optimize the timing of battery charge and discharge operations. Specifically, the battery is charged exclusively using the output from the solar plant, with the cost of charging calculated based on the historical price during the corresponding hours of energy production. The revenue generated from discharging the battery is similarly calculated using historical hourly electricity prices, ensuring that the model accurately reflects market conditions. Finally, the optimization process is conducted over an entire year in a single continuous run, rather than breaking it down into discrete periods. This approach allows for a comprehensive analysis of the system's performance over time, accounting for seasonal variations and market fluctuations.

Parameters of the model

The table 8 shows the parameters that will be used by the model.

Table 8. Optimization model internal parameters

Parameter	Symbol	Description
Timestep (hour)	t	Hourly timestep for the model
Max. charge or discharge power	P_{max}	Maximum power for charging or discharging the battery
Maximum battery capacity	C_{max}	The maximum energy capacity of the battery
Battery's remaining capacity at time t	C_t	The battery's state of charge at a specific time t
Efficiency	η	The efficiency of the battery system
Maximum discharge within 24 hours	D_{max}	The maximum allowable discharge over a 24-hour period
Electricity price at time t	P_t	The price of electricity at time t
Solar plant output at time t	O_t	The electricity generated by the solar plant at time t
Connection capacity of the plant to the grid	T	The maximum capacity at which the plant can connect to the grid

The table 9 below shows the decision variables that the model uses in its algorithm.

Table 9. Optimization model decision variables

Parameter	Symbol	Description
Energy delivered to the battery at time t	E_t^{in}	The amount of energy charged into the battery at time t
Energy discharged from the battery at time t	E_t^{out}	The amount of energy discharged from the battery at time t

Constraints

The optimization model for the BESS includes several key constraints to ensure realistic and efficient operation. Initially, the charge capacity of the battery is set to half of its maximum capacity, establishing a starting point for the optimization process. The remaining capacity at any time t is determined by the previous charge capacity, adjusted by the energy charged into or discharged from the battery, accounting for the system's efficiency. To maintain operational limits, the remaining charge at any time must always stay between 0 and the battery's maximum capacity C_{max}. The model also limits the energy that can be charged or discharged at any given time t to not exceed the battery's maximum power P_{max}. Furthermore, the energy charged into the battery is constrained by the output of the solar plant, ensuring that only available energy is stored. Discharge at any time is similarly restricted by the current remaining charge to prevent over-discharging. Finally, to manage long-term performance, the cumulative energy discharged within any 24-hour period is capped by a maximum discharge limit D_{max}, ensuring that the battery does not exceed its designed operational limits over time. These constraints collectively ensure that the BESS operates within safe and optimal boundaries, maximizing revenue while adhering to physical and technical limitations. Table 10 shows these constraints.

Table 10. Optimization model constraints

Constraint	Expression	Description
Initial charge	$C_1 = \frac{C_{max}}{2}$	The initial state of charge is set to half of the maximum capacity.
Remaining capacity	$C_t = C_{t-1} + \sqrt{\eta} \times E_{t-1}^{in} - \frac{E_{t-1}^{out}}{\sqrt{\eta}}$	The state of charge at time t based on the previous charge/discharge.
Remaining capacity at time t	$0 \le C_t \le C_{max}$	The state of charge at time t must be within the battery's capacity.
Charge and discharge energy at time t	$\forall t, E_t^{in} and\ E_t^{out} \le P_{max}$	Energy charged or discharged at time t must not exceed max power.
Charge at time t	$E_t^{in} \le O_t$	Energy charged into the battery at time t should not exceed the solar plant output.
Discharge at time t	$\forall t, E_t^{out} \le C_t$	Energy discharged at time t should not exceed the current state of charge.
Cumulative discharge in 24 hours	$\sum_{t'=t-23}^{t} E_{t'}^{out} \le D_{max} \forall t \subset (T, t \ge 24)$	The total energy discharged in any 24-hour period must not exceed the maximum daily discharge limit.

Objective function

The objective function for the optimization model is designed to maximize profit from the BESS over a defined 24-hour period. The optimization time horizon is an important factor, with a 36-hour period a good option for each optimization block. Since day-ahead electricity prices are released at 12 pm for the next 24 hours, the optimization process begins from 12 pm on the current day and extends until 12 am of the following day. At 12 pm on the next day, a new optimization cycle starts with fresh data, and the last 12 hours of the previous strategy are disregarded.

In this project, only 24-hour cycle is considered for the sake of simplicity. The profit is calculated as the sum of the product of the electricity price at each hour P_t and the net energy discharged from the battery $(E_t^{out} - E_t^{in})$ during that hour. The summation runs from 12 PM of the current day to 11 PM of the next day, ensuring that the model captures daily price fluctuations and optimizes the charge and discharge schedule to maximize revenue. This approach balances energy storage and release to take advantage of higher electricity prices, thereby optimizing the financial performance of the BESS. The following expression shows the objective function used in this model.

$$\boldsymbol{Profit}(\boldsymbol{P_t}, E_t^{out}, E_t^{in}) = \sum_{12\ pm\ of\ current\ day}^{11\ pm\ of\ next\ day} P_t \cdot (E_t^{out} - E_t^{in})$$

All the units are in Euro, MWh and MW.

When optimizing profit for a system that includes both a solar PV plant and a BESS, certain conditions must be considered to accurately assess financial performance. If the profit calculation focuses solely on the BESS, it may prioritize battery operations, potentially interfering with the direct delivery of the solar plant's output to the grid. In this scenario, differentiating profits between the solar plant and the BESS can be challenging. One approach is to treat the energy used to charge the BESS as a cost for the battery and revenue for the solar plant, thus distinguishing the financial contributions of each component. Alternatively, the entire system—both BESS and solar PV—can be treated as a single asset. Profits from this combined operation can then be compared to the standard profits generated by the solar plant alone, with the difference in profit attributed proportionally to the BESS and the solar plant. This method helps to clearly separate the financial impacts of each asset while optimizing the overall revenue.

6 RESULTS

6.1 Exploratory data analysis on electricity prices

The hourly electricity price data for the years 2020 and 2023 were obtained from OMIE and were explored to understand the pattern and trend that could help a BESS project to capitalize on the price variations in the market. A python script was used to generate insightful charts from these data. The exploration results demonstrate significant changes between 2020 and 2023 prices. The price difference between 2020 and 2023 can be attributed to several factors. First, the increasing integration of renewable energy sources, particularly solar and wind, has led to greater price volatility as these sources are intermittent and can cause fluctuations in supply. Additionally, geopolitical events, such as the energy crisis in Europe, have driven up energy prices, especially for natural gas, which is a key input for electricity generation. The growing demand for electricity, coupled with challenges in energy storage and grid management, has further exacerbated price swings. These factors combined have contributed to the broader range and higher average electricity prices observed in 2023 compared to 2020. As can be seen in the histogram chart pictures 10 and 11 below, the hourly electricity prices show different patterns for both the years.

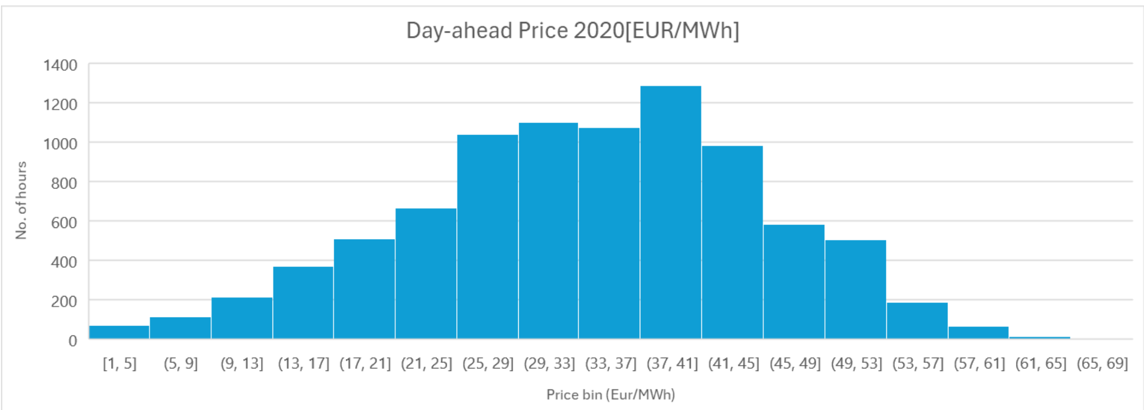

Figure 10. Day-ahead electricity price histogram for year 2020

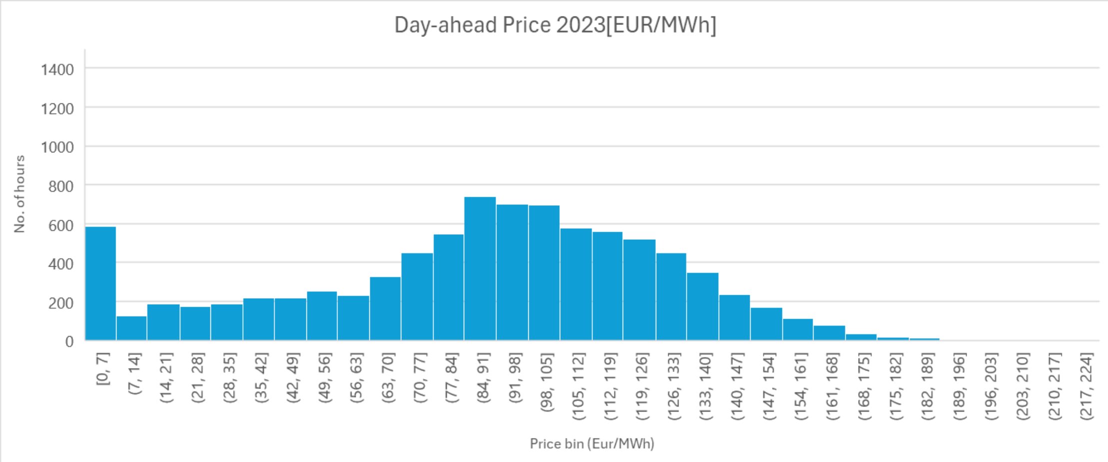

Figure 11. Day-ahead electricity price histogram for year 2023

The table 11 provides a comparison of electricity price variations between the years 2020 and 2023, focusing on four key aspects: the median value of electricity price, the range of electricity price, the number of hours at low electricity prices, and the number of hours at high electricity prices.

Table 11. Electricity prices exploration summary

Aspect	2020	2023
Median Value of Electricity Price	30-40 €/MWh	85-95 €/MWh
Range of Electricity Price	0-65 €/MWh	0-190 €/MWh
Number of Hours at Low Electricity Prices (20% of the range)	350 hours	1300 hours
Number of Hours at High Electricity Prices (20% of the range)	250 hours	250 hours

The substantial rise in the median value from 2020 to 2023 reflects a broader trend of increasing energy prices in the market. The average price almost doubled from 2020 to 2023. Similarly, the expansion in the range of electricity prices shows a threefold increase from 2020 to 2023 indicating increased volatility in the energy market. This suggests that while prices can still drop to zero, they can also spike to very high levels, possibly due to factors such as supply shortages, fluctuating demand, or grid management issues. This volatility could be challenging for energy consumers and producers, particularly those without long-term price stability mechanisms like PPAs. However, this could open up opportunities for storage assets like BESS.

The increase in the number of hours at low electricity prices in 2023 suggests a greater frequency of low-demand periods or times when renewable energy production (like solar or wind) exceeded demand, leading to lower prices. This also highlights the need for co-locating BESS with IPPs to protect them from "price cannibalization". A report from S&P Global suggests that 3% of the daytime hours in Spain saw negative electricity wholesale prices during the year 2023 (S&P Global, 2023). While the high-priced hours seem similar in number for both the years, the bulk of the hours are shifted towards higher than the median price for the year 2023 as compared to 2020.

The figures 12 and 13 below show a more in-depth analysis of the electricity price patterns. These charts depict the median day-ahead electricity prices (in €/MWh) for each hour of the day across the weeks of the year. They present heatmaps where the colour intensity varies from light yellow (indicating lower prices) to dark blue (indicating higher prices).

There are two trends emerging from these figures, hourly variation over the day and weekly variation over the year. The year 2020 has a consistent pricing pattern with clearer clusters as compared to the year 2023. The early morning and late evening hours of the day see a higher price compared to other hours, consistent with industrial and household activities. The trend is similar in 2023, however with prices more in contrast with the low-priced hours. The weekly variations in these heatmaps point to a seasonal trend. The seasonal price variation for the year 2020 is very gradual and the lower priced hours are concentrated in the summertime, related to higher solar electricity generation. For the year 2023, apart from the summer, some periods of winter also saw lower electricity prices, due to reduced gas prices and higher electricity contributions from wind and hydropower (Haya Energy Solutions, 2024).

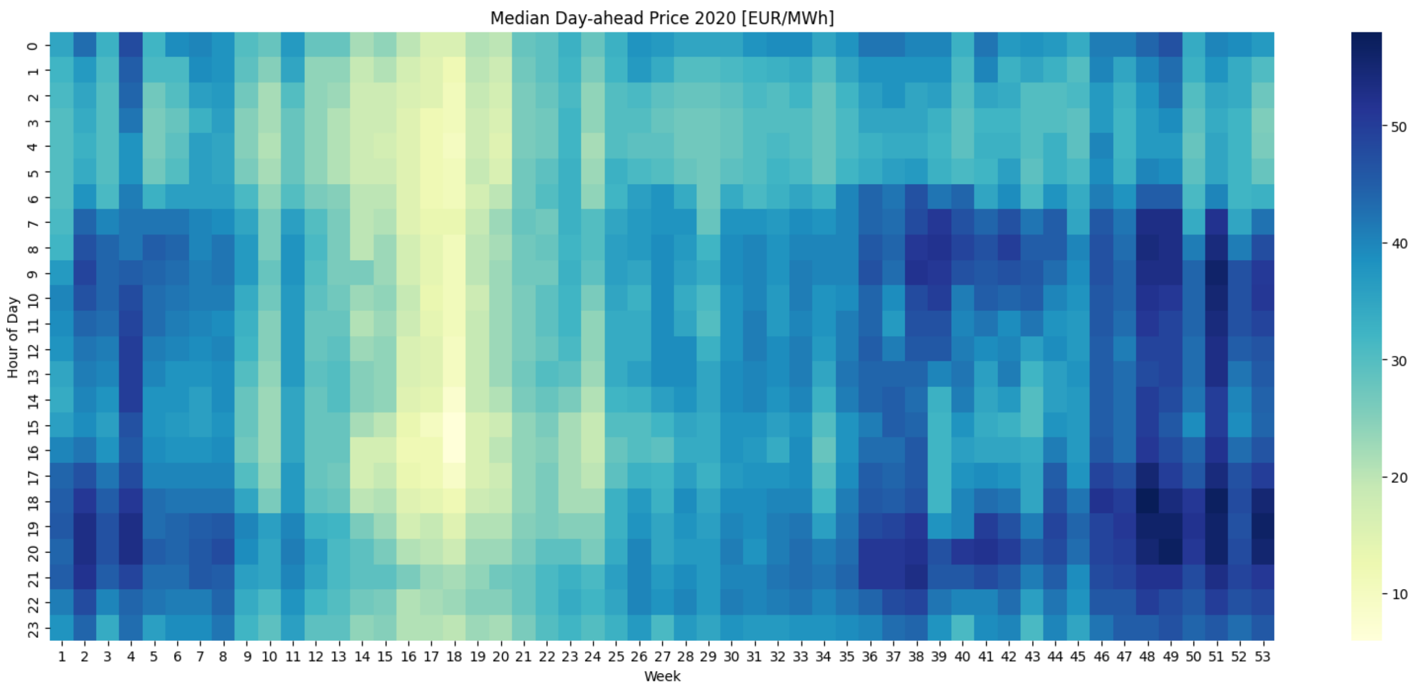

Figure 12. Heatmap of electricity prices for the year 2020 (Spanish market)

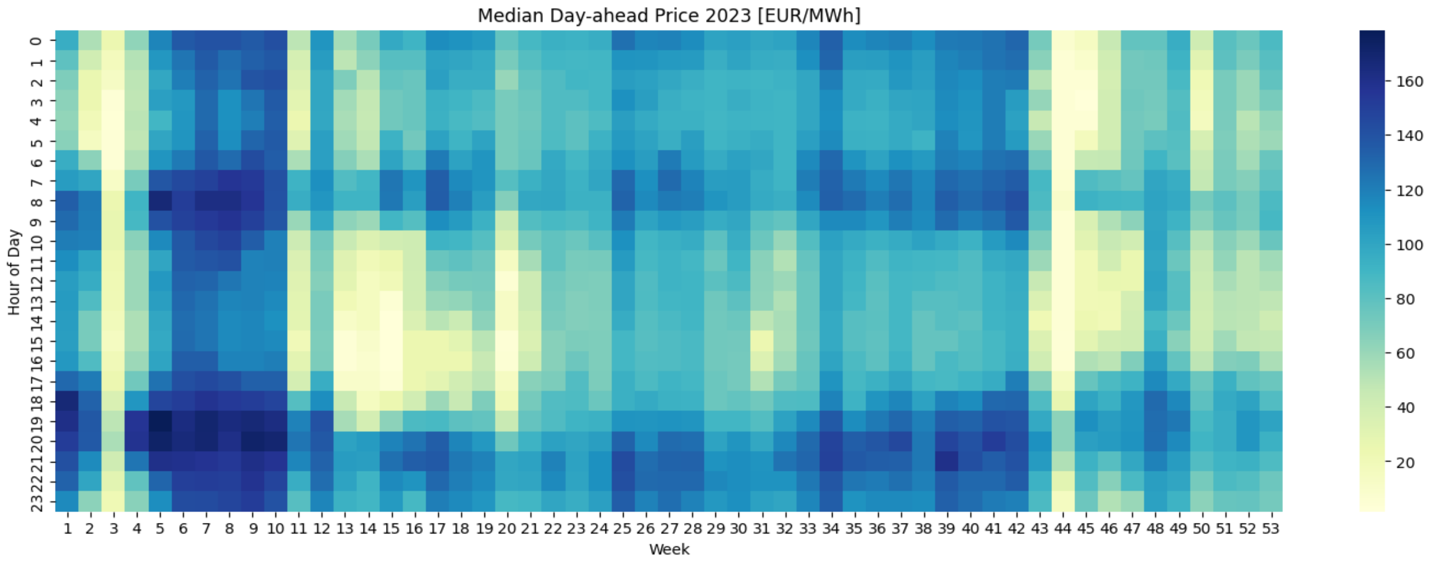

Figure 14. Heatmap of electricity prices for the year 2023 (Spanish market)

Another set of heatmaps shown in the figures 14 and 15 display the quarterly analysis of electricity prices with weekly patterns of prices. Saturdays and Sundays in general show lower electricity prices related to lower electricity demand due to reduced industrial activities on those days. In the figure 15 for the year 2023, Sundays are shown as day 2 of the week. Also, similar to the previous charts, quarter 4 of year 2023 shows lower average electricity prices for the reasons already mentioned.

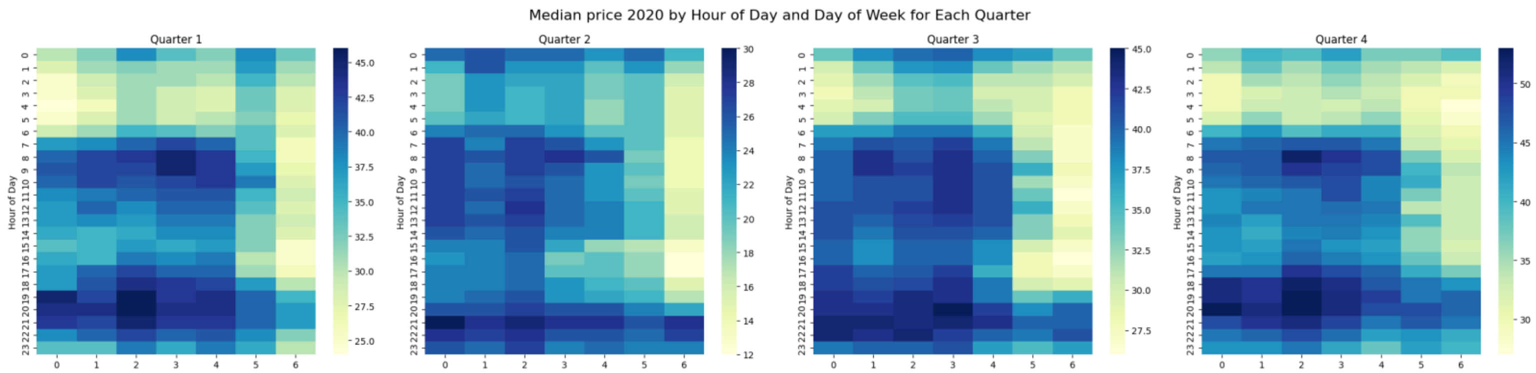

Figure 13. Heatmap of electricity prices shown quarterly for the year 2020 (Spanish market)

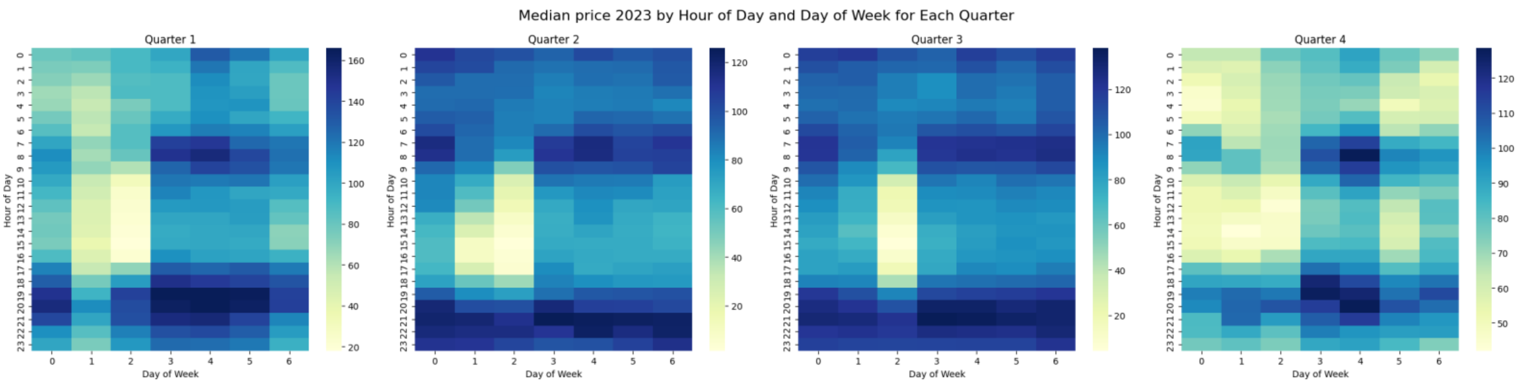

Figure 15. Heatmap of electricity prices shown quarterly for the year 2023 (Spanish market)

6.2 Optimization results

The following section provides a comprehensive overview of the optimization results obtained for the years 2020 and 2023. The analysis includes key financial and operational metrics. These metrics reflect the impact of market conditions and operational efficiency on the performance of the BESS during these two distinct periods. The table 12 shown below gives a summarized annual output of the BESS. This table highlights the substantial increase in both revenue and profit from 2020 to 2023, along with a significant rise in the discharged throughput, reflecting the enhanced performance and economic returns of the BESS under varying market conditions. The charging cost for the BESS is taken as one third of the market electricity price as the BESS takes electricity directly from the solar PV plant, thereby removing the taxes and tariffs levied in the wholesale electricity price.

Table 12. Optimization results summary for 2020 and 2023

Metric	2020	2023
Annual Revenue (€)	€ 1,498,290	€ 7,543,781
Annual Charging Cost (€)	€ 381,575	€ 1,427,007
Annual Profit (€)	€ 1,116,715	€ 6,116,775
Annual Discharged Throughput (MWh)	37,575	62,411

The following figures 16, 17, 18 and 19 show the weekly and monthly profits respectively for the year 2020 and 2023.

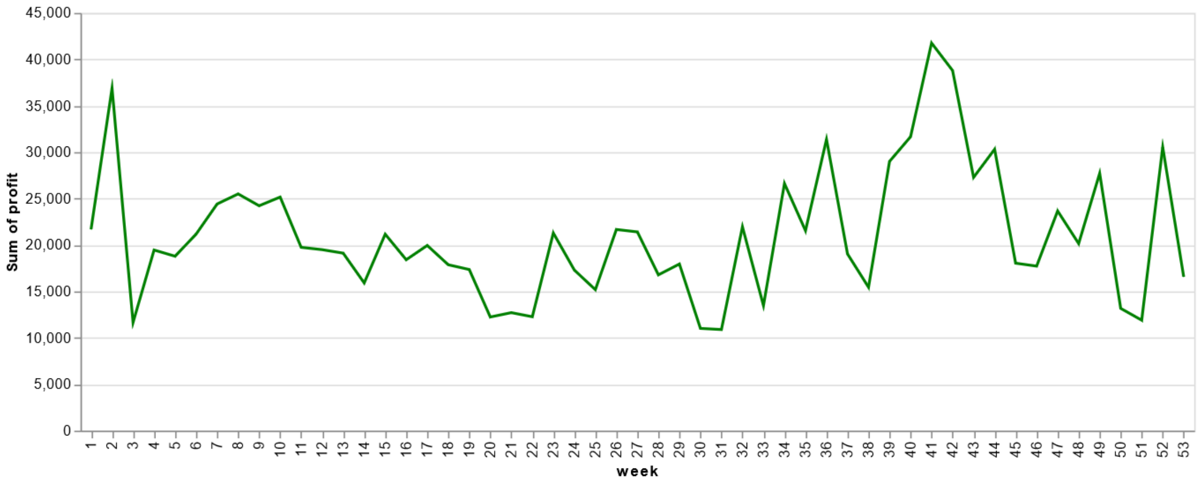

Figure 16. Weekly profit chart for the year 2020

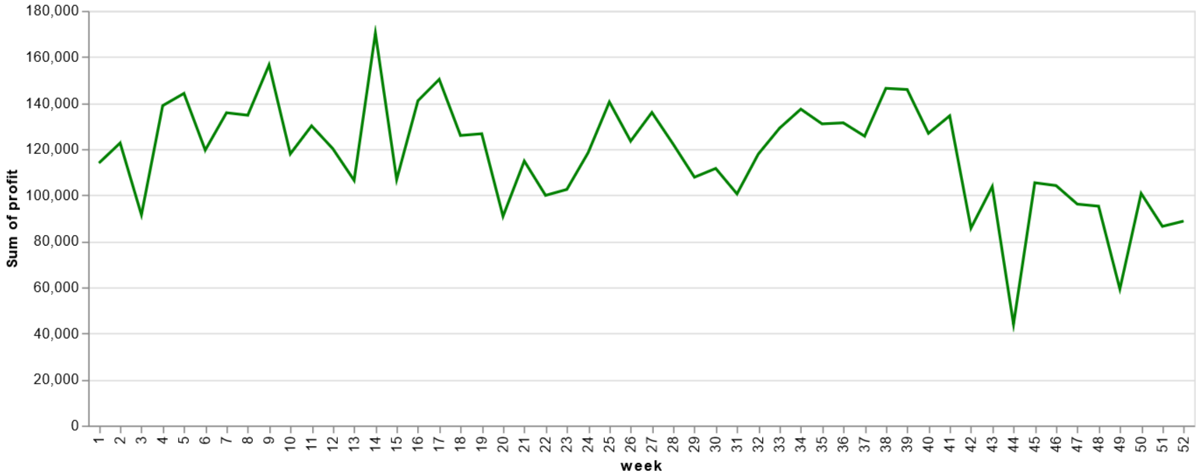

Figure 17. Weekly profit chart for the year 2023

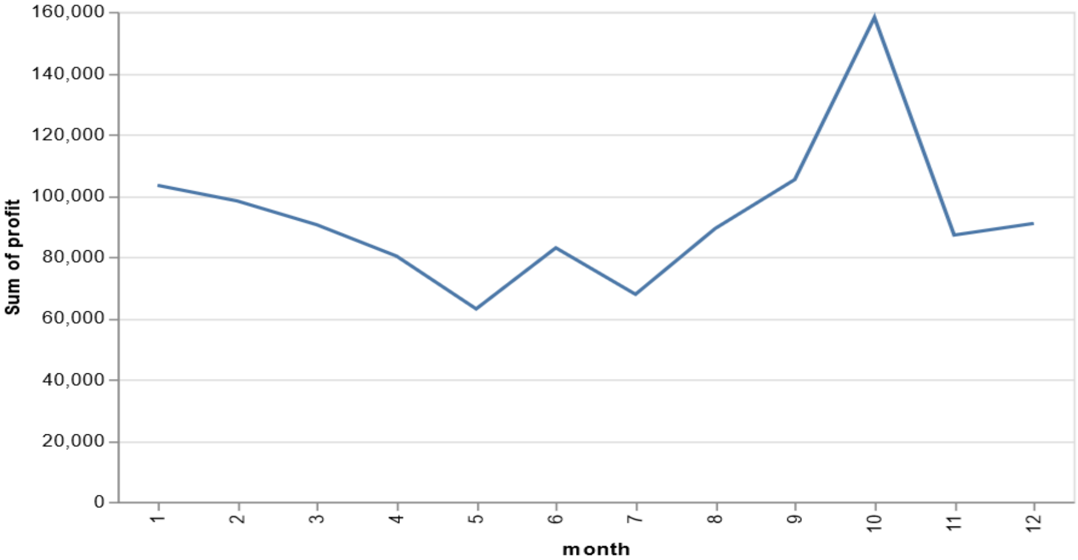

Figure 19. Monthly profit chart for the year 2020

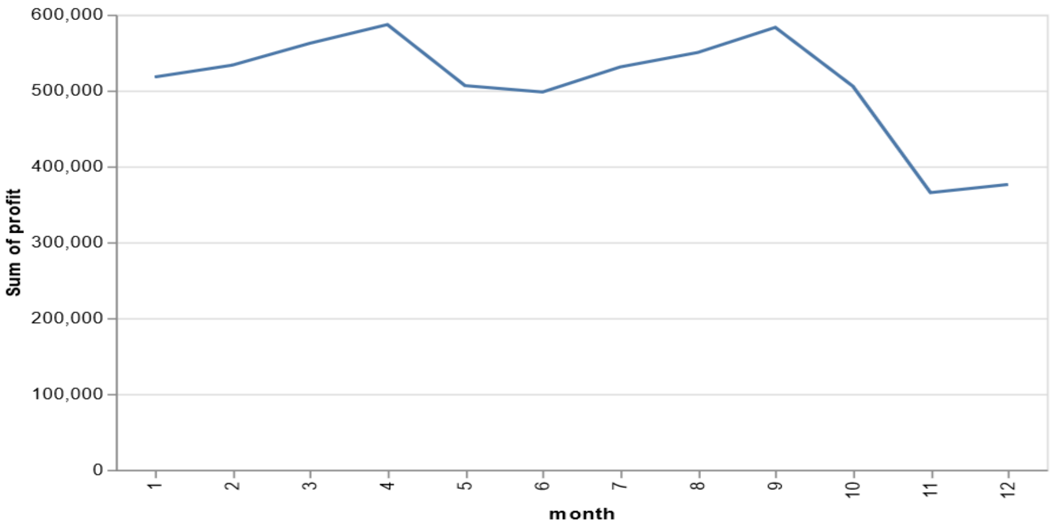

Figure 18. Monthly profit graph for year 2023

The figure 20 below shows the BESS operating behaviour as suggested by the optimization model for the week 52, which has the highest profit for the year 2020. The top chart in the figure shows the charging and discharging power of the BESS over the timespan of a week corresponding to the electricity prices shown in the bottom chart of the figure. In that bottom chart, the battery dispatch behaviour is show as spots with orange colour showing charging and blue colour showing the discharging power. The intensity of the colour shows the changes in charging/discharging power in a range of 0 to 50 MW. The BESS behaviour result from the model seems very optimal according to the electricity price variation.

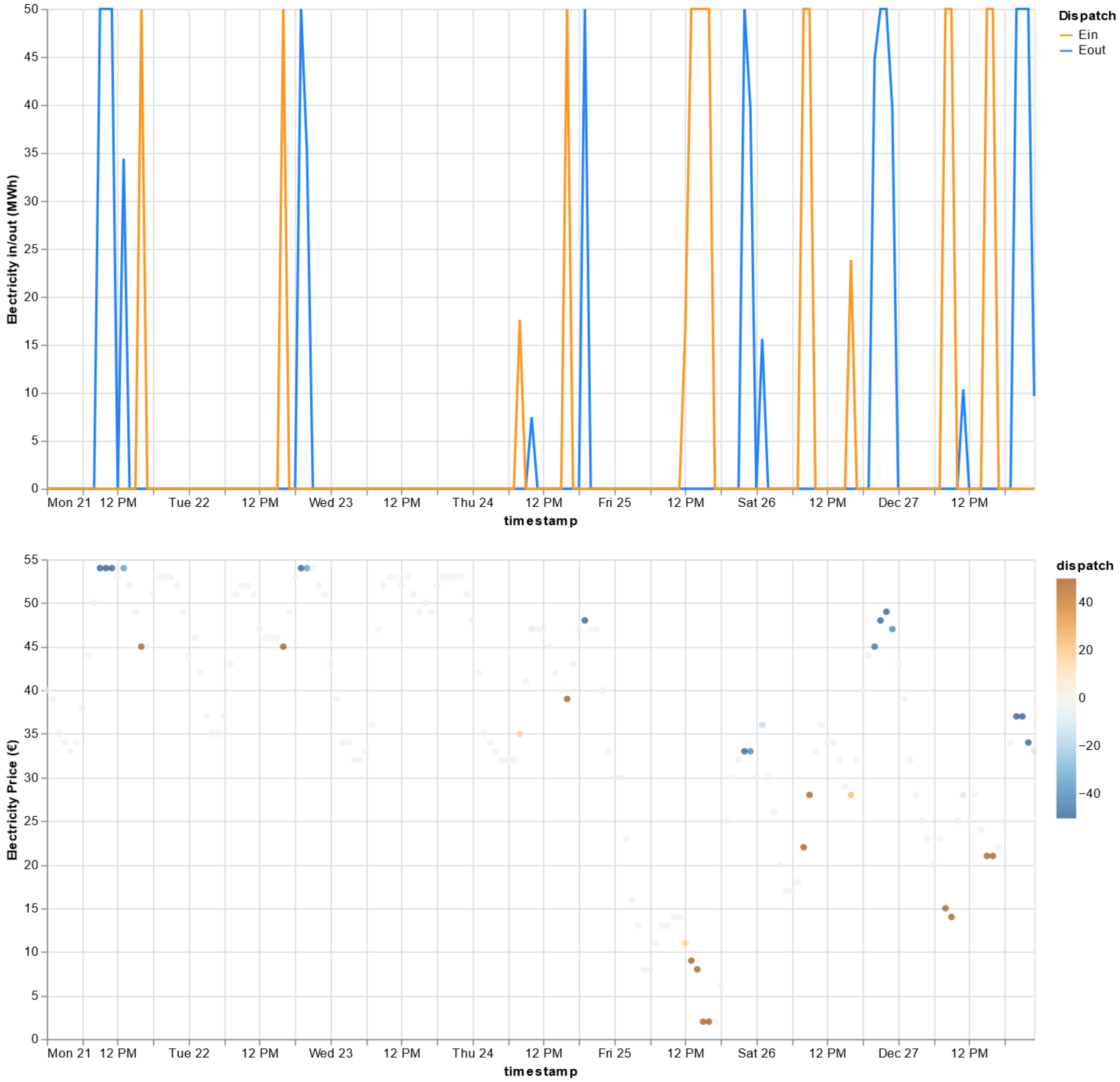

Figure 20. BESS operating pattern mapped against electricity prices for the most profitable week (52) of year 2020

For the year 2023, the figure 21 shown below shows the week 14 as the most profitable and the optimum charge/discharge pattern is outlined. A similar colour coded scatterplot in the bottom of the figure shows charging and discharging at lower and higher prices respectively. Compared to 2020, this chart shows more operational activity for the BESS due to large price differentials.

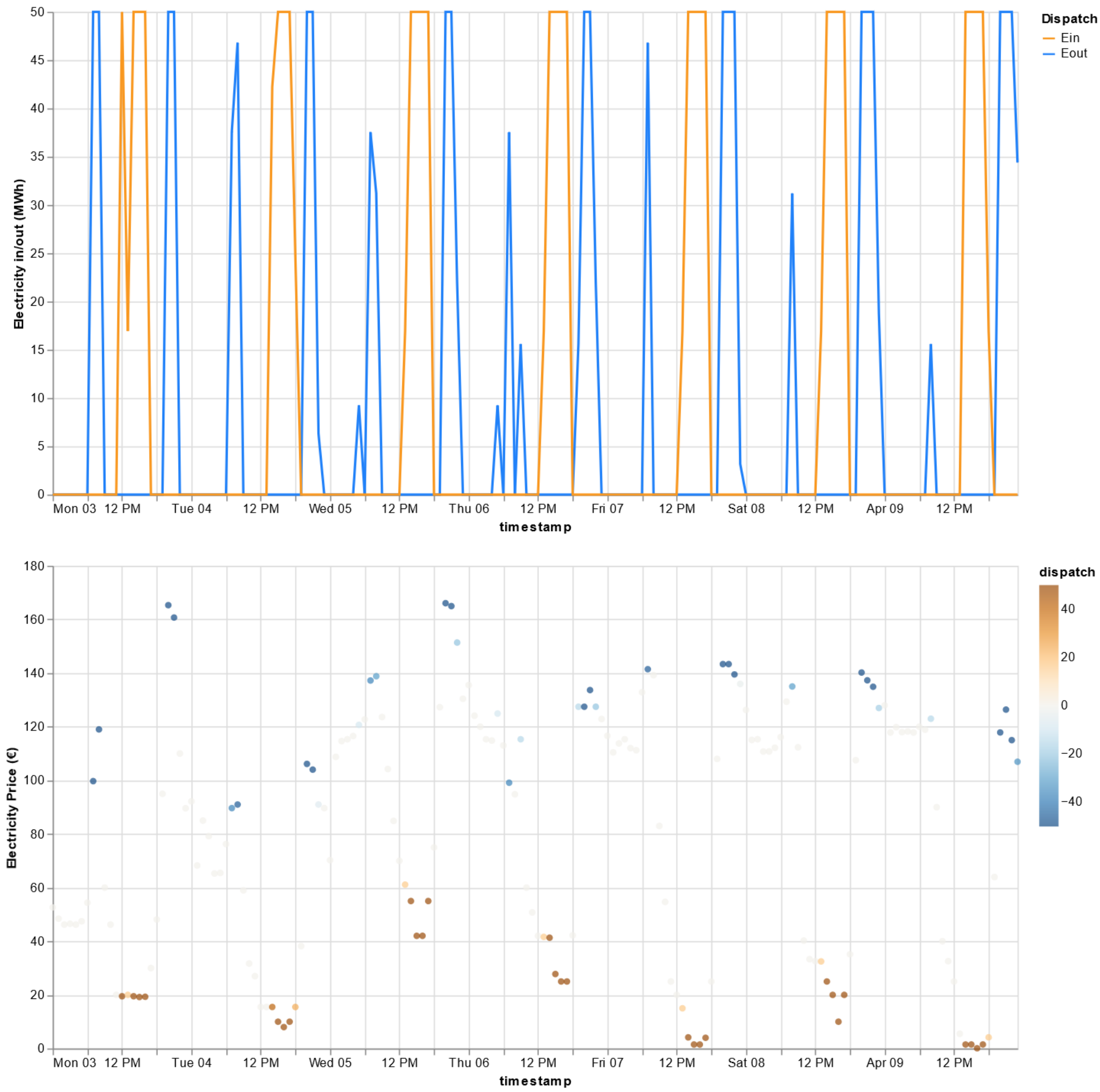

Figure 21. BESS operating pattern mapped against electricity prices for the most profitable week (14) of year 2023

The following table 13 compares the amount of monthly profits for both the years side by side.

Table 13. Monthly profits comparison for the years 2020 and 2023

Month	Profit 2020	Profit 2023
1	€ 103,353	€ 517,828
2	€ 98,243	€ 533,464
3	€ 90,468	€ 562,297
4	€ 80,249	€ 586,929
5	€ 63,002	€ 506,463
6	€ 82,950	€ 498,041
7	€ 67,771	€ 531,071
8	€ 89,246	€ 550,153
9	€ 105,245	€ 583,253
10	€ 158,154	€ 505,649
11	€ 87,115	€ 365,430
12	€ 90,919	€ 376,197

6.3 Optimization including BESS project costs

To optimize the parameters of a BESS project and find out the optimal sizing in any particular case, it is important to account for both the CAPEX and OPEX associated with the project into the optimization model. One key metric for the optimization could be the profit-to-cost ratio, which ensures that the investment in BESS yields maximum financial returns relative to its costs. In this subsection, results of the optimization considering the cost of the BESS project is explained.

CAPEX includes the initial costs of the system. The values for some of these costs were obtained from a BESS asset operating company. These are the costs for a turn-key system shown in the table 14.

Table 14. BESS project CAPEX values

Cost Component	1-hour Storage	2-hour Storage	4-hour Storage	Notes
Battery Cost	500 kEUR/MW	750 kEUR/MW	1,140 kEUR/MW	
Land Acquisition/Rent	60 kEUR/MW	60 kEUR/MW	60 kEUR/MW	Fixed across all storage durations
EPC (Engineering, Procurement, and Construction) Costs	50 kEUR/MW	65 kEUR/MW	80 kEUR/MW	Included in battery cost
Connection Cost	100 kEUR/MW	100 kEUR/MW	100 kEUR/MW	Included in battery cost

OPEX covers the ongoing expenses for the system's operation and maintenance, and are shown in table 15 below.

Table 15. OPEX cost values for BESS project

Cost Component	1-hour Storage	2-hour Storage	4-hour Storage	Notes
Maintenance and Replacement Costs	Included	Included	Included	Part of the overall operation costs.
Operation of BESS Costs	Included	Included	Included	Encompasses land lease, operations & maintenance, grid charges, insurance, and trading fees.
Total OPEX (% of Battery Cost)	4%	3.50%	3%	Percentage of battery cost dedicated to OPEX varies based on storage duration.

Optimizing the BESS parameters involves balancing these costs against the potential profits generated from energy storage and arbitrage. The objective is to achieve the highest possible profit-to-cost ratio, ensuring that the system not only recoups the initial investment but also provides substantial returns over its operational lifespan. By fine-tuning the storage duration, capacity, and operational strategies, the BESS can be optimized to perform efficiently under varying market conditions, ultimately maximizing profitability.

The objective function needs to be modified to include the cost aspect of the project, as shown in the expression below.

$$\frac{\boldsymbol{Profit}(\boldsymbol{P_t}, E_t^{out}, E_t^{in})}{\boldsymbol{Cost}\ (C)} = \frac{\sum_{12\ pm\ of\ current\ day}^{11\ pm\ of\ next\ day} P_t \cdot (E_t^{out} - E_t^{in})}{Battery\ cost \times S_{max} + \ Power\ cost \times R\_max}$$

While including cost in the objective function improves the practicality of the resulting calculation, there is another important factor in BESS operation to be included. Although the optimization model runs over the time frame of one year, it should also look at BESS costs in each 24-hour cycle of optimization. The daily cost of BESS can be introduced in the model as

$$Daily\ BESS\ cost\ (\frac{€}{cycle}) = \frac{Total\ BESS\ CAPEX + OPEX\ (€)}{Battery\ lifetime\ (cycles)}$$

This daily cost factor is introduced in the model as a profitability constraint where in each optimization cycle, the model checks whether the profit for that window of 24 hours exceeds the daily cost. If the cost exceeds the profit, operating BESS in that 24-hour period would result in a loss and the model outputs no charge/discharge operations in that period. This profitability constraint can be expressed as

$$\sum_{i=t}^{t+23}\left(E_i^{\text{out}} \times P_i - \frac{E_i^{\text{in}} \times P_i}{3}\right) \geq \text{CycleCost} \quad \forall t \in \{1, \ldots, T-24\}$$

In terms of the constraint variables:

E_t^{out} is the energy discharged from the battery at time i.

E_t^{in} is the energy charged into the battery at time i.

P_t is the electricity price at time i.

$CycleCost$ is a constant representing the minimum required profit over a 24-hour period.

T is the total number of time steps in the optimization horizon.

The challenge in this optimization lies in balancing both the hourly battery operation, which is dependent on electricity prices and solar output data, and the overall battery parameters such as capacity and discharge rate. Given this complexity, the optimization was performed manually by adjusting the BESS parameters and recording the results of the annual profit and cost optimizations. This approach allowed for a more manageable process while aiming to maximize the profit-to-cost ratio.

The following table 16 show the results of optimization for the year 2020, while varying the BESS capacity from 50 to 500 MWh in steps of 25 MWh. Two sets of results show the numbers for a 2-hour and a 4-hour BESS system.

Table 16. Optimization results - Varying the BESS parameters (2-hour storage) to find optimum P/C ratio

Duration (hours)	Capacity (MWh)	Total Revenue (€)	Total Charge Cost (€)	Total Discharge (MWh)	Total Profit (€)	Total BESS Cost (€)	P/C Ratio
2	50	462,323	117,205	11,441	345,118	37,500,000	0.009203
2	100	905,850	229,159	22,431	676,690	75,000,000	0.009023
2	150	1,344,808	340,212	33,306	1,004,596	112,500,000	0.00893
2	200	1,773,385	448,779	43,909	1,324,607	150,000,000	0.008831
2	250	2,189,694	554,141	54,197	1,635,552	187,500,000	0.008723
2	300	2,598,306	657,506	64,270	1,940,800	225,000,000	0.008626
2	350	3,002,601	760,086	74,214	2,242,515	262,500,000	0.008543
2	400	3,397,456	860,509	83,947	2,536,946	300,000,000	0.008456
2	450	3,783,287	958,777	93,385	2,824,510	337,500,000	0.008369
2	500	4,158,454	1,054,562	102,581	3,103,892	375,000,000	0.008277

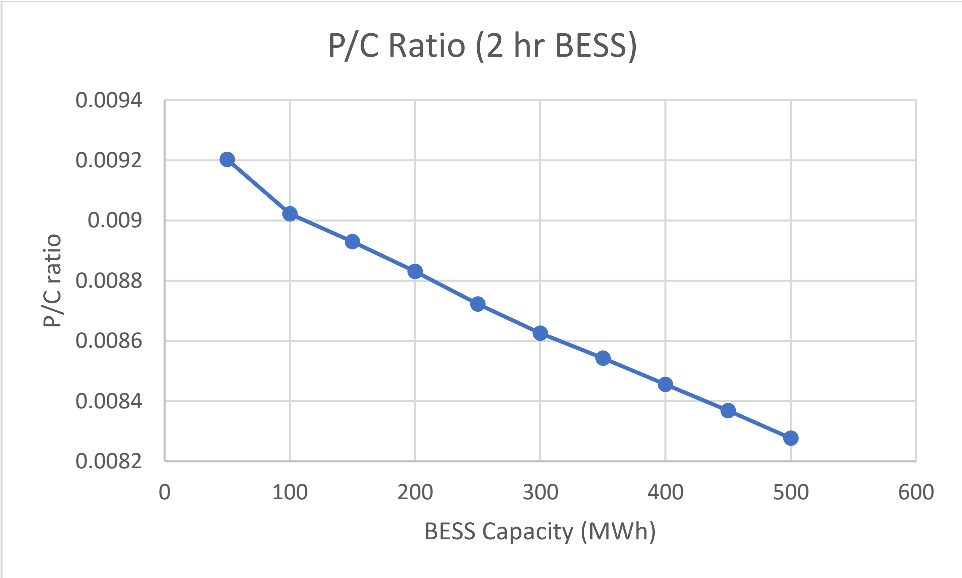

Figure 22. Chart showing a decreasing trend in P/C ratio as BESS capacity increases

For the 2-hour BESS, as the capacity increases from 50 MWh to 500 MWh, there is a consistent rise in total revenue, profit, and discharge, reflecting the ability of larger systems to handle more energy transactions. However, the P/C ratio gradually decreases from 0.009203 for the 50 MWh capacity to 0.008277 for the 500 MWh capacity, indicating diminishing returns as the BESS size increases. This decline suggests that while absolute profits rise with capacity, the relative efficiency of investment decreases.

Similarly, for the 4-hour BESS, increasing capacity from 50 MWh to 500 MWh results in higher revenue and profit, but with a more pronounced drop in the P/C ratio, starting from 0.005523 and falling to 0.004828. The decline is steeper compared to the 2-hour system, highlighting that although the 4-hour systems generate higher absolute profits, they are less cost-efficient relative to their initial investment, shown in table 17 and figure 23.

Table 17. Optimization results - Varying the BESS parameters (4-hour storage) to find optimum P/C ratio

Duration (hours)	Capacity (MWh)	Total Revenue (€)	Total Charge Cost (€)	Total Discharge (MWh)	Total Profit (€)	Total BESS Cost (€)	P/C Ratio
4	50	429,259	114,472	10,926	314,788	57,000,000	0.005523
4	100	806,529	210,986	20,401	595,543	114,000,000	0.005224
4	150	1,183,708	308,130	29,871	875,578	171,000,000	0.00512
4	200	1,557,891	404,582	39,246	1,153,309	228,000,000	0.005058
4	250	1,931,437	501,133	48,592	1,430,304	285,000,000	0.005019
4	300	2,299,788	596,262	57,814	1,703,525	342,000,000	0.004981
4	350	2,666,843	691,433	66,994	1,975,410	399,000,000	0.004951
4	400	3,021,877	783,348	75,845	2,238,529	456,000,000	0.004909
4	450	3,371,116	873,710	84,548	2,497,405	513,000,000	0.004868
4	500	3,714,638	962,485	93,077	2,752,154	570,000,000	0.004828

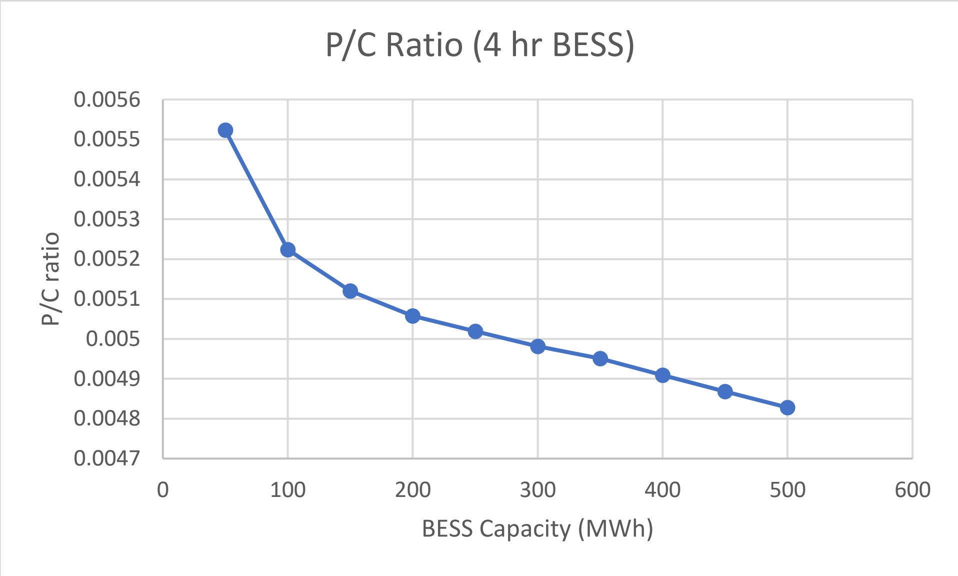

Figure 23. Chart showing a similar decreasing trend in P/C value although lower value that 2-hour results

When comparing the two systems, the 2-hour BESS consistently shows higher P/C ratios than the 4-hour BESS, suggesting that shorter-duration systems provide a better return on investment in these scenarios. However, the total profits for 4-hour systems are also significantly lower, implying that the extended duration, while useful for handling larger energy storage, comes at a cost of reduced economic efficiency. Thus, the choice between 2-hour and 4-hour BESS should consider not only the profit maximization but also the diminishing returns and overall cost-efficiency.

7 DATA CENTRE WITH BESS BUSINESS CASE

Data centres are critical infrastructure that support the backbone of the modern digital economy, with large servers, networking and storage systems. As the demand for data processing continues to grow exponentially, data centres face increasing pressure to ensure uninterrupted operations, reduce operational costs, and minimize their environmental impact. BESS present a viable solution to meet these challenges by providing reliable backup power, enhancing energy efficiency, enabling participation in energy markets, and supporting sustainability goals.

7.1 Business opportunities for BESS in Data Centres

Enhanced Operational Resilience

One of the most critical advantages of BESS in data centres is its ability to extend UPS battery runtime by one to four hours. This extension is crucial for maintaining data centre operations during utility outages, which can occur due to various factors such as grid instability or natural disasters. Traditionally, data centres rely on diesel generators as a backup power source. However, these generators can fail to start or take several minutes to become operational, posing a significant risk of downtime. By utilizing BESS, data centres can continue to operate seamlessly through short to medium-length outages, thus significantly reducing the reliance on diesel generators. This not only minimizes the risk of operational disruptions but also cuts down on emissions and air pollution associated with generator use.

Financial Opportunities through Market Participation

Beyond its role in ensuring operational continuity, BESS presents substantial financial opportunities for data centres through participation in energy markets. As a behind-the-meter asset, BESS can be used to provide grid services such as frequency regulation, spinning reserves, and demand response. These services are vital for maintaining grid stability, especially during periods of high demand or generation shortfalls. Data centres equipped with BESS can offer these services and receive compensation, effectively offsetting their energy costs. This market participation not only enhances the economic viability of BESS but also reduces the operational risks and emissions compared to traditional generator-based backup power solutions.

Demand charge avoidance and time-of-use/tariff management

Energy costs are a significant concern for data centres, particularly with regard to demand charges, which are fees based on the highest level of power demand during a billing period. BESS can help mitigate these charges through a process known as peak shaving. By discharging stored energy during periods of high demand, BESS lowers the peak demand and, consequently, the associated charges. In addition to peak shaving, BESS can optimize energy costs by taking advantage of time-of-use tariffs. By charging the battery during off-peak hours when electricity prices are lower and discharging during peak hours when prices are higher, data centres can manage their energy expenses more effectively. The extent of these savings depends on factors such as the size of the BESS, the sophistication of the energy management software in use, and the specific rate structures and energy programs available in the region.

Increased use of renewables

Sustainability is becoming a key focus for many data centres, driven by both regulatory requirements and corporate social responsibility initiatives. BESS facilitates the increased integration of renewable energy sources such as solar and wind power into data centre operations. During periods of high renewable energy availability, such as daytime for solar photovoltaic (PV) systems, BESS can store excess energy that would otherwise be curtailed or sold at low prices. This stored energy can then be used when renewable generation is low or demand is high, ensuring a more consistent and efficient use of clean energy. By maximizing the use of renewable energy and reducing the need to sell it at lower prices, BESS not only supports the data centre's sustainability goals but also contributes to the overall stability of the grid.

Emission Reduction and Environmental Impact

With increasing scrutiny on the environmental impact of data centres, BESS offers a pathway to reduce emissions associated with backup power generation. By reducing the dependency on diesel generators, which are significant sources of greenhouse gas emissions and air pollutants, BESS can help data centres minimize their environmental footprint. The use of BESS during utility outages or for grid services reduces the need to start up generators, which typically run on fossil fuels. Furthermore, by participating in demand response programs and providing ancillary services to the grid, BESS contributes to the broader decarbonization efforts within the energy sector.

7.2 Components of the Business Case

Costs

CAPEX primarily involves the initial investment in the BESS, including battery costs, power conversion systems, and installation, which vary based on system duration and capacity as already explained in the previous section. The costs are considered here are same as taken earlier, ranging from 500 kEUR/MW for a 1-hour system to 1,140 kEUR/MW for a 4-hour system. Infrastructure costs, such as land acquisition, construction, and integration with existing infrastructure, also contribute significantly to the overall investment.

On the other hand, OPEX covers ongoing expenses, including maintenance and operations, which are essential for ensuring the BESS's optimal performance and longevity. This includes routine inspections, battery replacements, energy management, and potential system upgrades.

Revenue Streams

The revenue streams for a BESS in data centres could be multifaceted and contribute significantly to its financial viability. Energy savings represent a primary source of revenue, achieved through strategies like peak shaving, demand charge reduction, and energy arbitrage, which directly lower operational costs. Additionally, participating in grid services offers an additional income stream by enabling the BESS to provide valuable services to the grid, thereby enhancing the overall ROI. Finally, data centres may benefit from sustainability incentives, such as government subsidies or incentives, for integrating energy storage solutions that support renewable energy adoption and contribute to carbon reduction efforts.

7.3 Data centre load

The energy consumption within a data centre is primarily driven by several key components and systems, each with its own specific load characteristics.

Server Farm

The server farm is the core component of any data centre, responsible for delivering the information and communication technology (ICT) services that define the centre's purpose. Due to the processing, storage, and networking tasks performed by these servers, the server farm is the largest energy-consuming unit within the data centre.

Power Supply Equipment

The power supply system is another critical component, as it ensures that the servers and other equipment receive a stable and reliable power supply. Typically, electricity enters the data centre through a high voltage transformer, often in the range of several tens of kilovolts (kV). This power is then fed into an UPS system, which provides short-term power backup, allowing the data centre to maintain operations during the brief period it takes for backup generators to start in the event of a utility failure. Power is then distributed to the server racks through Power Distribution Units (PDUs), which step down the voltage to levels appropriate for the servers, usually below 1 kV.

Heat and Airflow System

As servers operate, they generate substantial amounts of heat, which must be efficiently removed to prevent overheating and potential damage. Data centres employ sophisticated heat and airflow management systems to maintain optimal operating temperatures, typically between 20 to 25°C, with an allowable range of 15 to 32°C as recommended by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (R. Rahmani, 2018). Two common systems used for this purpose are the Computer Room Air Handler (CRAH) and Computer Room Air Conditioning (CRAC) units. CRAC units are equipped with their own condensers to cool the air, while CRAH units rely on external cooling systems to supply chilled water. These systems work by creating cold and hot air aisles within the server rooms, with cold air directed to the servers and hot air exhausted and cooled for recirculation.

Cooling System

Beyond the immediate heat removal from server rooms, data centres often utilize large-scale cooling systems based on water chiller plants. These systems operate using either vapor-compression or absorption cycles to lower the temperature of the cooling fluid. The cooling system is typically the second-largest consumer of power in a data centre, following the server farm. The efficiency of these systems is heavily influenced by external climate conditions; for instance, data centres located in colder climates, such as Google's facility in Hamina, Finland (Datacenters.com, 2024), and Facebook's data centre in Luleå, Sweden (Hitachi Energy, n.d.), leverage natural cooling methods, significantly reducing energy consumption by utilizing natural water flows and cold air.

Control and Security Systems

While the control and security systems of a data centre consume only a small fraction of the total energy—typically just a few percent—they are essential for the facility's operation. These systems manage data and power flows, ensure the security of the data stored, and make critical decisions during emergencies. They play a crucial role in maintaining the safety and integrity of the data centre's operations, especially under adverse conditions.

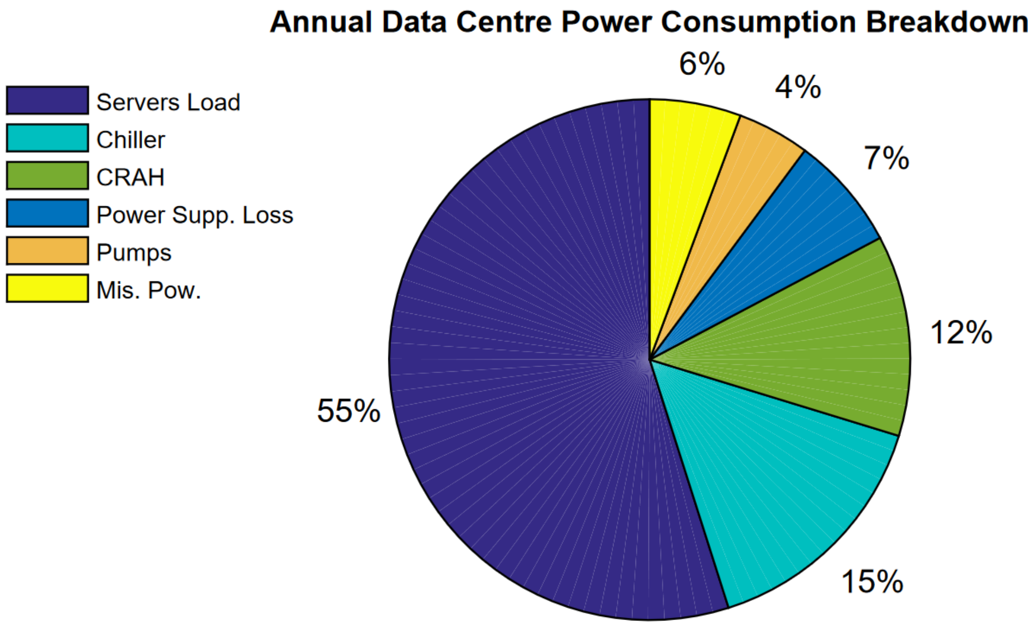

Figure 24. A general breakdown of the electrical requirements in a data centre

Figure 24 shows the annual power consumption breakup of a data centre with 40,000 computer servers, with each server's power range varying from 120 W to 250 W. This data was simulated in a research study on data centres (R. Rahmani, 2018). Data centre loads are dynamic, with IT equipment undergoing constant changes throughout the data centre's life. IT refresh cycles typically occur every three years, introducing more powerful or efficient devices. The electrical power service should be sufficiently sized to handle both current and anticipated loads.

7.4 BESS Optimization for Data Centre

To better fit the requirements of a data centre, an optimization study is necessary to quantify and analyse potential savings in electricity costs and determine the optimal sizing of the BESS for the facility. This study requires load data with hourly granularity to accurately assess the energy consumption patterns of the data centre. A forecasted load breakdown for one week, as shown in Figure 25, provides a visual representation of the data centre's energy demand, serving as a basis for the optimization analysis. From this load breakdown chart, hourly datapoints needed to be extracted in order for the optimization model to find out the most optimum strategy for the BESS to operate.

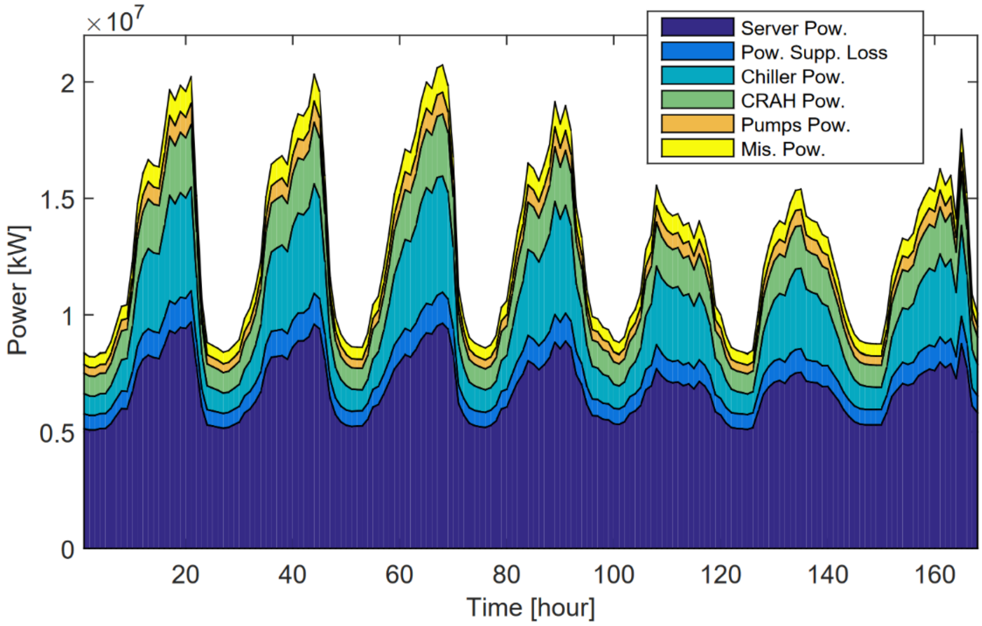

Figure 25. Total power consumption profile and its breakdown for one week

From this load profile chart, hourly total load data was extracted in a spreadsheet for the whole week for use in the optimization model. This total load is plotted separately in the following figure 26

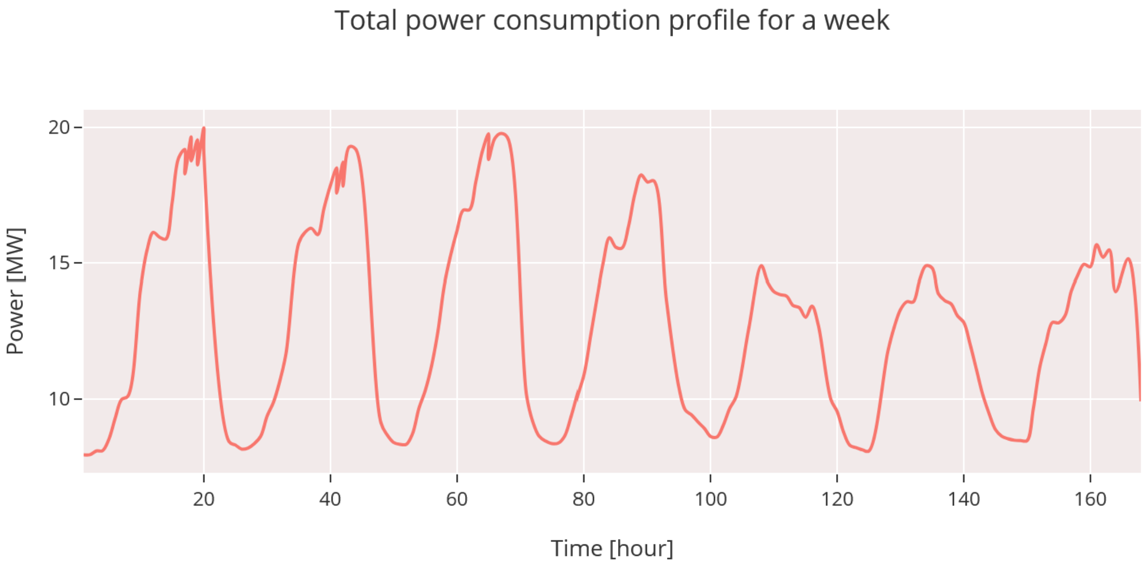

Figure 26. Total power consumption of the data centre plotted for 168 hours of a week

For the optimization, day ahead electricity price data of the Spanish market for week 33 in year 2024 has been taken from the ENTSO-E platform. The optimization algorithm architecture and tools are similar to the one used for co-located BESS optimization earlier in this project.

7.5 BESS optimization results

The objective of this optimization was to utilize BESS in a data centre to generate savings in electricity costs. By analysing hourly data collected over a week, the model was able to determine the optimal charge and discharge behaviour for the BESS. The strategy involved charging the BESS when electricity prices were low and discharging it to supply the data centre when grid electricity prices were high. An initial BESS size of a 20 MW 2-hour system was selected for this study. The following figure 27 illustrates the operational pattern of the BESS, clearly showing its charging activity during periods of lower electricity prices and discharging during periods of higher prices, thereby maximizing cost savings.

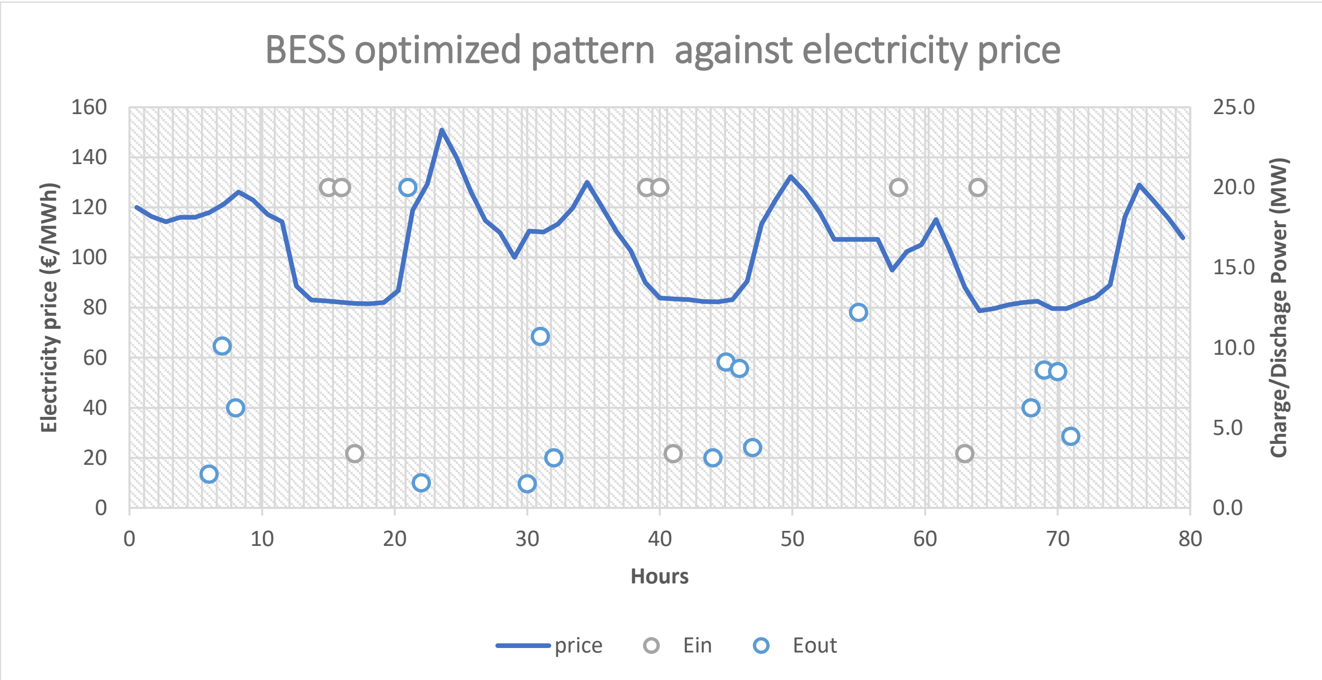

Figure 27. Optimized BESS pattern showing charging at low prices while discharging at high prices

In the baseline scenario, where the data centre operates without a BESS, the weekly electricity cost amounts to €204,348. To quantify the savings generated by implementing BESS, the electricity cost was recalculated after the optimization model determined the optimal operational pattern for the BESS. With BESS in place, the weekly electricity cost for the data centre was reduced to €186,910. This resulted in a weekly saving of approximately €17,438, or about 9% of the original electricity cost. With larger BESS size, the savings would increase considerably, however it becomes important to consider the additional costs associated with the larger BESS infrastructure when evaluating the overall financial benefits.

To account for the costs associated with BESS infrastructure, the optimization was performed by varying the size of the BESS and calculating both the savings in electricity costs and the profit-to-cost (P/C) ratio for the BESS project. This approach provides a comprehensive financial analysis by considering both the potential profits and the associated costs of the

BESS implementation. Specifically, the P/C ratio takes into account the total cost of the BESS over its lifetime, which is assumed to be 8 years, to determine the annual cost.

Figure 28 below illustrates this analysis by showing the annual profit, which is based on extrapolated weekly profits, as well as the P/C ratio. This figure provides a clear visualization of how different BESS sizes impact both the financial returns and the efficiency of the investment, allowing for an informed decision on the optimal BESS size for maximizing financial performance.

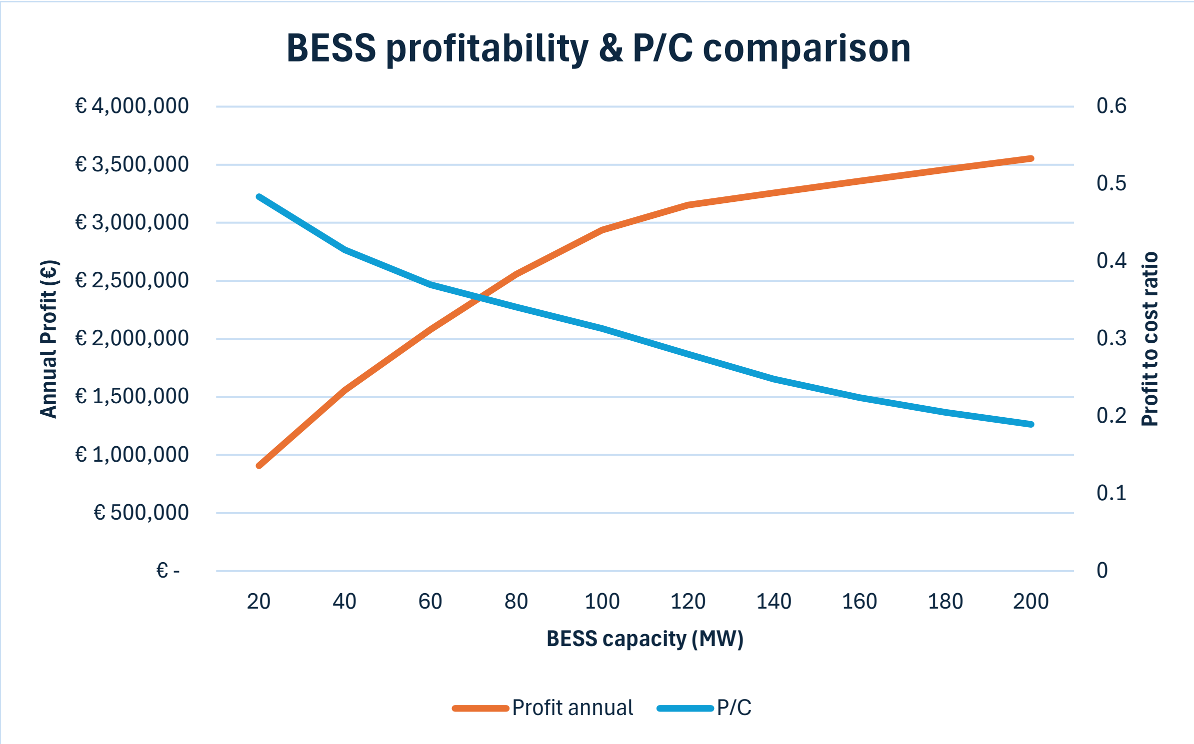

Figure 28. BESS profits and P/C ratio over a range of BESS sizes

It can be seen that the profits increase with BESS size however they eventually reach a saturation point. This occurs because the data centre's energy demands are fully met, and no additional savings can be achieved beyond a certain BESS size. On the other hand, the profit-to-cost (P/C) ratio is high at smaller BESS sizes and gradually decreases as the size increases. This trend suggests that an optimal BESS size, likely in the range of 60-100 MW, would be most effective for this particular use case, considering the specific load profile.

The findings of this study are particularly interesting because, although the analysis is tailored to a specific use case, the approach is versatile and can be applied to any demand centre with available load data.

8 CONCLUSION

The techno-economic evaluation of co-located BESS presents a significant opportunity to enhance the efficiency and profitability of renewable energy projects. This study underscores the critical role of BESS in mitigating the variability of renewable energy sources, such as solar and wind, by providing a reliable means of energy storage and dispatch.

The analysis demonstrates that co-located BESS can significantly improve the economic performance of renewable energy installations. By enabling energy arbitrage, frequency regulation, and peak shaving, BESS can enhance revenue streams while reducing operational costs. The investment in BESS is particularly justified in markets with high electricity price volatility and robust ancillary service markets. Co-location of BESS with renewable energy sources offers several technological synergies. These include shared infrastructure, reduced transmission losses, and enhanced grid stability. The integration of BESS can also smooth out the power output, ensuring a more consistent and predictable supply to the grid, which is crucial for maintaining grid reliability. Despite the promising potential of co-located BESS, several challenges remain. These include high upfront capital costs, evolving technology standards, and uncertainties in long-term performance and degradation. Additionally, the economic case for BESS is highly sensitive to market conditions, such as electricity price trends, regulatory changes, and the availability of ancillary service revenues. These factors necessitate careful consideration in the planning and deployment of BESS projects.

The objective of the modelling phase was to determine the economic viability of BESS projects when co-located with renewable energy plants or installed to supply loads such as data centres. The results showed the trends that can help project developers to choose BESS parameters based on their specific project. Additionally, these insights can aid in structuring contracts and Power Purchase Agreements (PPAs) between BESS assets and renewable energy plants, ensuring optimal integration and financial performance.

In conclusion, while the integration of co-located BESS with renewable energy projects presents substantial opportunities for enhancing efficiency and profitability, it requires careful consideration of market dynamics, technological advancements, and regulatory frameworks to fully realize its potential and address the inherent challenges.

9 FUTURE WORKS

This thesis project is based on market research and optimization modelling for the major part. The basis of these activities has been data collection, processing and analysis. Therefore, several areas for future research and improvements could be identified to enhance the accuracy and applicability of the findings.

Firstly, the solar PV data used in this project was simulated using tools like PVGIS. For more precise results, it would be beneficial to obtain real PV output data from an operational solar

PV plant. This real-world data could provide a more accurate representation of the system's performance and help refine the simulation models.

Secondly, while the optimization model results were analysed independently, comparing these results with actual BESS operations from a co-located site could offer valuable insights. Such a comparison could highlight discrepancies and suggest improvements to the optimization model, potentially identifying additional factors or corrections to consider.

Additionally, the emergence of hybrid PPAs presents new opportunities for financial optimization. As these agreements become more prevalent, further research could explore innovative financial solutions and contract structures between BESS and IPPs.

Furthermore, the data centre load information in this study was simulated and sourced from a research paper. Access to real electricity demand data from a data centre would enhance the study's accuracy and applicability. Analysing a variety of load patterns could also improve the visibility and effectiveness of BESS projects. By addressing these areas, future research can build upon this thesis to develop more robust and practical solutions for integrating BESS with renewable energy systems.

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