

Article

A Hybrid Energy Storage System and the Contribution to Energy Production Costs and Affordable Backup in the Event of a Supply Interruption—Technical and Financial Analysis [†]

Carlos Felgueiras ^{1,*}, Alexandre Magalhães ², Celso Xavier ³, Filipe Pereira ^{1,4}, António Ferreira da Silva ^{4,5},
Nídia Caetano ^{1,6}, Florinda F. Martins ¹, Paulo Silva ¹, José Machado ⁷ and Adriano A. Santos ^{4,5}

- ¹ CIETI, ISEP, Polytechnic of Porto, Rua Dr. António Bernardino de Almeida, 4249-015 Porto, Portugal; fal@isep.ipp.pt (F.P.); nsc@isep.ipp.pt (N.C.); ffm@isep.ipp.pt (F.F.M.); 1190053@isep.ipp.pt (P.S.)
- ² ISEP, Department of Electrical Engineering, Polytechnic of Porto, R. Dr. António Bernardino de Almeida 431, 4249-015 Porto, Portugal; 1160964@isep.ipp.pt
- ³ Finerge, Av. Dom Afonso Henriques 1345, 4450-017 Matosinhos, Portugal; celso.xavier@finerge.pt
- ⁴ INEGI, Institute of Science and Innovation in Mechanical Engineering and Industrial Engineering, R. Dr. Roberto Frias, 4200-465 Porto, Portugal; afs@isep.ipp.pt (A.F.d.S.); ads@isep.ipp.pt (A.A.S.)
- ⁵ ISEP, Department of Mechanical Engineering, Polytechnic of Porto, R. Dr. António Bernardino de Almeida 431, 4249-015 Porto, Portugal
- ⁶ LEPABE—Laboratory for Process Engineering, Environment, Biotechnology and Energy, ALiCE—Associate Laboratory in Chemical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
- ⁷ METRICs Research Centre, School of Engineering, University of Minho, Campus of Azurém, 4800-058 Guimarães, Portugal; jmachado@dem.uminho.pt
- * Correspondence: mcf@isep.ipp.pt
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Abstract

Alternative energies are essential for meeting the global demand for environmentally friendly energy, especially as the use of fossil fuels is being reduced. In recent years, largely due to diminishing fossil fuel reserves, Portugal has been actively promoting investment in renewable energies to reduce its reliance on energy imports and fossil fuels. However, despite the country's high daily sunshine hours and utilization of wind and hydropower, energy production remains unstable due to climate variability. Climate instability leads to fluctuations in the energy supplied to the grid and can even partially withstand blackouts such as the one that occurred on 28 April 2025 on the Iberian Peninsula. To address this problem, energy storage systems are crucial to guarantee the stability of the supply during periods of low production or in situations such as the one mentioned above. This paper analyzes the feasibility of implementing an energy storage system to increase the profitability of a wind farm located in Alto Douro, Portugal. The study begins with a demand analysis, followed by simulations of the system's performance in terms of profitability based on efficiency and power. Based on these assumptions, a modular lithium battery storage system with high efficiency and rapid charge/discharge capabilities was selected. This battery, with less autonomy but high capacity, is more profitable, since a 5% increase in efficiency results in high profits (€84,838) and curtailment (€70,962) using batteries with lower autonomy, i.e., 2 h (power rating of 5 MW combined with 10 MWh energy storage). Therefore, two scenarios (A and B) were considered, with one more optimistic (A) in which the priority is to discharge the batteries whenever possible. In the more realistic scenario (B), it is assumed that the batteries are fully charged before discharge. On the other hand, in the event of a blackout, it enables faster commissioning



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of the surrounding water installations, because solar and battery energy have no inertia, which facilitates the back start protocol.

Keywords: battery; blackout; curtailment; inertia; price arbitrage; renewable energy; wholesale electricity market; wind power plant

1. Introduction

The search for alternatives to energy production policies based on fossil fuels has been a pressing issue in the world's energy policies. Portugal, a peripheral country with no fossil resources, has been investing in alternatives to conventional electricity production, using clean hydro, wind, and solar energy. According to the 2024 Yearbook of the Portuguese Renewable Energy Association (APREN) [1], this investment represented a total of 70.6% of the energy produced in 2023. Energy production from renewable sources, such as solar (12.1%, 5800 GWh) and wind (27.3%, 13,116 GWh) [1], is crucial for decarbonization, mitigating climate change, and diversifying energy sources, which enhances the resilience of the energy grid [2,3]. Nonetheless, despite the growth in renewable energy production capacity (resulting in a saving of 750 million euros in CO₂ emission licenses and a reduction of 9.7 million tons of CO₂-eq [1]), the variability of wind and solar energy causes instability in the grid and consequently affects the consistent supply of these sources to the electricity grid remains intermittent [4]. This instability results in unpredictable, inaccurate forecasts and the necessity of implementing measures to address these variations [2,3].

This project is just one part of an economic feasibility study for [5]. This Independent Power Producer (IPP) has 25 years of experience and is the second largest producer of renewable energy in Portugal. The study aims to assess the energy storage system of a wind farm and its hybridization and solar modelling to ensure an energy balance [4].

The objective of this study is to identify and manage the energy produced, considering the market offers and the diversity of energy producers. To achieve the objective, the effective integration of an energy storage system is essential to obtain the expected operational and economic benefits. The benefits of reduction can be achieved using static battery storage systems or mobile systems, such as electric vehicles, which will represent a significant share of around 10% to 15% in the future [6]. Therefore, integrating these systems into renewable energy production farms (80 wind farms and 17 solar power plants, 850 wind turbines and thousands of photovoltaic modules) is crucial for minimizing energy variability and enabling these renewable energy sources, improving the overall efficiency and reliability of production systems [2–4]. Another key objective of the analysis is to compare it with other storage models, described below, particularly in terms of storage capacities and presentation of actual results measured in the field, given the lack of real data in the scientific literature. Improved electrothermal or simple degradation models and the Sustainable Fast Charging Strategy for Lithium-Ion Batteries, as well as others, such as differential current-based relaying for bipolar Line-Commutated Converter (LCC) High-Voltage Direct Current (HVDC) lines, among others, were not considered in this initial study, given that the main objective was to study profits from energy sales.

The purpose of this work is to perform a comprehensive technical and financial analysis of a specific energy storage system (considering the use of batteries with 2 or 4 h of autonomy), with a particular focus on the Alto Douro wind farm. The implementation of this system has the potential to mitigate the effects of wind and solar variability on the grid, promote greater integration of renewable energy sources and contribute to a significant increase in the system overall efficiency [2,3]. The implementation of these systems is aimed

to support Portuguese sustainability and contribute to meeting international commitments, such as the Paris Agreement and European Union carbon neutrality objectives. This, in turn, will promote the reduction in carbon emissions and facilitate the transition to clean and sustainable energy sources [7–10]. This analysis will serve as an important key contribution to the development of investment strategies in renewable energy and Hybrid Energy Storage Systems (HESSs), focusing on resolving issues related to instability, reliability, and quality of the energy supplied to the grid [11] and financial return.

Innovation/novelty is based on a real analysis of data collected in the field. In other words, it is based on a real study and not on simulation models, which are no less important, using proven equipment, lithium-ion batteries, considering their efficiency and the charge–discharge cycles most suitable for the location and objectives of the company.

This document is structured in five sections. The first section presents the contextualization of the study, and the objectives are defined. The second section contextualizes the problem of energy storage, presents its advantages and disadvantages and discusses current applications and technology, while the third section presents the characterization of the wind farm analyzed in this project, equipment upgrades, hybridization, and the respective production results. The fourth section looks at the process of assessing curtailment (energy produced beyond the grid supply limit) in two distinct scenarios. It also includes a price arbitrage and a sensitivity analysis, as well as an assessment of the evolution of curtailment events and their implications for future projects with similar characteristics and their ability to respond promptly as an affordable backup [12] and in blackout situations [13]. The last section presents the project's conclusions and recommendations for future research based on this work.

2. Energy Storage Systems

An energy storage system is made up of technical installations designed to capture, store and deliver energy. These systems function as accumulators, storing excess energy generated during periods of low demand and supplying it when it increases. Energy storage plays a vital role [14], and it is essential for improving the energy optimization of production farms, particularly in installations where the grid's capacity cannot absorb all the generated capacity installed. Some of the advantages of these systems include minimizing energy variability (variability of wind and solar resources due to fluctuations in wind speed and changes in solar radiation), enhancing stability, generating additional revenue, reducing operating costs, and supporting sustainability goals. They also need to provide a rapid response to sudden and catastrophic energy events, such as outage backup or blackouts [12,13]. On the other hand, supply reliability is enhanced during periods of low wind speed, reduced solar intensity, or scheduled maintenance outages, ensuring a continuous and stable supply to the grid [15], frequency regulation, and voltage support and thus contributing to the overall stability and performance of the grid as a guarantee of additional revenue. Furthermore, the incorporation of energy storage systems is fundamental to addressing the issue of intermittency in renewable energy generation [16] and generate additional revenue by participating in ancillary service markets and price arbitrage. These systems contribute to sustainability goals (Sustainable Development Goal 7) by facilitating the integration of renewable energy sources into the energy matrix and reducing dependence on fossil fuels [17–19]. Therefore, energy storage systems play a crucial role in the optimization of hybrid power plants (wind and solar) especially when the installed power exceeds the capacity of the grid. Some of their advantages include the following [20]:

- Minimizing the variability of energy production.
- Enhancing the reliability of energy supply.

- Maximizing the utilization of wind and solar resources.
- Contributing for grid stability.
- Creating opportunities for additional revenue.
- Reducing operational and maintenance costs.
- Contributing to sustainability goals.

Storage provides greater flexibility in power plant operations and maintenance planning, optimizing resource utilization, reducing internal losses, and pursuing sustainability goals, i.e., reducing dependence on fossil fuels [16–19].

2.1. Types of Storage Systems

There are several types of energy storage systems, each one with distinct characteristics depending on their technology. These systems can be categorized as mechanical, chemical, electrical, electrochemical, or thermal systems [11–31].

The storage of mechanical energy is achieved by converting and storing energy as kinetic energy through the application of a force (flywheels, inertia of a rotating mass with minimal degradation over time) and/or potential energy (hydraulic energy storage at different elevations and high energy conversion efficiency) or in a fluid under pressure (steam, compressed air, and oil) [18–21]. Chemical energy is stored in the form of chemical fuels, such as hydrogen produced through water electrolysis [22], which can be converted into thermal, electrical, or mechanical energy. Meanwhile, electrical energy is stored in highly efficient electromagnetic fields, such as supercapacitors and magnetic superconductors, for long periods of time [23]. Electrochemical energy storage occurs in batteries, which consist of multiple electrochemical cells composed of an anode (negative terminal), a cathode (positive terminal), and an electrolyte. During the charging process, chemical reactions enable energy to be stored in the anodes and cathodes material. Upon discharging, this stored chemical energy is converted back into electrical energy. This type includes lead-acid, nickel, sodium-sulphur, lithium, and sodium batteries, each with distinct characteristics [24–26]. Thermal energy is stored as heat or cold. In concentrated solar power plants, the heat is stored to drive turbines at high temperatures. However, they require a substantial amount of storage space and typically have relatively low energy density [27].

Comparison of Storage Batteries

Among the battery technologies available, lithium-ion batteries offer the most suitable characteristics to integrating hybrid installation. Their high performance and overall cost-effectiveness, along with factors such as efficiency, reliability, longevity, and safe operations, make them a perfect choice [28].

Lithium-ion technology has emerged as the preferred solution, essentially due to its short discharge times, high performance (at 100 °C), and the reduced risk, compared to other technologies. They can be designed to tolerate a wide range of unloading times, optimizing price arbitrage in different markets [29–39].

2.2. Case Implementation

Some examples of projects with energy storage systems in hybrid renewable energy power stations are presented below:

- South Australia—Hornsedale Power Reserve [40]: This project uses Tesla lithium-ion batteries systems. It ensures grid stability and provides backup power with rapid response to fluctuations in renewable energy production.
- Morocco—Noor Complex [41]: It is one of the biggest solar energy installations equipped with thermal energy storage. Using parabolic collectors, they focus on the

sunlight to generate power and heat. Surplus heat is stored in molten-salt reservoirs, and it is used at night or on overcast days allowing for electricity production.

- Australia—Yandin wind farm [42]: It is one of the biggest wind installations in Western Australia. It incorporates an energy storage system based on lithium-ion battery to ensure grid reliability and optimize the renewable energy production.
- Switzerland—Nant de Drance [43]: It is a pumped-storage hydroelectric project located in the Swiss Alps. This system uses a pair of artificial reservoirs on different elevation planes. The water is pumped upwards during the period of surplus production, and it is released to produce energy when it is needed, enhancing the stability and the fluctuation of the renewable energy.
- Portugal: In Portugal, the most common storage facilities are based on electric pumping, as is the case with the Baixo Sabor (downstream), Alto Rabagão, Vilarinho das Furnas, Torrão, Baixo Sabor (upstream), Frades I and II, Salamonde II, Foz do Tua, Aguieira, Alqueva, and Vendas Novas III units. From the point of view of battery storage, the facilities in Évora (lithium ions) [44] and Alcoutim [45] are noteworthy.

These case studies show the diverse applications of energy storage systems in renewable energy projects, including lithium-ion batteries, thermal storage, and pumped hydro storage. They highlight the advantages of each technology in different contexts and provide valuable insights into the successful integration of energy storage in hybrid power plants.

3. Implementation of the Case Study

The project originated from Finerge's [5] requirement to enhance the capacity of the wind turbines installed at the Alto Douro wind farm, as well as from the goal of hybridization. Finerge installs offline photovoltaic modules (hybridization) to supplement the wind farm's energy production, with the aim of reducing the output variability of production during periods of low winds. The goal was to reduce variability in energy production, since the solar resources around this project were normally available when wind speeds were lower. The following flowchart (Figure 1) briefly outlines the steps required to conduct the study.

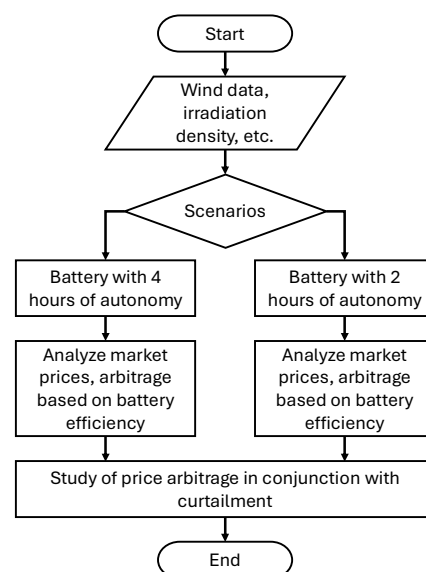


Figure 1. Flowchart of the study process.

As the installed capacity grew, energy production exceeded the amount that the public grid could absorb, resulting in an energy surplus (curtailment). In the absence of storage, all surplus energy would be totally wasted. In this context, the primary goal was to assess

the economic feasibility of the storage energy of the battery system by the analysis of the optimum features of the wind Alto Douro farm. To study the implications of stored energy, several databases were employed to estimate the available energy to be used and to simulate the required storage capacity. Simultaneously, the database served to define and identify the technical specification of the batteries. For this purpose, the total energy surpassing the export capacity was quantified, considering current production alongside the anticipated growth from wind energy expansion and the hybridization of the system. Through computer simulation, key parameters, such efficiency, capacity, losses, autonomy, battery power, and electricity prices, were quantified to enable the identification of the optimal battery specifications. Figure 2 shows the schematic of the implementation of the project.

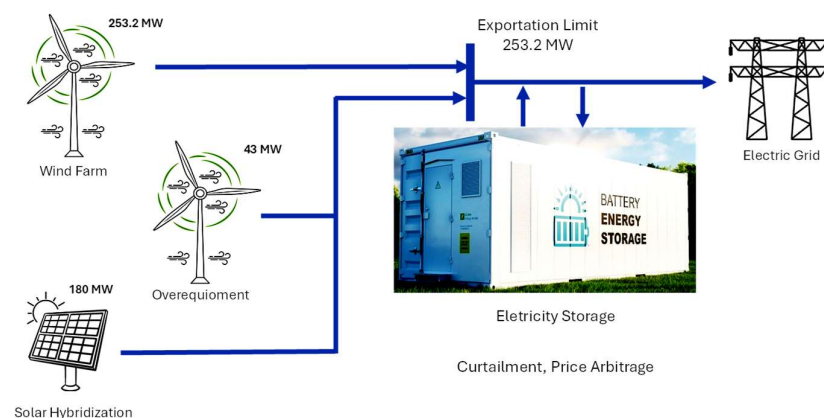


Figure 2. Schematic project presentation, adapted from [46].

3.1. Overview of the Wind Farm

The wind farm is in Alto Douro, in the district of Viseu, in the north of Portugal (see Figure 3a) and is made up of seven sub-farms divided into three branches connected to a high-voltage substation. Figure 3b shows the wind indices for areas of mainland Portugal. The Alto Douro region is marked in red circle in Figure 3.

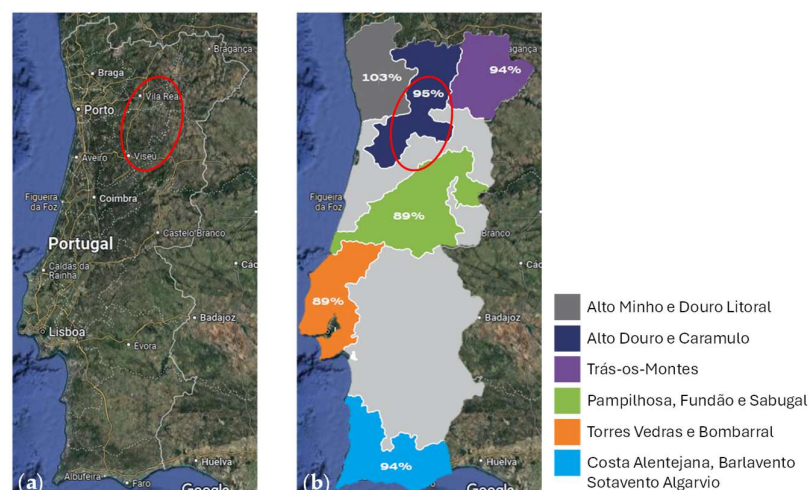


Figure 3. (a) Location of the Alto Douro wind farm; (b) wind index per zone (Alto Douro—95%).

The wind farm consists of seven sub-parks divided into three branches, all connected to a substation, the geographical location of which is illustrated in Figure 4. The first branch is made up only of the Sendim sub-farm, while the second branch consists of the sub-farm

Diagrama de rede elétrica do sistema de transmissão de 230 kV. O diagrama mostra a conexão entre a SE São Martinho e várias subestações de transmissão (Sub-PE) e centros de subfusão (CSF). A SE São Martinho é conectada a Sub-PE Armamar II (11.5 MVA), Sub-PE Chavões (40 MVA), CSF Sendim (100 MVA), Sub-PE Sendim (50 MVA), CSF Riodades (50 MVA) e Sub-PE Serra de Sampaio (34.5 MVA). A Sub-PE Armamar II é conectada a Sub-PE Armamar I (32.4 MVA). A Sub-PE Chavões é conectada a Sub-PE Armamar I (32.4 MVA). A CSF Sendim é conectada a Sub-PE Armamar I (32.4 MVA). A Sub-PE Sendim é conectada a Sub-PE Armamar I (32.4 MVA). A CSF Riodades é conectada a Sub-PE Armamar I (32.4 MVA). A Sub-PE Serra de Sampaio é conectada a Sub-PE Armamar I (32.4 MVA). A Sub-PE Armamar I é conectada a Sub-PE Serra da Nave (43.7 MVA). A Sub-PE Serra da Nave é conectada a Sub-PE Testos II (50.6 MVA). A Sub-PE Testos II é conectada a OVP (50 MVA). A Sub-PE Serra de Sampaio é conectada a Sub-PE Ranhado (50 MVA).

<https://doi.org/10.3390/en19020306>



Figure 6. The São Martinho substation in Alto Douro.



Figure 7. The São Martinho substation with starter batteries.

Table 1 presents a summary of the multi-year energy production data provided by Finerge. These data, recorded at 15 min intervals and measured in kWh, show the total energy produced at each park, as well as the total energy, and are therefore fundamental for calculating the curtailment obtained throughout the day, considering all losses associated with energy transport. The sample values presented in Table 1 are actual data provided by Finerge and are therefore confidential, as they are part of the production control data of the company in question. For this reason, they will not be presented in full.

Table 1. Sample production data provided by the plant in kWh (Finerge).

Time of Register [h]	Armamar	Armamar II	Serra da Nave	Testos II	Chavães	Serra de Sampaio-Ranhados	Sendim
00:15	10	0	5970	2080	550	1060	320
00:30	10	90	6120	2160	750	1300	760
00:45	100	130	7090	2120	800	1050	840
01:00	60	140	7090	1880	900	1710	1040
01:15	160	30	6700	1400	630	2400	680
01:30	240	150	5740	1400	1150	1440	2360
01:45	490	20	5980	1560	1890	2350	2560
02:00	90	0	7370	1640	1460	2670	1040
02:15	20	0	6930	1640	1120	2550	680
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

3.2. Energy Quantification

The additional energy production was estimated using wind speed measurement taken at 80 m above ground level in the Serra de Montemuro. Data recorded were taken every 15 min interval over a duration of 3 h. The observed average wind speed recorded

was approximately 3.23 m/s, and the additional installed capacity was 43 MW, in line with the current legislation which permits a 20% increase over the existing capacity. This estimate is based on the power curves of the new turbines (Vestas V150–4.5 MW 50/60 Hz [49] and GE 5.8–158—50/60 Hz [50]). Table 2 presents a sample of the expected values for the use of the new Vestas V150 turbine model, considering operating conditions at a height of 80 m as a function of wind speeds and air density.

Table 2. Sample data for the Vestas V150–4.5 MW 50/60 Hz model.

Wind Speed [m/s]	Air Density (ρ) [kg/m ³]											
	1.050	1.067	1.074	1.075	1.082	1.097	1.100	1.104	1.112	1.120	1.136	1.150
Electrical Power for the Vestas Model in kW												
3.0	62.0	64.0	64.9	65.0	65.6	66.8	67.0	67.5	68.4	69.4	71.3	73.0
3.1	77.6	79.9	80.9	81.0	81.7	83.1	83.4	83.9	85.0	86.1	88.2	90.0
3.2	93.2	95.8	96.8	97.0	97.8	99.5	99.8	100.4	101.6	102.8	105.1	107.0
3.3	108.8	111.7	112.8	113.0	113.9	115.8	116.2	116.9	118.2	119.6	122.0	12.0
3.4	124.4	127.5	128.8	129.0	130.0	132.2	132.6	133.3	134.8	136.3	138.9	141.0
3.5	140.0	143.4	144.8	145.0	146.1	148.5	149.0	149.8	151.4	153.0	155.8	158.0
3.6	159.4	163.1	164.6	164.8	166.1	168.8	169.4	170.3	172.0	173.7	176.7	179.2
3.7	178.8	182.7	184.4	184.6	186.1	189.2	189.8	190.7	192.6	194.4	197.7	200.4
3.8	198.2	202.4	204.2	204.4	206.0	209.5	210.2	211.2	213.2	215.2	218.7	221.6
3.9	217.6	222.1	223.9	224.2	226.0	229.8	230.6	231.7	233.8	235.9	239.7	241.8
4.0	237.0	241.8	243.7	244.0	246.0	250.2	251.0	252.1	254.4	256.6	260.6	261.0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Table 3 presents a sample of the expected values for the use of the new GE 5.8 turbine model, considering operating conditions at a height of 80 m as a function of wind speeds and air density.

Table 3. Sample data for the GE 5.8–158—50/60 Hz model.

Wind Speed [m/s]	Air Density (ρ) [kg/m ³]											
	1.050	1.067	1.074	1.075	1.082	1.097	1.100	1.104	1.112	1.120	1.136	1.150
Electrical Power for the GE Model in kW												
3.0	58.0	58.7	59.4	60.0	60.3	62.6	63.0	63.4	64.2	65.0	66.6	67.0
3.1	75.0	75.8	76.7	77.4	77.7	80.1	80.6	81.1	82.0	83.0	84.8	85.2
3.2	92.0	93.0	94.0	94.8	95.1	97.7	98.2	98.8	99.9	101.0	102.9	103.4
3.3	109.0	110.1	111.2	112.2	112.6	115.3	115.8	116.4	117.7	119.0	121.1	121.6
3.4	126.0	127.3	128.5	129.6	130.0	132.8	133.4	134.1	135.6	137.0	139.2	139.8
3.5	143.0	144.4	154.8	147.0	147.4	150.4	151.0	151.8	153.4	155.0	157.4	158.0
3.6	164.8	166.3	167.9	169.2	169.6	173.9	173.6	174.5	176.2	178.0	180.9	181.6
3.7	186.6	188.3	190.0	191.4	191.9	195.5	196.2	197.2	199.1	201.0	204.4	205.2
3.8	208.4	210.2	212.0	213.6	214.1	218.0	218.8	219.8	221.9	224.0	227.8	228.8
3.9	230.2	232.2	234.1	235.8	236.4	240.6	241.4	242.5	244.8	247.0	251.3	252.4
4.0	252.0	254.1	256.2	258.0	258.6	263.1	264.0	265.2	267.6	270.0	274.8	276.0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

The average wind speed and the low turbulence, as well as the powers values corresponding to air density, were determined using the ideal gas law in conjunction with the barometric formula [51–53]. The power value at a given point was obtained as a function of

wind speed and air density (as specified by the manufacturer), according to the following Expression (1):

$$\rho = p \times \frac{M}{R \cdot T} \quad (1)$$

where ρ is the density in kg/m^3 , p is the absolute pressure in Pa, M is the molar mass of dry air in kg/mol , R is the ideal gas constant in $\text{J}/(\text{mol} \cdot \text{K})$, and T is the temperature in K. However, given the dependence of the previous expression on absolute pressure, we initially had to calculate it using the following Expression (2) [51]:

$$p = p_0 \left(1 - \frac{L \cdot h}{T_0} \right)^{\frac{g \cdot M}{R_0 \cdot L}} \quad (2)$$

where p_0 is the static pressure at mean sea level and is considered to be 101,325 Pa, L is the temperature gradient in K/m (0.0065), h is the altitude of the installation site (Serra de Montemuro) in meters (1382), T_0 is the standard temperature at mean sea level in K (288.15), g is the acceleration constant in m/s^2 (9.80665), and M is the molar mass of dry air in kg/mol (0.028964), and R_0 is the ideal gas constant in $\text{J}/(\text{mol} \cdot \text{K})$. It is important to highlight that the temperature was calculated as a monthly average at the elevation of the S. João Lagoon, based on data provide by the Portuguese Institute for the Sea and Atmosphere (IPMA) [52].

On the other hand, knowing that the wind data provided corresponded to a height of 80 m, it was necessary to calculate all the values according to the working height of 105 m for the new turbine models to be installed. Thus, the wind speed at this new height was calculated by the following Expression (3):

$$v_2 = v_1 \cdot \left(\frac{z_2}{z_1} \right)^\alpha \quad (3)$$

where v_2 represents the wind speed at the target height z_2 in m/s , v_1 is the speed at height z_1 in m/s , z_2 is the height at which we want to calculate the wind speed in m, z_1 is the initial reference height in m (meters), and α is the wind power coefficient, dimensionless and equal to 1/7. A sample of the results calculated at 105 m for the early hours of the day is shown in Figure 8. It should be noted that this adjustment, as expected, differs very little from the base values obtained at 80 m.

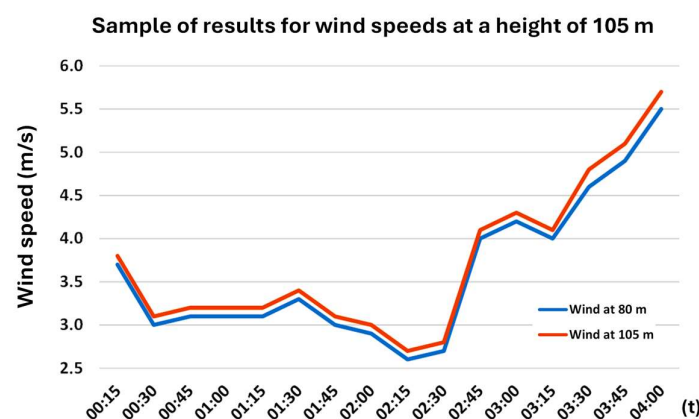


Figure 8. Sample results for wind speeds at heights of 80 and 105 m.

Based on the overall analysis, the decision to install the GE model was essentially based on the lower installation cost and the reduced number of turbines required compared to the previously considered model. Eight turbines were chosen, considering the additional installed capacity of 43 MW, limited to a power of 5.3 MW. In addition, a total loss value of

2.5% was considered, a percentage provided by Finerge, which corresponds approximately to the losses of the turbines already installed in the Alto Douro wind farm. These changes in the park result in an average of 3161 equivalent hours per year of production, which corresponds to a significant improvement over the factory's average of 2367 equivalent hours, i.e., an increase of around 33.5% equivalent hours.

3.2.1. Hybridization

Regarding hybridization, the number of photovoltaic modules installed was determined considering diffuse and direct irradiance (diffuse radiation accounts for around 20% of direct radiation) data provided by the producer, which led to a hybridization installation of 180 MWp. Table 4 shows the solar radiation affecting the solar park on the first day of January as a function of hourly solar availability. The solar model was used for its efficiency and peak power.

Table 4. Irradiation data from a partial day sample (Wh/m²).

Month	Day	Hour	Irradiation [Wh/m ²]
1	1	:	0.0
1	1	7	0.0
1	1	8	1.1
1	1	9	199.3
1	1	10	802.7
1	1	11	1331.3
1	1	12	1688.6
1	1	13	1809.8
1	1	14	1682.6
1	1	15	1402.4
1	1	16	921.2
1	1	17	320.6
1	1	18	1.5
1	1	19	0.0
1	1	:	0.0

However, the energy output of the photovoltaic modules was determined based on their irradiance levels, module efficiency, and surface area [51–53]. Considering this formulation, the partial energy production from hybridization was estimated on an hourly and in 15 min intervals, as presented in Table 4. The following formula was used to calculate the energy produced by each solar panel over a given period:

$$P = I \cdot \eta_g \cdot A_m \cdot \eta_m \quad (4)$$

where P is the production of each solar panel in Wh, I is the direct and diffuse irradiation in Moimenta da Beira, Viseu, where the solar panels were installed in Wh/m², η_g is the overall efficiency (dimensionless), A_m is the area of each solar panel module in m², equal to 2.8, and η_m is the solar panel efficiency (dimensionless), equal to 22%.

To calculate the overall efficiency value (η_g), losses due to temperature, dirt, angle of incidence, shadows, module quality, irradiance level, LID (Light-Induced Degradation), system unavailability, ohmic losses, and module and string losses with mismatch and inverter losses were considered. The overall efficiency then resulted in a value of around

75%. However, to calculate the total energy produced by hybridization, in kWh, the following formula was used:

$$P_t = P \cdot \frac{P_m}{P_p} \quad (5)$$

where P_t is the total power produced in Wh, P_m is the maximum hybridization power, and P_p is the maximum power produced per solar panel in Wh, bearing in mind that the resulting total production cannot exceed 180 MW, as mentioned above. Table 5 shows a sample of the total energy produced, based on hourly solar availability and the number of panels to be installed, by hybridization, in kWh. These values were subsequently recalculated considering 15 min intervals to establish correspondence with the period of the previously calculated values.

Table 5. Partial sample of the energy produced by hybridization (kWh).

Month	Day	Hour	Irradiation [Wh/m ²]	Production per Panel [Wh]	Production [kWh]
1	1	:	0.0	0.0	0.0
1	1	7	0.0	0.0	0.0
1	1	8	0.0	0.0	0.0
1	1	9	55.0	25.4	7424.6
1	1	10	223.0	102.9	30,103.4
1	1	11	370.0	170.7	49,947.4
1	1	12	469.0	216.3	63,311.7
1	1	13	503.0	232.0	67,901.5
1	1	14	467.0	215.4	63,041.7
1	1	15	390.0	179.9	52,647.3
1	1	16	256.0	118.1	34,558.2
1	1	17	89.0	41.0	12,014.4
1	1	18	0.0	0.0	0.0
1	1	19	0.0	0.0	0.0
1	1	:	0.0	0.0	0.0

The results of the analysis showed unequivocally that the solar irradiation for Moimenta da Beira reached a value of 1718 h, which corresponded to the expected value due to the high efficiency of the panels model used. However, to validate the results obtained, a comparison was made with the values collected by the National Aeronautics and Space Administration (NASA) [54] for the same location and time, and a certain homogeneity was verified. The values obtained from NASA data (2001 to 2024) correspond to an equivalent of 1811 h. The difference between the equivalent hours between Finerge and NASA is only about 5%, so it was considered that the data obtained locally by Finerge could be validated and used.

3.2.2. Total Production

The overall energy generated in the Alto Douro wind farm, as well as the additional wind turbines and the hybridization, was calculated using 15 min intervals. The estimated annual average energy production of the wind farm was approximately 919 GWh, capable of covering the energy consumption of approximately 280,000 inhabitants [55]. Figures 9–11 illustrate the solar generation, wind generation, and the combined annual energy production, respectively.

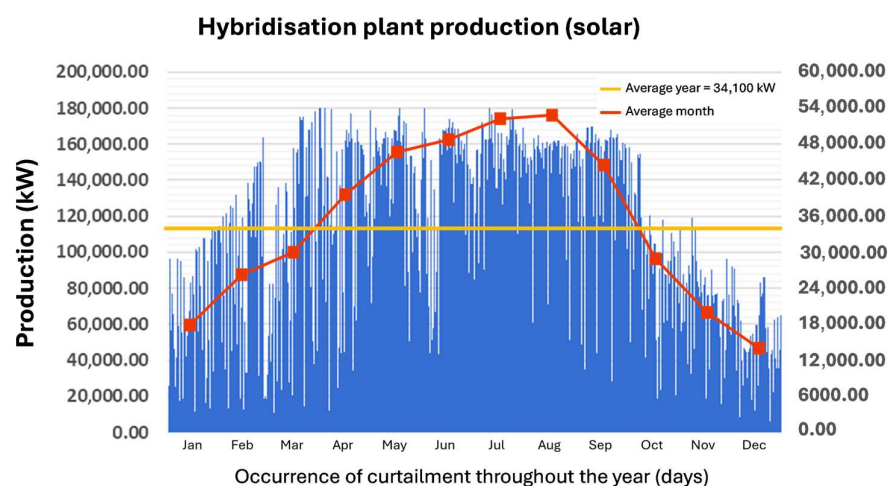


Figure 9. Hybridization production of the Alto Douro power station.

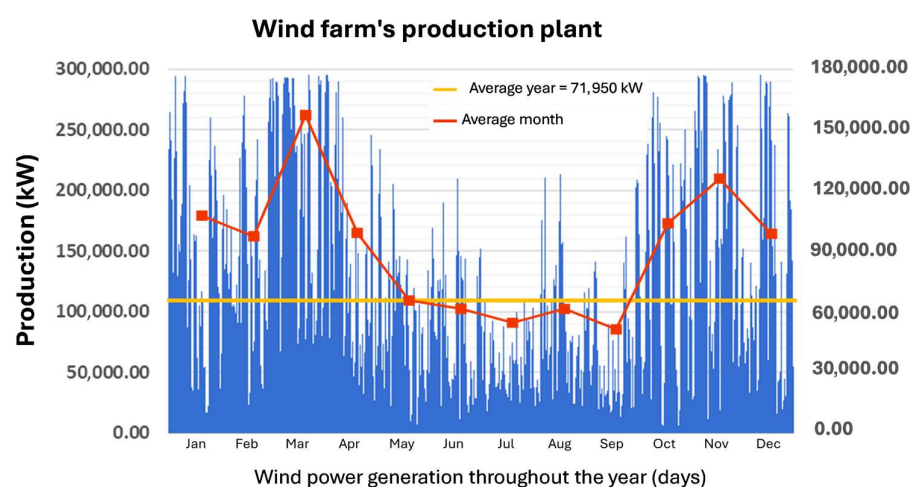


Figure 10. Wind production at the Alto Douro power station.

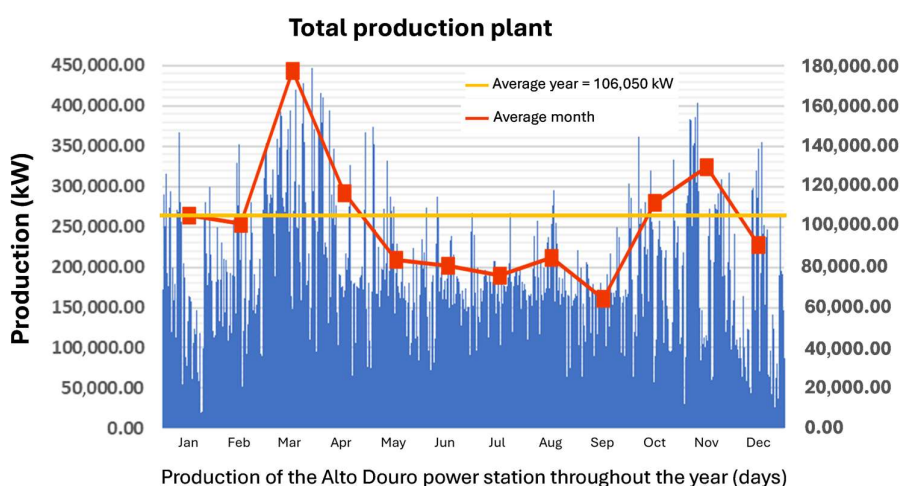


Figure 11. Total production of the Alto Douro power station.

4. Simulation of Storage System Performance

This section shows the analysis of energy storage in the context of the Portuguese electricity market, including a sensibility analysis, as well as the future of curtailment and its effects on electricity market prices. At the national level, the price of electricity for purchase and sale is determined by the daily electricity market—managed and controlled

by the Energy Services Regulatory Authority (ERSE) and the Iberian Electricity Market Operator (OMIE)—in articulation with the Spanish electricity market. As a result, the daily price of electricity is indexed to the Iberian market [56,57].

The daily electricity market has various stakeholders, each with specific roles and responsibilities, such as traders, network operators, energy producers, and consumers. Each stakeholder plays a crucial role in market dynamics, as prices fluctuate based on historical data, seasonal events, and weather conditions [56,57]. Thus, electricity prices are determined by the balance between supply and demand, ensuring the sector efficiency and competitiveness.

Daily planning of energy production requires the coordination of multiple energy sources (such as solar, thermal, wind, hydro, and others) to grant that supply aligns with forecasted demand, which directly influences the final electricity price. The operator National Energy Networks (REN) continuously monitors the stability between production and electricity consumption, making real-time adjustments to ensure network stability and, consequently, prices stabilization.

In addition, participation in the Iberian Electricity Market (MIBEL) promotes stability and competitiveness, facilitating cross-border trade in electricity and implementing rules and tariffs—set by ERSE—that guarantee fairness and competition in the sector. Average prices for each month and year were calculated by first averaging the hourly prices within each month and averaging those monthly means. This methodology was chosen to generate representative hourly prices for future years. The resulting average prices are presented in Figure 12.

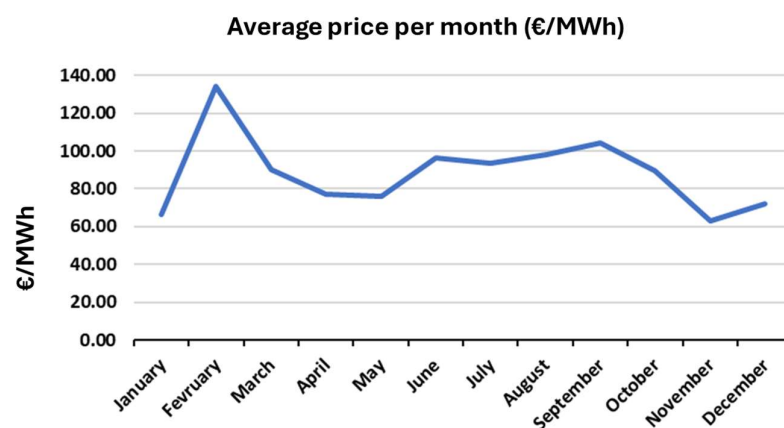


Figure 12. Average price of electricity in Portugal for the last year.

4.1. Curtailment

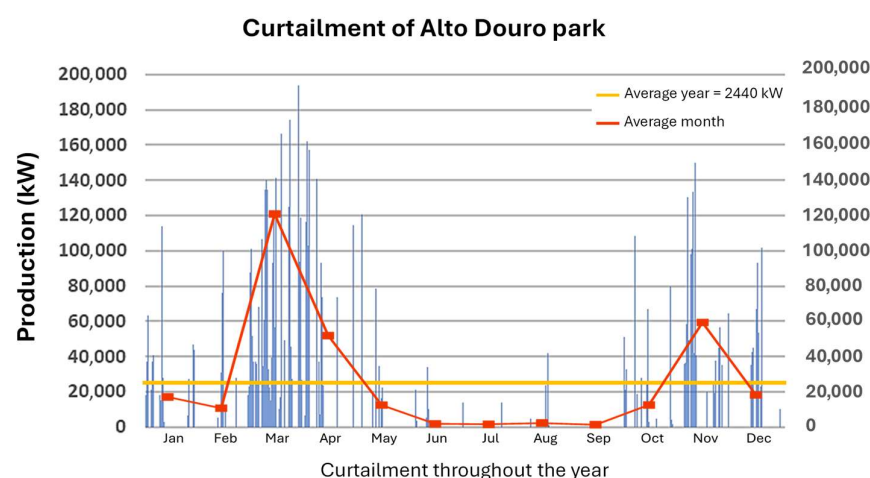
As already mentioned, the main use of the Battery Energy Storage System (BESS) is for curtailment, i.e., the energy produced above the export limit. This storage then becomes necessary due to excess energy production that cannot be utilized in any other way. This surplus energy will be stored in the batteries for later export to the grid, selling energy during periods when production is below the wind farm's export limits.

On the other hand, to calculate the effective curtailment, in kW, it was necessary to define the maximum power limit to be exported, set at 253,200 kW, so the available energy to be stored would be obtained from the difference between total production and the power limit. The curtailment was calculated over a period of 15 min. Table 6 shows a sample of the values obtained on each sub-farm and the curtailment obtained throughout the day.

Table 6. Partial sample of total production and curtailment (kWh).

Production [kWh]											
Time	Armamar	Armamar II	Serra da Nave	Testos II	Chavães	Serra de Sampaio Ranhados	Sendim	Overproduction Equipment 43 MW	Hybridization 180 MW	Total	Curtailment [kWh]
09:00	27,200	9200	37,460	47,840	17,520	25,800	19,560	32,769.9	5535.0	222,884.9	0.0
09:15	23,870	9200	38,510	47,560	15,420	27,290	20,640	23,618.8	5535.0	211,643.8	0.0
09:30	21,470	9630	40,460	46,440	19,870	24,010	15,120	17,629.0	5535.0	200,164.0	0.0
09:45	20,190	9160	38,180	42,560	21,660	21,620	11,760	16,269.3	5535.0	187,934.3	0.0
10:00	19,240	7940	37,060	38,880	23,440	20,770	14,080	22,036.6	35,424.1	218,870.7	0.0
10:15	21,710	4990	35,470	35,040	22,690	24,270	18,000	35,192.0	35,424.1	232,786.1	0.0
10:30	24,400	5380	34,600	39,040	25,640	26,760	25,080	40,818.2	35,424.1	257,142.3	3942.2
10:45	23,000	6830	34,180	42,240	26,940	28,340	25,640	24,439.0	35,424.1	247,033.1	0.0
11:00	22,540	6550	32,220	42,920	23,820	27,060	25,040	18,308.9	42,804.1	241,263.0	0.0
11:15	24,050	6420	25,510	43,640	23,110	28,470	24,160	28,601.7	42,804.1	246,765.8	0.0
11:30	23,140	7700	27,400	42,240	24,670	30,310	29,840	25,259.1	42,804.1	253,363.2	163.2
11:45	22,860	8310	32,350	43,040	26,990	31,040	30,720	22,798.6	42,804.1	260,912.7	7712.7
12:00	20,650	9160	31,860	40,400	28,120	32,290	33,040	21,274.7	46,678.6	263,473.3	19,273.2
12:15	20,430	9160	29,320	35,200	23,660	30,960	28,880	11,559.2	46,678.6	235,847.8	0.0
12:30	18,890	6480	26,240	33,080	17,940	30,380	23,000	16,269.3	46,678.6	218,957.9	0.0
12:45	13,720	4350	28,200	32,280	18,580	31,880	21,680	30,304.0	46,678.6	227,672.6	0.0
13:00	18,960	4440	29,520	31,800	18,920	31,840	23,320	25,259.1	65,866.6	249,925.7	0.0
13:15	22,710	6040	27,280	33,200	20,650	31,860	26,360	16,269.3	65,866.6	251,135.9	0.0
13:30	21,060	5710	29,490	31,080	19,680	32,720	21,160	28,601.7	65,866.6	256,368.3	3168.3
13:45	23,180	4610	34,190	32,080	22,820	32,760	24,760	39,543.7	65,866.6	279,810.3	26,610.3
14:00	23,390	3910	35,050	34,160	27,060	32,230	34,640	49,818.2	85,608.1	317,866.3	64,666.3
14:15	24,020	7580	35,020	34,280	27,940	33,790	33,160	41,925.0	85,608.1	323,323.1	70,123.1
14:30	24,540	8130	34,950	37,640	24,360	34,020	30,680	41,925.0	85,608.1	321,853.1	68,653.1
14:45	29,530	8010	35,170	39,080	24,640	33,980	34,560	41,925.0	85,608.1	332,503.1	79,303.1
15:00	29,920	10,770	28,590	35,200	23,370	33,760	39,000	41,925.0	45,202.6	287,737.6	34,537.6
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.

The result of these measurements indicated an average curtailment of around 2.3% of the total energy produced, around 19 GWh per year. Curtailment occurred infrequently throughout the year, but when it occurred, it exceeded the power plant's export limit, promoting the use of batteries with high energy capacity and fast discharge, as can be seen in Figure 13.

**Figure 13.** Curtailment of the farm's power station during the last year.

An analysis of Figure 13 shows that curtailment occurred only a few times during the year/day and, when it did, it would far exceed the plant's export limit, which favored the use of batteries focused on high power capacity and the possibility of rapid discharge. Therefore, considering the values shown in the previous graph (Figure 13 and Table 6), two scenarios were defined for energy curtailment, considering different combinations of battery storage systems. For each of the scenarios (scenario A and scenario B), a set of variables was considered, and the storage time (in hours), power (in kW), losses as a percentage (%), and the maximum battery capacity (in kWh) are presented below:

- **Scenario A**—This is considered a very optimistic scenario. It does not consider the limitation of daily cycles. Priority is given to releasing the stored energy as quickly as possible. The main objective is to discharge the batteries whenever feasible, particularly during low production periods when output falls below the export limit.

- **Scenario B**—This is the most realistic scenario. It assumes that the batteries are fully charged before the discharged process is carried out. In this case, unlike scenario A, the limits of the storage cycles are respected. With this procedure, it is possible to extend the life cycle of batteries as much as possible [58]. This is a scenario which, although it presents slightly lower profits than scenario A, is essentially aimed at satisfying the daily charge/discharge cycles of the batteries.

Although scenario A is the most optimistic and presents more prudent values, it should not be discarded, since higher profits can be obtained in this scenario compared to in other scenarios to be defined [59–61]. Naturally, although scenario B is more realistic and initially points to lower profits, it leads us to analyze other problems/disadvantages that should be mentioned before choosing the scenario:

- The complete charge/discharge cycles of the batteries may not be carried out in full. This is due to varying weather conditions which, although they can lead to incomplete charging of the batteries, lead to more advantageous operating conditions, i.e., cases in which there may not be any cuts for a long time.
- The energy charged in a 15 min period will be considered to correspond to the maximum charge cycle, even if it is less than the battery's capacity in that period. This phenomenon is not very relevant, as it will occur sporadically.
- The absence of a daily cycle limit which, if exceeded, will lead to a decrease in battery efficiency or even damage. On the other hand, these batteries will only be used for storing curtailment, so we cannot consider this a disadvantage as they will not be overused to achieve this goal.

4.2. Battery Storage Price Arbitrage

Price arbitrage consists of buying and storing energy at lower prices and then selling it at higher prices. This mode of operation focuses on reducing excess energy through storage, to take advantage of energy that will otherwise be wasted at zero cost. Looking at the process as a whole, it is possible to analyze this process by considering three different phases of price arbitrage simulation: (i) the valuation of the battery based on market prices and efficiency; (ii) the price arbitrage profits generated in two periods of battery autonomy, considering cycles of 2 and 4 h; and (iii) the combination of price arbitrage with energy reduction [59–61]. On the other hand, Finerge also defined that the system's charging cycle would be carried out twice a day whenever the main objective was price arbitrage, considering the number of hours of battery autonomy.

4.2.1. Battery with 4 h of Autonomy

Analysis of a 4 h autonomy battery storage system (with a power of 2.5 MW and a storage capacity of 10 MWh) showed that an efficiency of 90% provides more favorable conditions for price arbitrage at a specific time of the seasons. Figure 14 shows the differences, in €/MWh, in the average price of charging and discharging throughout the year. It also shows that in the less profitable months, such as summer, arbitrage is not economically viable, while at other times it generates high profits.

However, according to calculations made for each day, a battery with these specifications and a 90% efficiency produces an average profit of €49,123, dedicated to the profit from curtailment management and price arbitrage. In the case of January, for example, the battery charged from 3 a.m. to 6 a.m. and discharged from 10 a.m. to 1 p.m. In this case, it charged again from 3 a.m. to 6 a.m. and discharged again from 7 a.m. to 10 a.m. Figure 15 shows the price variation throughout a day in January and the respective purchase/sale times, considering a battery with a 4 h charge/discharge cycle. Table 7 shows the viability

of months for price arbitrage performed with a 4 h autonomy battery, assuming a 90% total efficiency.

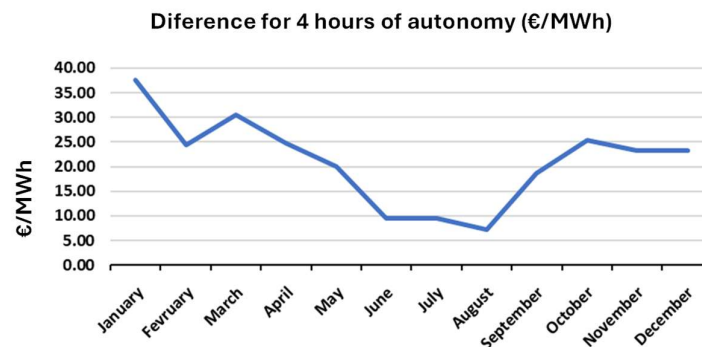


Figure 14. Arbitration prices for a battery of a 4 h charge/discharge cycle.

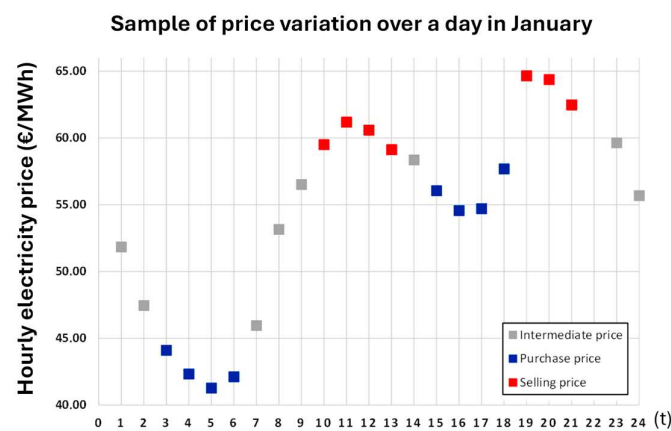


Figure 15. Price variation for a battery of a 4 h charge/discharge cycle in January.

Table 7. Feasibility of price arbitrage: battery with 4 h of autonomy and a 90% efficiency.

Price (€/MWh)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average charge	52.55	120.90	74.31	62.23	64.25	90.58	87.19	93.36	93.95	75.32	49.83	59.16
Average discharge	90.15	145.23	104.84	87.00	84.57	100.13	96.65	100.56	112.54	100.58	73.16	82.48
Average price	69.35	134.23	89.92	76.96	76.09	95.59	93.80	97.86	104.15	89.77	63.26	72.20
Difference	37.60	24.34	30.53	24.77	20.05	9.55	9.46	7.20	18.60	25.26	23.32	23.32
Profit per discharge	81.14	130.71	94.36	78.30	76.11	90.12	86.98	90.50	101.29	90.52	65.84	74.23
Feasibility of price arbitrage	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes

In contrast, the analysis evaluated on the battery efficiency showed that there can be situations in which price arbitrage results in a loss of money. This situation can occur when the energy to be charged and discharged does not correspond exactly to their capacity, but rather to the efficiency of their capacity. Therefore, considering the total amount of energy that will be paid to charge the battery to full capacity, there will only be a profitable arbitrage if the difference between the lower price and the higher price compensates for the loss of energy inherent in the battery's efficiency.

From the analysis of the table above, it is evident that during the months of June, July, and August, price arbitrage would not be economically viable for the battery with 4 h autonomy and a 90% overall efficiency, while during the rest of the months arbitrage is profitable. Otherwise, the average monthly profit per discharge is around €66.04136/MWh,

including the months in which the viability of price arbitrage is not recommended, with an annual average of around €44,994.

4.2.2. Battery with 2 h of Autonomy

Analyzing the storage carried out in batteries with an autonomy of 2 h (with a power of 5 MW and a storage capacity of 10 MWh) with a 90% efficiency, comparable to the 4 h battery, it was observed that, except for the month of July, all would be monetarily profitable in terms of price arbitrage. With these specifications and a 90% efficiency, the system generates an average profit of €63,930 resulting from curtailment management and price arbitrage.

Also considering the month of January, it was found that in this approach (battery autonomy of 2 h), the battery started charging from 5 a.m. to 6 a.m., discharging from 11 a.m. to 12 a.m., and so on. Figure 16 shows the differences, in €/MWh, in the average charge and discharge price throughout the year.

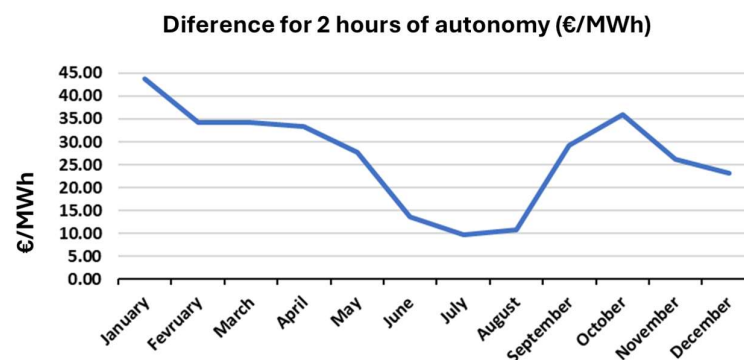


Figure 16. Arbitration price for a battery of a 2 h charge/discharge cycle.

Similarly, considering the above assumptions, only arbitrage is profitable. Table 8 shows the difference between the lowest price and the highest price (the viability of months for price arbitrage) using a battery with an autonomy of 2 h and an overall efficiency of 90%.

Table 8. Feasibility of price arbitrage: battery with 2 h of autonomy and a 90% efficiency.

Price (€/MWh)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average charge	48.78	117.81	71.57	60.70	62.50	87.98	90.30	91.75	91.64	73.28	51.09	60.07
Average discharge	93.54	151.96	105.85	94.08	90.31	101.52	99.87	102.96	120.96	109.27	77.27	83.14
Average price	66.35	134.23	89.96	76.96	76.09	96.59	93.80	97.86	104.15	89.85	63.26	72.20
Difference	43.76	34.15	34.28	33.37	27.81	13.54	9.58	10.72	29.31	35.99	26.17	23.07
Profit per discharge	84.19	136.76	95.27	84.67	81.28	91.37	89.89	92.23	108.86	93.34	69.54	74.82
Feasibility of price arbitrage	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes

From the analysis of the table above, it is evident that, during the months of July, price arbitrage would not be profitable for the battery with 2 h of autonomy and a 90% overall efficiency, while during the rest of the months arbitrage is profitable. On the other hand, the average monthly profit per discharge is around €84.77681/MWh, including the month in which the viability of price arbitrage is not recommended, with an annual average of around €34,566. To draw a relationship between these two approaches, Table 9 shows the values associated with the profits obtained depending on these operating conditions, i.e., the utilization of batteries with 4 h and 2 h cycles.

Table 9. Comparison between batteries (4 and 2 h).

Battery Autonomy	Average Monthly Profit per Discharge (€/MWh)	Curtailement/Price Arbitrage Profits (€)
4 h	66.04136	49,123
2 h	84.77681	61,731

However, it should be borne in mind that they have different powers (2.5 and 5 MW), but both systems operate with a 90% overall efficiency and an energy storage capacity limited to 10 MWh. This assessment, carried out according to the limitations of each battery and considering its commercial cost, showed that the investment is promising. The base values presented were chosen because they are realistic in relation to the batteries currently on the market and what is intended for this project, according to Finerge. Thus, for each of the scenarios under analysis, five distinct variables (listed above) were defined in accordance with the client's guidelines and the initial investment to be made: storage time in hours, power in kW, charge and discharge losses as a percentage, and maximum battery capacity in kWh.

It can be concluded that, as the comparison of batteries is based on energy storage capacities and not according to price—which depends on capacity [58]—a battery with a shorter autonomy will bring greater profits to the project, considering that both battery have the same capacity and efficiency.

4.2.3. Sensitivity Analysis of the Project

The sensitivity of the project should be tested in various situations to evaluate aspects considered critical in the implementation of batteries for storing surplus energy, purchasing electricity and, essentially, obtaining operational gains. Thus, the variables that play a preponderant role in the final objective must be considered: the wind farm's production, batteries efficiency, and the limit on exporting energy to the grid. The stress test was carried out with these aspects taken into account by changing the operating conditions of the batteries for 2 h (power rating of 5 MW combined with 10 MWh energy storage), varying their parameters by 5%. The results of the variation in curtailment profits combined with price arbitrage are shown in Table 10.

Table 10. Sensitivity analysis for an autonomy of 2 h.

+5% Plant Production (€)	+5% Battery Efficiency (€)	+5% Curtailment (−5% Exportation Limit) (€)
75,527	84,838	70,962

This sensitivity analysis indicates that battery efficiency and autonomy of a battery play a crucial role in determining the profitability of the project, making them the primary factor for decision-makers to consider when evaluating purchases.

4.2.4. Evaluation of the Future Curtailment

Naturally, these factors are preponderant and fundamental elements for decision-makers when buying batteries. However, the analysis must be extended beyond the parameters of the current analysis, as past data were analyzed. The data are crucial from a current perspective, but they do not provide insights into the future. Therefore, the investment decision cannot only depend on past data, but also on the prospects for the evolution of energy purchase and sale prices. To get a better idea of the evolution of similar projects, we used the data available in [62] to obtain a forecast of the evolution of prices. Figure 17 shows the forecast for the evolution of electricity prices over the next few years.

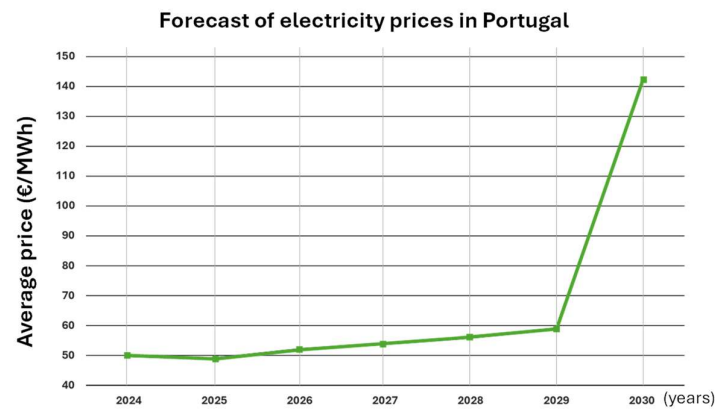


Figure 17. Electricity price trends in Portugal, adapted from [62].

Although several reports point out stable electricity prices in the short term, they indicate a slight decrease in costs, around 13 euros MWh, by 2050 [62]. This trend may suggest lower profitability, as it is closely related to the volatility of the current and future electricity markets. An example of this is the 2023 annual report on the evolution of the electricity market presented by “OMIE” [63], which mentions fluctuations of around 91.3%, resulting in a decrease in prices compared to in 2022. The arithmetic average price of the daily market in the Iberian Electricity Market (MIBEL) fell to €87.69/MWh, with the average price of the intraday auction being €87.99/MWh and the price of the continuous intraday market being around €89.43/MWh. This is an example of how significant fluctuations between high and low prices are an important factor in deciding when to buy or sell. Figure 18 shows the daily variation in energy prices in 2024.

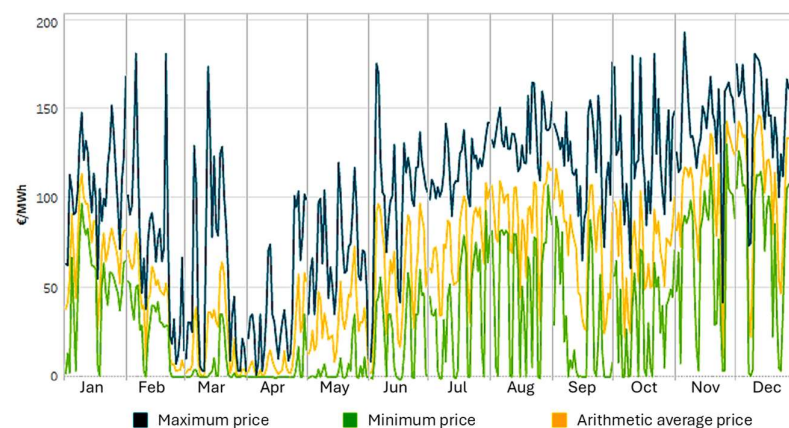


Figure 18. Maximum, minimum, and mean prices on the daily market in Portugal, adapted from [63].

On the other hand, although there may be a slight decrease in electricity consumption, an increase in alternative energy production is expected, such as wind and solar power. This increase will be reflected in a reduction in dependence on thermal power stations, particularly natural gas combined-cycle power stations, and as such, will make it possible to increase the profitability of projects based on price arbitrage combined with government incentives.

Despite the above, it can be concluded that over the next decade, energy storage in wind and solar farms will be a very profitable investment and in line with the average price of electricity. It should also be considered that, according to Baringa [44], electricity costs are projected to rise considerably (see Figure 13), and as a result, the profits associated with energy storage will also increase. On the other hand, it seems that future curtailment is expected to grow, with the Levelized Cost of Energy (LCOE) evolving in the opposite

direction, which makes the profitability of this mode of operation even more viable. A project of this size must therefore be modularized to adapt to the evolution of the electricity market [64].

When analyzing these two storage approaches, it becomes clear that the solution based on batteries with less autonomy and high energy capacity would be more profitable in this case, considering that both have the same efficiency and storage capacity. It should also be noted that changes in battery efficiency translate into a significant variation in profitability; as has been shown, a +5% variation in battery efficiency results in an increase in profits. The most important factor when buying a battery is, in fact, its efficiency and not its cost. This is the factor that determines the battery when making the purchasing decision.

4.3. Curtailment as an Accessible Backup

The blackout which happened on 28 April 2025, classified by the European Commission as the biggest in the last 20 years, was a wake-up call for the fragility and dependence of the national electricity system, essentially due to an unstable supply caused by an Iberian connection. This is a clear warning of the urgent need to strengthen the resilience of the European electricity system. For the national electricity grid to become more resilient, it is necessary to guarantee energy sovereignty and reduce or even end its energy dependence on oil and natural gas. To achieve this goal, the Association for Renewable Energies (APREN) [13] advocates the following: (i) strengthening national interconnections with Europe; (ii) increasing renewable capacity, which is essential for system redundancy; (iii) greater efficiency in the management and administration of electricity companies, to integrate the growing volumes of renewable energies; and (iv) increased energy storage capacity, both through chemical storage using batteries and hydraulic storage using the capacity of dams. The Iberian blackout, which occurred last April, demonstrated the need to find ways to build robust, interconnected networks capable of integrating renewable energies more efficiently in response to extreme events.

In response to these and other hypothetical occurrences, renewable energies—solar and wind, as in the case under study—will make a fundamental contribution, not only to reducing climate change, but also, when properly integrated, to stabilizing prices, the energy produced [65] and providing energy reserves. However, the technology used by most wind and solar farms, based on inverters, means that the farms are disconnected from the grid when disturbances are minimal, that is, due to their status as followers rather than leaders of the grid, they are completely disconnected from distribution when the grid fails. The case study presented here, in addition to the main objective of making the sales of energy profitable and in addition to the online supply of energy, aims to establish an offline supply that guarantees the stability of supply through batteries or synchronous compensators, minimizing the so-called ‘island effect’ in which Portugal finds itself [65]. However, considering that we have abundant renewable energy that we cannot share, this eliminates the possible resilience of the grid, which could be considered a luxury and therefore cannot come to the rescue of the grid in exceptional cases, such as a future blackout, acting as an energy backup. Therefore, renewable energies and their capacity to store energy in batteries, as well as energy storage in dams, represent an extremely important contribution to the start-up of reversible hydroelectric power stations [66] in future possible blackouts. João Bernardo [65] also states that existing energy communities need to function as ‘islands’, microgrids, because equipped with batteries and grid-forming inverters, they will become electrical fortresses capable to supporting the main grid in the event of a failure as well as responding promptly as an accessible backup [12].

The supply to small regions, hospitals, schools, and other institutions could be ensured, mitigating the times associated with the cold start-ups protocol [67,68].

This is the context of our study. Located in the Alto Douro, between water valleys, it is a differentiating factor that could, with the necessary conditions, guarantee energy to the surrounding region (as an accessible backup), but above all act as a motor for activating the black-start protocol in situations where the frequency/voltage limits are exceeded or one or more hydroelectric power stations in the Douro valley fail (see Figure 19). It should also be noted that almost all the various energy storage systems in mainland Portugal are based on water storage, either by hydraulic pumping or by continuous river flow. On the other hand, pumping requires electrical energy which, in the event of a blackout or electrical failure, will have to be obtained from generators, renewable energy sources, or storage energy, available near the energy production dams and pumping units. Cold start-ups will be achieved more quickly, since, in addition to the energy produced by renewable sources for immediate consumption, the batteries will function as an energy supply that can be combined or used only when necessary. This is a self-sufficient system, capable of generating and storing wind and solar energy without consuming energy for storage, and therefore always available in critical situations.

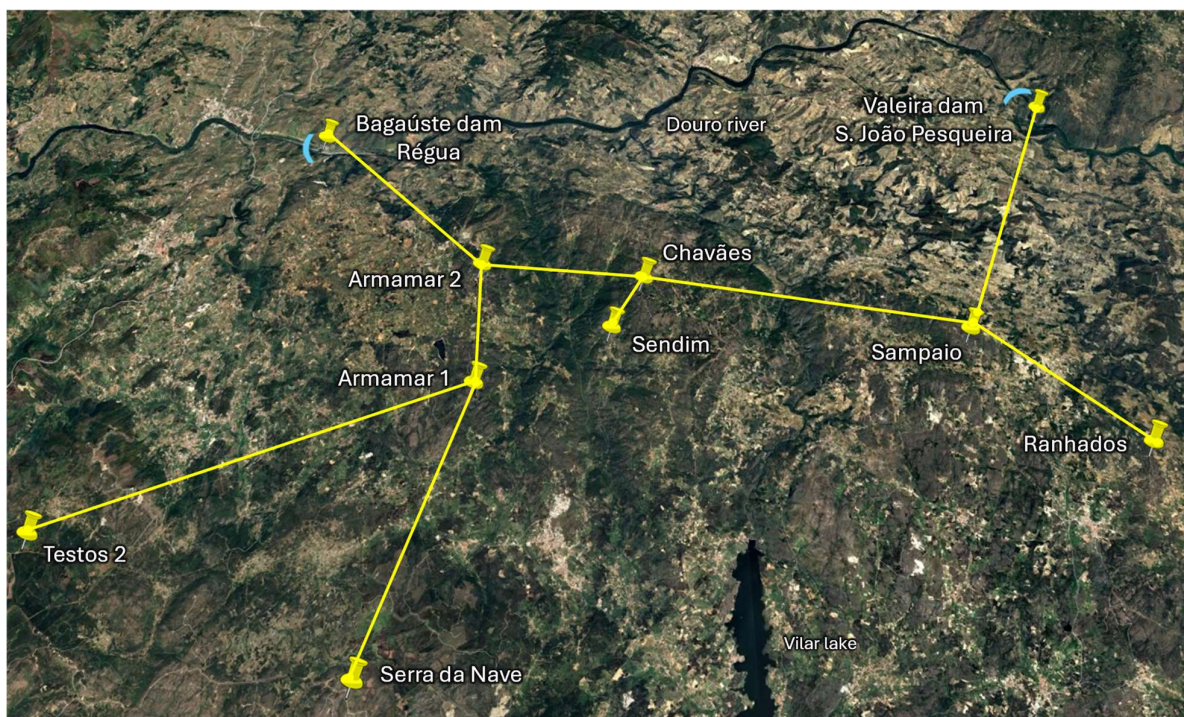


Figure 19. Locations of the wind farms in the context of possibility of a black start at Douro River.

5. Conclusions

This study presents the results of an analysis on the feasibility of implementing energy storage systems and their technical characteristics. It arises from the need to maximize the profit of hybrid wind and solar farms, taking into consideration the curtailment and price arbitrage. To do this, several confidential databases were used, which made it possible to formulate highly relevant conclusions about the operation of the system and its return, which are presented below:

1. The idea that lithium-ion batteries, currently used in hybrid power plants (wind and solar farms) to store surplus energy, are the most suitable technology was reinforced. The choice validates this assumption due to their high energy storage capacity, their modularity, which is fundamental to the project's growth, and their long-life cycle, and the knowledge of Capital Expenditure (CAPEX) and Operational and Maintenance

Costs (OPEX), or discount rate used. This decision is in line with many other similar projects that highlight the advantages of using lithium-ion batteries.

2. Based on the data collected, it can also be concluded that the combined energy produced by the wind farm rarely exceeds the limits for export to the national grid over the course of a year. The average curtailment rate is around 2.5% of the total energy produced and is in line with European renewable energy projects [69] in the Nordic energy system [70] and with wind curtailment in the US, Canada, and China [71]. These are also in line with the results obtained by the system dynamics model developed by [72], which estimates a reduction of between 500 and 3000 GWh by 2030, i.e., a curtailment between 2.5 and 14%.
3. Batteries with shorter daily operating cycles have proved to be the most cost-effective, if the operating conditions are the same: energy storage capacity, power capacity, and the same daily charge–discharge cycles. This is because the surplus energy limit is rarely reached, albeit in large quantities, which makes a battery with a high energy capacity and fast charge–discharge cycles the most suitable for the project, in line with various installations and scientific literature, which validates the energy producer’s choice (Finerge). The greatest profit is obtained from the one that operates with the highest energy capacity and the shortest autonomy time.
4. The efficiency of the battery selected is extremely important. This is due not only to the profit that can be made in the price arbitrage process for the project viability, but also to the strong dependence of efficiency on the performance of the selected battery. At this stage of the project, efficiency was considered the most important variable in the study, rather than CAPEX and OPEX.
5. An additional conclusion is that energy storage will become a very important advantage for supplying energy to priority organizations, and when properly integrated into the national grid, can serve as a support for the restart protocol or as an accessible backup, if parameters such as power and energy capacity, integration, and others are specified. In the event of a blackout on 28 April 2025, the existence of small producers or even national producers has become very important in personal terms, since systems like [9] can continue to benefit from solar energy as well as energy stored overnight. On the other hand, it facilitates price arbitrage by taking advantage of fluctuations in daily electricity [73].

This type of approach to hybrid energy production farms will have a lot of gains from the volatility of the market and the daily variations in the cost of energy (see Figure 18). Another factor is the high amount of curtailment that will be very frequent in the coming years and the upward trend in the cost of energy. In contrast, hybrid systems improve the profitability of farms, as they allow the grid to be fed at times of greater need or at times of higher sales prices. The investment will be increasingly profitable, not only due to fluctuations in the price of energy, but essentially because of the modular system’s adaptability, allowing both expansion and reduction or even replication to other parks, as well as adjusting its storage capacity to obtain greater profitability.

In conclusion, it is important to highlight that the average monthly profit obtained with a battery of 2 h of autonomy, around €84.77681/MWh, is very close to the average sales value, €87.69/MWh, in the year covered by the study. These economic results demonstrate that the solution with the lowest autonomy—2 h—will result in a monthly profit very close to that of direct energy sales and confirms the added value of the project, considering that, at this stage, the investment is entirely the responsibility of Finerge. The Return on Investment (ROI) would be higher and achieved in less time if the company considered incentive policies, subsidies, or regulatory frameworks, such as the Recovery and Resilience Plan (RRP) [74], for example, which would reduce the initial investment and provide a

higher ROI. The analysis is supported by real data (collected at 15 min intervals where modelling focuses on analyzing profits from energy sales). The study of the investment and possible returns resulting from energy storage in a hybrid production facility will also be an invaluable contribution to the scientific community and, therefore, an invaluable contribution to its analysis, given the limited or non-existent scientific literature reporting real cases of its applicability. On the other hand, it is consistent with known scientific data that the financial viability of BESS is positive, showing that the Net Present Value (NPV) is profitable, as are the Internal Rate of Return (IRR) and the rapid return on investment; through energy arbitrage, returns can be generated in a few years.

As for future work, we point to the need to carry out detailed financial and economic studies (CAPEX, OPEX, the degradation model and discount rate used, among others) on the feasibility of using this storage system, considering the secondary energy market and electricity services, and a system coupled with the electricity price prediction model that can dynamically collect the most important data for sales decisions in real time. On the other hand, incorporating the Monte Carlo method can be used to explore different growth trajectories and calculate the ideal growth applied to other regions, considering the data already defined [75].

As an example, we present a simplified battery degradation model for solar systems, a simplified linear model, considering the known values stipulated by the customer. Thus, the following approximation is considered:

$$Q_{res}(N) = Q_{nominal} \cdot (1 - Degradation / Cycle \cdot N) \quad (6)$$

where Q_{res} is the residual capacity, $Q_{nominal}$ is the nominal capacity, degradation/cycle rate in percentage (0.05%), and N is the number of cycles. Therefore, if we use some of the data provided by the customer, such as the nominal capacity (5 MW) and the number of cycles per day (2), the daily residual capacity will be approximately 4.995 MW. On the other hand, we must admit that many other parameters, not provided by Finerge, could be used, among which we highlight, for example, Depth of Discharge (DoD), Temperature, Charge/Discharge Currents (C-rate), or even the Acceleration Factor (Arrhenius), which we point to future work.

Alternative approaches should be considered, such as hydrogen fuel cells and supercapacitor systems (SCs). As a system for storing energy, various systems have aroused interest, but SCs play a significant role among researchers due to their remarkable attributes. They can be considered as complementary elements to batteries, so the study of their potential and implementation should be considered. Another factor to consider involves how batteries are configured according to their ability to receive energy for subsequent exports to the electrical grid. The legislation, implementation, and localization of the battery system, considering the agglomerations that make up the farms, should be considered when implementing future projects.

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