

# An Energy Storage System for the Alto Douro Wind Power Plant: A Technical Study

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**Abstract.** Renewable energies are crucial to meeting global demand for environmentally friendly energy at a time when fossil fuels are being cut back. In recent years, and essentially due to the reduced reserves of fossil fuels, Portugal has been promoting investment in renewable energies as a way of freeing itself from energy imports and dependence on fossil fuels. However, despite the high number of hours of sunshine per day and the use of wind and hydraulic energy, production is unstable due to climate variability. All this climate instability translates into fluctuations in the energy released to the grid. In order to minimize this problem, energy storage systems have become a key element in guaranteeing the stability of the renewable energy supply at times of low production. This article presents a feasibility analysis of a renewable energy storage system with the aim of maximizing the profitability of a wind farm located in Portugal's Alto Douro region. As a starting point, a demand analysis is presented, as well as simulations of the system's performance in terms of energy use and profitability as a function of efficiency and power. Taking these assumptions and the analysis into account, a modular lithium battery storage system with high efficiency and fast charging and discharging powers was chosen.

**Keywords:** Battery, Curtailment, Price arbitrage, Renewable Energy, Wholesale electricity market, Wind Power Plant.

## 1 Introduction

At a time when the search for alternative energy sources is a pressing issue in global energy policies, Portugal has invested in renewable energies as an alternative to fossil fuels. This investment will account for 56.3% of total energy production in 2022, as stated in the yearbook of the Portuguese Renewable Energy Association (APREN) [1]. The production of energy from renewable sources, solar and wind, is fundamental for decarbonization, for reducing climate change and for the diversity of energy sources, making the grid more resilient [2,3]. Despite the increase in renewable energy production capacity, the variability of solar and wind production causes instability and, consequently, intermittency in the supply of these energy sources to the electricity grid [4]. This variability leads to random production and erroneous forecasts, as well as the need to take measures to deal with these fluctuations [2,3].

The project developed in this research is part of a study carried out for [5], an Independent Power Producer (IPP), to evaluate a wind farm energy storage system and its hybridization and solar modelling, ensure a balance of power [4]. The aim of this research is to select the energy produced, taking into account the market offers and the different manufacturers. To achieve this goal, the integration of an energy storage system is essential. Thus, integrating these systems into renewable energy production parks makes it possible to minimize energy variability and integrate these renewable energy sources, improving the overall efficiency of the production systems [2-4].

The implementation of these systems is aimed at Portuguese sustainability and contributing to the fulfillment of international commitments (Paris Agreement and European Union carbon neutrality) and, as such, the reduction of carbon emissions and the transition to clean and sustainable energies [6-9]. This analysis will be an important contribution to the implementation of investment strategies in renewable energies and hybrid energy storage system (HESS), aimed to solving the problems of instability, reliability and power quality of the energy supplied to the grid [10].

This paper is divided into 5 chapters. In the first chapter, the study is contextualized, and the objectives are defined. In the second chapter the problem of energy storage is put into the context, its advantages, technology, and current applications are discussed. The third chapter characterizes the wind farm studied in this project, and the equipment upgrades, hybridization, and their respective production results. The fifth chapter describes the process for evaluation curtailment (energy produced above the export limit) through two different scenarios. It also includes a price arbitrage study, sensitivity analysis, and a study on the evolution of curtailment and its consequences for similar future projects. Finally, in the last chapter, the conclusions drawn throughout the thesis are presented, along with suggestions for future work complementary to this research.

## 2 Energy Storage Systems

Energy storage systems are technical installations designed to capture, store and supply energy. They act as accumulators of the energy generated when demand is low,

supplying it when is needed. Energy storage plays a crucial role in optimizing energy production parks, particularly in installations where the grid's capacity cannot absorb all the installed power. Some of advantages of these installations are the minimisation of the variability, contributes to stability, additional revenue, reduces operational costs and sustainability objectives. On the other hand, supply reliability is improved during periods of lower wind speed and solar intensity or during maintenance shutdowns, ensuring a stable supply to the grid [11]. In addition, frequency regulation and voltage support are guaranteed and, as such, the overall improvement and stability of the grid, as well as additional revenues. Furthermore, integrating energy storage systems contributes to sustainability goals by increasing the integration of renewable energy sources into the energy mix, reducing reliance on fossil fuels [12-14].

### **2.1 Storage system types**

There are various energy storage systems. Each one has characteristics that are closely linked to its type and can be classified as mechanical, chemical, electrical, and electrochemical or thermal systems [11-21].

Mechanical energy storage is achieved by applying a force in the form of kinetic energy (flywheels) and/or potential energy (water storage) or in a fluid under pressure (steam, compressed air, and oil) [11-15]. Chemical energy is stored in the form of chemical fuels that can be converted into mechanical, electrical, or thermal energy (hydrogen by the electrolysis of water) [16], while electric one's store electricity in highly efficient electromagnetic fields (supercapacitors and magnetic superconductors) [17]. Electrochemical energy storage takes place in batteries. This process consists of a set of electrochemical cells made up of an anode (negative terminal), a cathode (positive terminal) and an electrolyte. During charging, chemical reactions store energy in the anodes and cathodes. During discharge, they release the stored chemical energy in the form of electricity [18-20]. Thermal energy is stored in the form of heat. This can be released later and used, for example, to drive turbines [21].

### **Storage battery comparison**

Among the various battery technologies, lithium-ion batteries have the ideal characteristics for installation in hybrid power stations. Their performance and overall cost-effectiveness are some of the many factors (efficiency, reliability, etc.) that justify this choice.

Lithium-ion technology has become the preferred option essentially because of the discharge times compared to other technologies. They can be designed for a wide range of discharge times, optimizing price arbitrage in various markets [22-30].

### **Case implementation**

Here are some examples of energy storage system projects in hybrid renewable energy power plants:

- South Australia – Hornsdale Power Reserve: a project using lithium-ion batteries supplied by Tesla. It provides grid stability and backup power with fast response times in managing renewable energy fluctuations.

- Morocco - Noor Complex: one of the world's largest solar energy projects with integrated thermal storage. It uses parabolic troughs to concentrate solar energy, generating electricity and thermal energy. The excess thermal energy is stored in molten salt tanks and can be used to generate electricity at night or on cloudy days.
- Australia – Yandin wind farm: Western Australia's largest wind farm with a lithium-ion battery energy storage system. The battery system stabilizes grid reliability and maximizes the use of renewable energy.
- Switzerland - Nant de Drance: pumped storage hydroelectric project located in the Swiss Alps. Two artificial reservoirs at different altitudes. The water is pumped out in times of excess and used again in times of need. Stability of intermittent renewable energy sources.

### 3 Case Study Implementation

The project arose from Finerge's [5] need to increase the capacity of the wind turbines installed at the Alto Douro wind farm and from hybridization. Finerge installs offline photovoltaic modules that complement the wind farm's production to reducing the variability of production in periods of low winds.

As installed capacity increases, there is a surplus of energy (curtailment) that is greater than the power the public grid can accept. Without storage, the excess energy would be wasted. With this in mind, the main objective was to determine the economic viability of a battery energy storage system, analyzing the optimal characteristics of the wind farm. To study its implementation, various data were used to quantify the energy used and to simulate the energy stored. At the same time, the technical characteristics of the batteries are identified. To do this, the total amount of energy that would exceed the export limit was quantified, based on current production and the growth of wind energy and hybridization. The simulation quantified the battery's power, efficiency and capacity, autonomy, losses, and electricity prices and, with this, the ideal battery specifications were defined (Fig. 1).

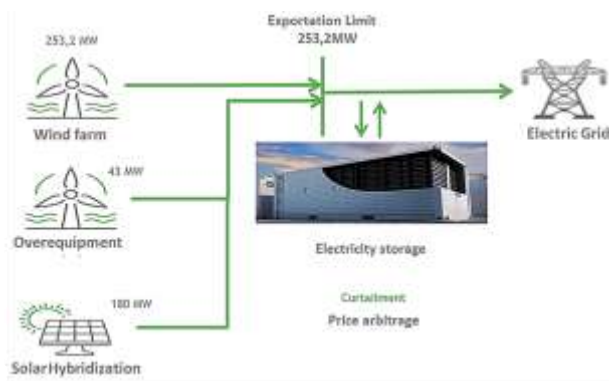


Fig. 1. Schematic presentation of the Project.

The production data was supplied by Finerge and used to calculate the curtailment. The production data is acquired in 15-minute periods in kWh. Losses through connections have already been discounted. A sample of the data provided is shown in Fig. 2.

Production (kWh)						
Armamar	Armamar II	Serra da Nave	Testos II	Chavões	Serra de Sampaio-Ianhados	Sandim
54 458 038	21 185 328	91 096 200	96 700 370	63 703 593	70 123 953	75 169 830
10	0	5970	2080	550	1060	320
10	90	6120	2160	750	1300	760
100	130	7090	2120	800	1050	840
60	140	7090	1880	900	1710	1040
160	30	6700	1400	630	2400	680
240	150	5740	1400	1150	1440	1080
490	20	5980	1560	1890	2350	2360
90	0	7370	1640	1460	2670	2560
20	0	6930	1640	1120	2550	1040
20	10	5960	2080	930	1980	680
260	180	6070	2640	1100	1360	1000
420	250	7220	3080	2140	1780	1760

Fig. 2. Sample production data provided.

### 3.1 Energy Quantification

The calculation of additional production was based on the wind speed at a height of 80 meters, measured in the Serra de Montemuro. The values were recorded based on 15-minute measurement periods over a 3-hour. The average speed obtained was around 3.23 m/s, and the additional installed power is 43 MW, in accordance with the legislation (20% of installed power). Based on the power tables of the new turbines, the average wind speed and the low turbulence, the powers corresponding to the density were calculated according to the ideal gas law and the barometric formula [31-33]. Our decision fell on a GE model based essentially on the smaller number of turbines that made up the previously defined, 8 turbines of 5.3 MW.

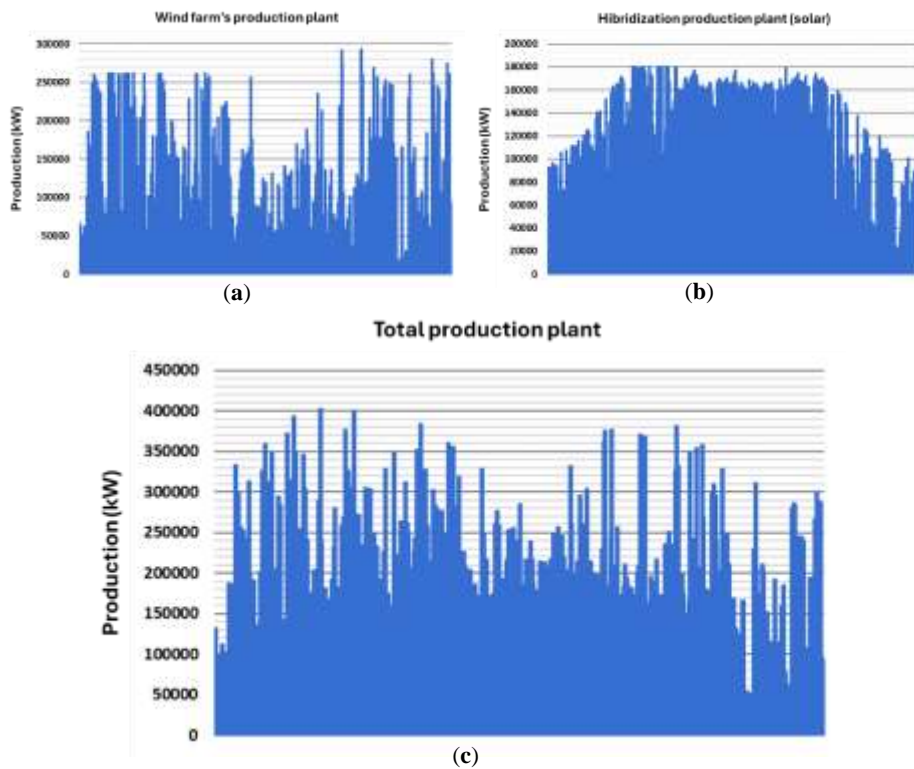
#### hybridization

As far as hybridization is concerned, the installed photovoltaic modules were calculated based on the direct and diffuse irradiance data provided by the producer, which led to a hybridization installation of 180MWp as peak power.

Month	Day	Hour	Irradiation (Wh/m <sup>2</sup> )
1	1	7	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

Fig. 3. Partial sample irradiation data of the day.

However, the productivity of the photovoltaic modules was calculated based on their irradiance, efficiency, and area [31-33]. Taking this formulation into account, the partial hybridization production values per hour and in 15-minute periods were determined as you can see in Fig. 3. So, the estimated average annual energy production of the wind farm was approximately 919 GWh, which meets the energy needs of around 280,000 inhabitants. Fig. 4 illustrates wind production (a), solar energy production (b) and total annual production (c) [31].



**Fig. 4.** Production plant: (a) wind, (b) solar and (c) total annual production.

#### 4 Storage simulation

In this chapter, energy storage will be analyzed, considering the Portuguese electricity market and its respective sensibility analysis, the future of curtailment and its impact on electricity prices. However, at a national level, the value of buying and selling electricity, the daily electricity market, which is regulated and managed by the Energy Services Regulatory Authority (ERSE) and the Iberian Electricity Market Operator (OMIE), in coordination with the Spanish market so, this is dictate daily values that are indexed to the Iberian market [34].

The daily electricity market involves several players, each with specific responsibilities, including energy producers, traders, consumers, and network operators. Each of them plays a vital role in the dynamics of this market since prices vary according to historical data, weather conditions and seasonal events [34]. In this way, the price of electricity will be determined on the basis of supply and demand, in order to guarantee the efficiency and competitiveness of the sector.

Daily energy production planning therefore involves coordinating of several sources of energy (thermal, hydro, solar, wind and others) to ensure that supply meets forecast demand, which affects the final price of electricity. The operator REN (Redes Energéticas Nacionais) permanently monitors the balance between electricity production and consumption, making instantaneous adjustments to guarantee the stability of the network and, consequently, the stabilization of prices. On the other hand, participation in the Iberian Electricity Market (MIBEL) ensures stability and competitiveness through cross-border electricity trade, and establishing rules and tariffs (ERSE) that ensure competition and fairness in the sector.

Average prices were calculated for each month of each year by averaging the prices for each hour of a specific month and averaging these monthly averages. This approach was adopted to obtain hourly prices representative of future years. The average prices can be seen in

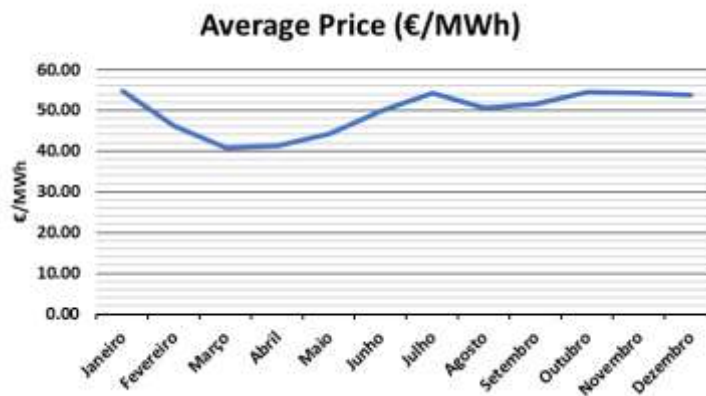
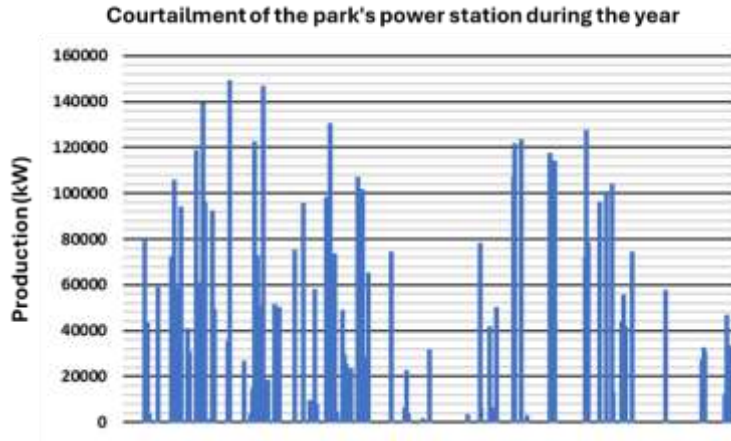


Fig. 5. Average price of electricity in Portugal for the last year.

#### 4.1 Curtailment

The main use of the energy storage system is curtailment, which refers to excess energy production that could not otherwise be used. In this way, batteries store it for later sale to the grid during periods of production below export limits. So, the limit of 253,200 kW was therefore taken into account when calculating the effective curtailment. This was also calculated taking into account the 15-minute intervals, using the difference between this limit and total production. This resulted in an average curtailment value of 19 GWh per year with a high frequency of occurrence, as can be seen in the Fig. 6.



**Fig. 6.** Curtailment of the park's power station during the last year.

Based on the values shown in the previous graph (Fig. 6), two scenarios were created considering curtailment energy in combination with the battery storage system. For each of the scenarios, a series of variables were defined, namely the storage time in hours, the power in kW, the losses in percentage (%) and the maximum battery capacity in kWh, which are shown below:

#### **Scenario A**

This scenario is considered very optimistic, since the daily cycle limits are not addressed. By focusing on discharging the stored energy as quickly as possible, the aim was to discharge the batteries whenever possible and during periods when production is below the export limit. In scenario A, the total profit obtained per year would be around 42158 euros for a total energy of 887,252 kWh.

#### **Scenario B**

Scenario B, which is more realistic, assumes that the batteries are charged to maximum capacity before being discharged. Unlike the previous scenario, scenario B respects the limits of the daily storage cycle. This action is fundamental to maintaining the life cycle of the batteries [35]. In this case, the total annual profit obtained was around 35463 euros for a total energy of 710,347 kWh. This scenario shows slightly lower profits than scenario A, but takes into account the limits of the batteries' daily cycle.

In view of the above analysis, we opted for the more realistic scenario B, with more prudent values. However, scenario A should not be ruled out since, from the point of view of results, a higher profit can be obtained and is also a base of comparing with other scenarios that can be defined [36-38].

## 4.2 Price Arbitrage for Battery Storage

Price arbitrage involves buying electricity when prices are low and selling it when prices are high. The main objective remains to reduce excess energy in order to capitalize on zero-cost energy storage. Three-step simulation for price arbitrage is possible.

In the first phase, the battery is evaluated based on market prices and its efficiency to determine the feasibility of price arbitrage. In the second phase, the profits from price arbitrage are calculated for two battery autonomy periods, 2 and 4 hours. Finally, in the third phase, price arbitrage is combined with curtailing energy, with being the priority [36-38].

### 4 hours of autonomy battery

The evaluation carried out on a battery with an autonomy of 4 hours (Power: 5 MW, Storage capacity: 10 MWh) showed that, at certain times of the year, an efficiency rate of 90% is more profitable for price arbitrage. The results show that during the months with the lowest values (summer), arbitrage would not be financially viable, while in other months there would be a profit. From the calculations made for the average profits to be made from this implementation, it can be concluded that a battery with an autonomy of 4 hours and an efficiency of 90% would result in 44994 euros when used exclusively for price arbitrage. On the other hand, when used exclusively for reduction, the profit would only be 23422 euros, see Fig. 7.(a).

### 2 hours of autonomy battery

From the evaluation carried out on the 2-hour battery (Power: 2.5 MW; Storage capacity: 10 MWh), which is similar to the 4-hour battery, it was found that every month would be profitable for price arbitrage, which is superior and would result in an average profit of 33913 euros when used exclusively for arbitrage, and 61731 euros when combined with curtailment, see Fig. 7.(b).

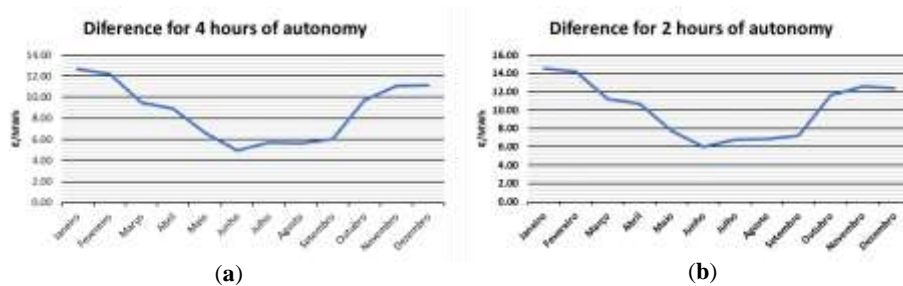


Fig. 7. Price arbitration battery: (a) 4 hours of autonomy, (b) 2 hours of autonomy.

Table 1 shows a comparison of the profits obtained from using the 4-hour and 2-hour batteries. Considering that both have an overall efficiency of 90% and a maximum capacity of 10 MWh, the comparison is made between the capacity of the batteries and not their price, it's proved to be very promising.

**Table 1.** Comparison between batteries (4 and 2 hours).

Battery autonomy	Curtailed profit (€)	Price arbitrage profit (€)	Curtailed and price arbitrage profits (€)
4 hours	23422	24897	44994
2 hours	33913	34566	61731

It can therefore be concluded that a battery with a shorter but longer autonomy time will give more profit to the project, assuming equal efficiencies and maximum capacities between the two batteries.

### Sensitivity Analysis

The sensitivity analysis focused on the most critical aspects of the battery implementation project, taking into account variables such as the plant's output, the efficiency of the batteries and the export limit. The changes were applied to the 2-hour battery with 5 MW of power and a storage capacity of 10MWh. Table 2 shows the profit variations for curtailing combined with price arbitrage resulting from a 5% variation in the variables in question.

**Table 2.** Sensitivity Analysis for a 2-hour autonomy battery.

+5% Plant production (€)	+5% Battery efficiency (€)	+5% Curtailment (-5% exportation limit) (€)
68042	76431	68764

It can therefore be concluded that the efficiency of the battery plays a crucial role in determining its profitability, making it a primary factor to consider when making purchasing decisions.

### Future Curtailment

Although electricity prices will remain relatively stable and decrease by around 13 euros per MWh by 2050 [39], which may suggest lower profitability, the volatility of the current and future electricity market, including significant price fluctuations between high and low prices, is an important factor. The decrease in electricity consumption and the increase in wind energy production, which reduces dependence on thermal power plants, especially natural gas combined cycle plants, will provide greater profit potential for projects involving price arbitrage. In addition, government incentives are expected to be introduced soon.

In addition, the prediction of future outages indicates that they will increase over time, while the Levelized Cost of Energy (LCOE) will decrease, further increasing the profitability of the project. Therefore, the modularity of the project is of the utmost importance [40].

Comparing these two cases, it was concluded that a battery with less autonomy, but more energy capacity would be more profitable, assuming equal efficiency and stor-

age capacity. On the other hand, the sensitivity analysis shows that battery efficiency significantly affects profitability, so that a 5% increase in efficiency results in significantly higher profits. This is why battery efficiency was highlighted when making purchasing decisions.

## 5 Conclusion

In this work, a study was carried out on the technical characteristics of an energy storage system to be installed in a hybrid power plant to maximize profit through curtailment and price arbitrage. Eight databases were used throughout this study, which allowed important conclusions to be drawn about the operation of a system of this type:

- 1- The most suitable technology for storing surplus energy produced by wind and/or solar power plants is currently lithium-ion batteries. This choice is due to their ability to store large amounts of energy, their long service life, and their modularity. This is further confirmed by the fact that many similar existing projects also take advantage of the benefits of using lithium-ion batteries.
- 2- The energy produced by the park exceeds the export limit relatively few times a year, with the average curtailment rate being 2% of the total energy produced.
- 3- Between batteries with the same maximum energy storage capacity, greater profits are achieved with batteries that operate with a higher power capacity and shorter operating times, assuming the same number of daily charge and discharge cycles between the two batteries. This is because the power plant produces energy above the export limit infrequently and the surplus energy is generated in large quantities, making it suitable for a battery with a high-power capacity and short charge/discharge times.
- 4- The efficiency of the battery selected is of the utmost importance. This is not only because the viability of price arbitrage is affected by this factor, but also because the profit made depends heavily on the efficiency of the battery, making it one of the most sensitive variables in the project.

It can therefore be generally concluded that projects implementing this type of solution will benefit from the volatility of the electricity market and the high levels of cuts, which are expected to continue over the next few years. The use of hybrid systems makes the park more profitable since energy can be supplied to the grid at peak consumption times and probably at higher selling prices. Investment in this type of solution will therefore be increasingly profitable, given its modularity for future expansion, greater storage capacity and profitability.

As future work, it would be important to carry out a detailed financial study on the use of this type of energy storage system in the secondary electricity market, for example, and in electricity services. This study could include a potential follow-up to the implementation of a hydrogen fuel cell or supercapacitor system (SCs). As energy storage systems, SCs have aroused significant interest among researchers due to their remarkable attributes and should therefore be properly studied as an applicability or

complement to batteries. Another aspect that should be analyzed is the configuration of the batteries, the capacity of the existing electricity grid, the legislation applicable to this type of project and the location of the battery, taking into account the agglomerations that make up the parks in future projects.

**Supplementary Materials:** Not applicable.

**Author Contributions:** Conceptualization, C.F. and F.P.; formal analysis and validation, C.X., C.F. and F.P.; investigation, A.M. and C.F.; writing—original draft preparation, F.P. and C.F.; writing—review and editing, C.F., A.A.S., A.F.S., N.C. and J.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was financially supported by Base Funding–UIDB/50022/2020 (LAETA) of INEGI–Institute of Science and Innovation in Mechanical and Industrial Engineering, Portugal, and UIDB/04730/2020 of CIETI–Center for Innovation in Industrial Engineering and Technology, funded by national funds through the FCT/MCTES (PIDDAC), Portugal.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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