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Sizing and Management of Energy Storage Systems in Large-Scale Power Plants Using Price Control and Artificial Intelligence

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Abstract: Energy storage systems are expected to play a fundamental part in the integration of increasing renewable energy sources into the electric system. They are already used in power plants for different purposes, such as absorbing the effect of intermittent energy sources or providing ancillary services. For this reason, it is imperative to research managing and sizing methods that make power plants with storage viable and profitable projects. In this paper, a managing method is presented, where particle swarm optimisation is used to reach maximum profits. This method is compared to expert systems, proving that the former achieves better results, while respecting similar rules. The paper further presents a sizing method which uses the previous one to make the power plant as profitable as possible. Finally, both methods are tested through simulations to show their potential.

Keywords: batteries; energy storage; particle swarm optimisation; power system management; supply and demand; arbitrage; day-ahead market

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1. Introduction

The decarbonisation of energy is a major objective for the decades to come [1]. In Europe, different directives [2,3] aim for at least 32% of energy to be renewable by 2030. These directives set targets for energy production and for the identification of economic or environmental barriers in the field of renewable energy integration and energy efficiency.

Renewable generation plays a key role in achieving these goals. These technologies allow the use of natural resources as energy sources, but are dependent on the availability of the natural resource, and therefore conditioned by their intermittency. In addition to intermittency, the gap between production and demand is another problem. This can be clearly seen in solar energy production, one of the most installed sources, whose production curve is significantly different from the demand curve. This means that it is not possible to match demand with generation at times. Studies such as [4–6] analyse the future of photovoltaic power plants in Europe for the coming decades.

In order to mitigate intermittency and solve differences between generation and demand, hybrid power plants with energy storage system (ESS) are an option. The use of an ESS in a power plant makes it possible to match energy demand without any need for fossil fuels. Storage systems and hybrid plants can increase the presence of renewable generation in electricity systems.

Two challenges arise in the field of hybrid power plants. One is developing a method of managing the charging and discharging of the storage system that suits the needs of the producer: market participation, solution of fluctuations, technical constraints. The other is the correct sizing of the installation, either for a complete plant or an extension of an existing one, for the conditions under which the storage is intended to be used.

There are several studies in the literature on storage sizing and its role in hybrid plants. In [7–9], methods of storage sizing and management to avoid fluctuations in intermittent generation are presented, where batteries can help to overcome these problems.

Energy storage systems are used in frequency response [10–12]. In these methods, storage systems are sized and their management is defined for frequency stability in intermittent generation plants, trying to avoid the impact of wind or photovoltaic energy. Similarly, there are also sizing and management methods to provide different ancillary services [13].

Another use of ESSs is their installation in power plants to participate in electricity markets, where the profitability of the hybrid plant and investments is sought. In [14–17], the use of storage systems for arbitrage (taking advantage of periods of low grid prices to store energy and discharging at higher prices) is analysed. These analyses are undertaken because of the opportunities that arbitrage can provide to make storage systems viable for investors. Other examples are [18–20], where storage systems are sized and managed together with power plants to maximise profits by participating in different electricity markets.

As indicated in [21], the economic aspect of profitability is essential to promote the large-scale energy storage system in the grid. Recent technical reports such as [22] point out two fundamental aspects in the evaluation, sizing and management of hybrid plants. On the one hand, there is the analysis of the possible sources of income for the energy markets, which anyone can be a part of. That is, in order to take into account the appropriate sizing and management of the plant, the business to be generated with the plant must be considered. The best size for a plant that participates may not be the same as for one dedicated to ancillary services, even if technical aspects such as voltage or frequency fluctuations are also taken into account. When investment projects are intended to be made attractive to all parties, it is necessary to assess their viability and profitability.

Another point mentioned, related to the analysis of cost-effectiveness, is the practice of evaluating projects using the levelized cost of energy (LCOE). This index measures the value of the total current cost of building and operating a power plant over its entire lifetime. As pointed out in [22], calculating and evaluating the LCOE does not lead to a cost-optimal design from a cost-effectiveness perspective, as it only evaluates the cost and energy of the installation, not the benefits obtained from it.

As indicated above, the most common use of storage systems in electricity markets is arbitrage, in addition to storing surpluses. Thus, in the search to obtain profitability and maximise the benefits of storage systems in power plants, which is one of the barriers to their integration in the plants [23], there are several management methods [24,25], such as those mentioned above.

Strategies to solve the arbitrage problem are shown in [26]. They range from simple linear programming (LP) [27–29] up to mixed integer linear programming models (MILP) [30,31].

Aiming for the maximum revenues from the use of the storage system, this paper presents three price-based battery management methods, as well as a sizing method.

First, an expert system for storage system management is proposed. Expert systems are part of knowledge-based systems (KBS). A knowledge-based system uses a knowledge base to solve complex problems. According to their methodologies, expert systems may be rule-based or case-based. Studies applying expert systems to battery management, like [32–34], can be found in literature.

After designing this initial expert system, a second method is designed as an improvement of the previous one. This is achieved by optimising some of its parameters. These methods could be solved by linear or non-linear programming, as are some of the methods mentioned above.

In contrast, a third method is presented that considers some of the concepts of expert systems, but with greater complexity and precision. Due to this complexity, artificial intelligence techniques are employed to optimize this third method. In particular, particle swarm optimisation (PSO) is used.

Once management methods have been defined, a multi-objective sizing method for both additional generation and storage is presented. Additional generation and storage are closely related as indicated in [35], so it is essential not to approach the size problem separately, but to treat them as one and the same power plant. This way, the advantages provided by multi-objective problem [36–39] solving will be exploited. This sizing method will be solved by the multi-objective particle swarm optimisation algorithm [40]. The use of heuristic optimisation is essential to obtain the best results due to the complexity and the high non-linearity of the problems to be solved, which numerical techniques such as LP, MILP or MINLP cannot solve.

Finally, after describing the methods, the results of applying these methods to a photovoltaic power plant dedicated to participate in the day-ahead market will be presented, calculating maximum daily income and 30-year profitability, to see the differences between methods and the power that heuristic methods offer to solutions.

To sum up, this paper proposes a method for optimising ESS management through price control. The objective is to obtain the best management of storage from an economic point of view. Thanks to this method capable of making batteries profitable, the sizing tool for generation plants with batteries, managed by this same method, is also presented.

2. Methods

When running a power plant with batteries or other storage capability, the decisions on whether and how much to charge or discharge them is of great importance. Nevertheless, expert systems tend to be preferred for their simplicity. These consist of a few simple and understandable rules which the method interprets to decide about battery management. One possible expert system is described in this paper, with its corresponding rules and parameters. Then, considering this expert system as an initial point, an optimisation method is applied to tune the expert system parameter in order to optimize it. This optimisation has the advantage of not requiring the knowledge of an expert to set the parameters.

Afterwards, a new energy management system is proposed and compared to the original and optimised expert systems. This new method is more flexible and provides more possibilities to the optimisation. Despite its additional flexibility, the proposed method has several similarities with the expert system. Due to its complexity and non-linearity, the particle swarm algorithm is used to solve it.

Despite being useful for managing the storage systems of a hybrid plant, the presented methods are not inherently prepared to design the plant and choose the best sizes. This can present a problem to investors and power plant designers. For this reason, a multi-objective tool for sizing hybrid power plants with storage is presented.

For all cases presented in this section and simulations in Section 4, the maximum battery SOC will be 97%, while the minimum will be 2.5%, a limitation of the Battery Management System (BMS) to avoid improper operation.

2.1. Expert System

The presented expert system aims to maximize the net monetary income from the sale of energy in the market. Two assumptions are made regarding the interaction with the grid. First, in addition to selling energy, the power plant can also buy it. Second, the prices for the energy bought and sold are known 24 h in advance. Regarding the power plant, the capacity of the storage system is assumed to be fixed, so the expert system can only decide what to do with it.

In order to achieve its goal, the expert system (Figure 1) considers four rules to decide charge, discharge or do nothing. Once each hour or interval, it checks the current these rules and acts accordingly.

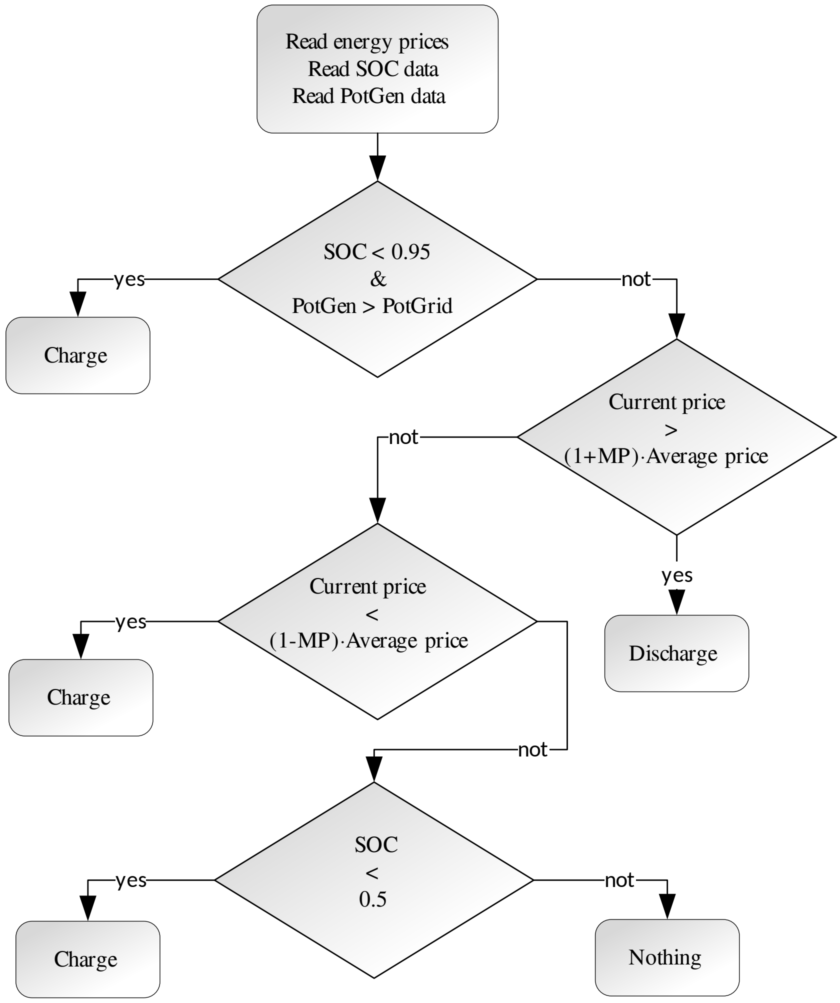

Figure 1. Storage system management scheme for heuristic method.

The first rule checks if the battery state of charge (SOC) is lower than a maximum (95%) and the generated power (PotGen) is greater than the maximum power (PotGrid) that the power plant can provide to the grid. If so, charging occurs. PotGrid is limited by the maximum power that can be evacuated, either by physical limitation of the connection or by contracts. This represents a simple rule: "whenever there is power excess, the battery must collect it".

The second and third rules, which are mutually exclusive, lead the battery to behave similar to a hydraulic pumping station. The idea behind them is: "the battery should buy energy when it is cheap and sell it when it is expensive". In order to define what exactly cheap and expensive mean, a price margin (MP) of 10% is considered. The buy price and the sell price of the grid energy are averaged along a time window of 8 h. If the sell current price of the energy is greater than the average plus the margin, then the energy is considered to be expensive (second rule) and the battery is commanded to discharge to sell its energy. On the other hand, if the current buy price is lower than the average minus the margin, then the energy is cheap (third rule) and the battery is commanded to charge, as it will be able to sell that energy later at a greater price. For simplicity of explanation, from now sale price and buy price will be considered the same price, grid price.

$$Decision = \begin{cases} Charge & \text{if Current price} > (1 - \text{MP}) \cdot \text{Average Price} \\ Discharge & \text{if Current price} < (1 + \text{MP}) \cdot \text{Average Price} \end{cases} \quad (1)$$

The fourth rule is linked to the fact that the power plant generates power using a non-controllable renewable source. For example, in a photovoltaic power plant, during the night, the plant will not be able to generate the necessary power to feed its internal loads. Consequently, it is necessary to keep some energy in the battery in advance. The rule for this is: "if energy is neither cheap nor expensive, then keep a reserve of at least 50% of the battery capacity". To do so, when the SOC is below 50% and the energy price is not expensive enough, the battery charges.

If none of the previous rules apply, then a the fifth and final rule states that the battery must neither be charged nor discharged.

The rules of this expert method are simple and intuitive, as well as easy to implement. Nevertheless, these rules require the adjustment of the price margin (10%), the width of the averaging time window (8 h) and the charge to reserve (50%). Therefore, this expert system may work well only on a situation that is similar enough to the one it was designed for. The method has been simulated for a variety of scenarios (see Section 3) with different results. The net present value (NPV) and internal rate of return (IRR) have been calculated (see the definition in the Section 2.4) according to the revenues, showing that the effectiveness of the method strongly depends on the sizes of the battery. A diagram of how this method works is shown in Figure 2.

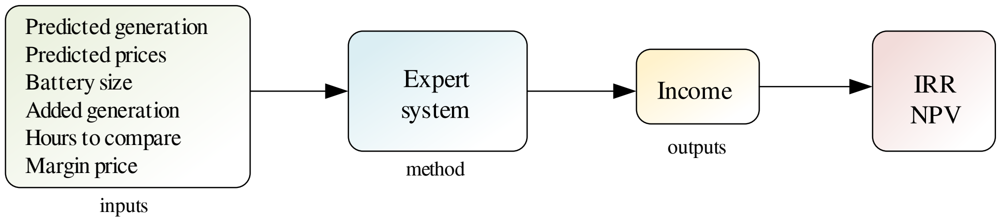

Figure 2. Input-output diagram system expert.

2.2. Optimised Expert System

Since the previous method relies on the expert knowledge for tuning the parameters, its use of the battery is not efficient in all situations. Depending on the power plant and market conditions, the parameters of the system may not necessarily be the most appropriate. The two most decisive parameters are the price margin and the averaging time window width. The system behavior is very sensitive to their values, and the best value of each one seems to depend on the current value of the other so manual tuning becomes difficult. For this reason, as an evolution of the method design, this work proposes to automatically adjust these two parameters by optimising them.

The output of the optimisation method (Figure 3) is the value of these two parameters (averaging time window width and price margin percentage). The input to the optimisation method includes the size of the battery, the market prices for the day and an estimation of the power plant generation for the day. To evaluate the objective function, the particle swarm method simulates the behavior of the system for the whole day and computes the net economic gain due to the energy bought and sold.

It is worth noting that, although the optimisation method simulates the behavior of the plant for the whole day, the expert system is still run according to the actual values of power and SOC measured during the day. That is, the charging and discharging of the battery does not blindly follow the simulation that produced the best results during the optimisation. The reason for this is that the plant generation may differ from the initial estimation. The consistency of the expert system, which depends on the actual values, will always be more robust than an open-loop control scheme based on mere predictions.

Despite the flexibility gained with the parameterisation and optimisation, the expert system is still rigid. In particular, it rarely charges or discharges the battery at a rate different from the maximum. This presents some limitations, especially for high power batteries, which the next method intends to solve.

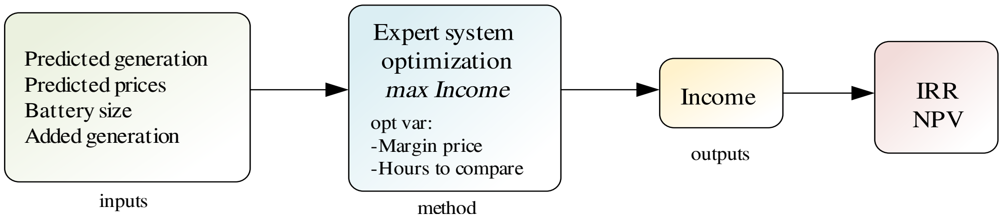

Figure 3. Input-output diagram optimised system expert.

2.3. Proposed Artificial Intelligence Method

To further improve the previously presented method, we propose to use an energy management algorithm: E-Broker [41,42], which makes it possible to manage power exchanges between the grid, generation, internal consumption and the storage system that is installed.

The main issue with the previous methods is how rigid they are regarding the behavior of the energy storage system. The battery can be charged or discharged, but there is no control about how much it should be charged or discharged. In addition, the SOC plays a very small part in the decision making: it can only be above 95%, below 50% or between those values. In order to gain more flexibility, a third method considers the possibility of charging (or discharging) the battery up (or down) to a certain SOC, which depends on the energy price. To do so, the E-Broker algorithm is employed.

The E-Broker is a method to decide how power is to be exchanged between different devices, agents or generation sources and consumers. Some of these devices demand power, others offer to supply it and others can act in either way. In particular, for the analysed power plant, 4 devices can be considered: generation (producer), the internal load due to losses and control systems (consumer), the grid as electricity market (prosumer) and the storage system (prosumer).

The E-Broker method is based on a priority system that sorts producers and consumers before matching their power requests. In this case, the generation has the highest priority among the producers and the internal load has the highest priority among the consumers. Consequently, generation will deal all the power it can produce whenever possible and the internal load will be feed as long as it is possible (which is always the case). This way, curtailment is avoided and the power plant ancillary systems are always fed.

This priority system also includes a limit priority for all devices which can be employed to forbid certain power exchanges. For example, under some circumstances, the battery may be allowed to receive power from generation, but not from the grid.

Finally, some devices may have a more complex behavior and act with different priority profiles. In particular, their profiles have been considered for the battery, which correspond to its aforementioned settings: charge (battery 1), stand by (battery 2) and discharge (battery 3). The battery will behave according to one or another profile, depending on its SOC and on the current energy price.

The priorities and allowed power exchanges are summarised in the schematic in Figure 4.

According to the E-Broker method, producers and consumers are sorted by priority. The highest priority producer provides power to the highest priority consumer, until one of them cannot provide or accept any more. The satisfied producer or consumer is then discarded and the next one continues to give or receive power. This process continues until the exchanges are no longer allowed between the remaining devices.

Demand \ Supply	Generation (Priority 1)	Battery 3 (Priority 2)	Grid supply (Priority 3)	Battery 2 (Priority 4)	Battery 1 (Priority 5)
Internal load (Priority 1)	Allowed	Allowed	Allowed	Allowed	Allowed
Battery 1 (Priority 2)	Allowed	-	Allowed	-	
Grid demand (Priority 3)	Allowed	Allowed		Not allowed	Not allowed
Battery 2 (Priority 4)	Allowed	-	Not allowed	-	-
Battery 3 (Priority 5)	Allowed		Not allowed	-	-

Figure 4. Priorities of suppliers–consumers and allowed transactions.

An example is given to clarify this method. Consider a case where the battery is acting according to its second profile (battery 2). At the moment of the example, the PV can only produce 25 kW; the battery can either provide or receive up to 70 kW, the grid can buy or sell up to 100 kW and the internal loads are consuming 5 kW. First, the highest priority supplier is matched with the highest priority power request, so the PV generator provides 5 kW to the internal loads. This consumer is now satisfied, so the rest of the supplier power is matched with the demand of the consumer with the second highest priority: the grid. The remaining 20 kW of the PV generator are then sold to the grid. The grid could accept more power, but the only remaining device (the battery) is not allowed to provide it. Similarly, the battery cannot receive power from the grid in this situation either.

For the selected priorities and battery profiles, the battery will always be allowed to receive power from the PV generator or to provide power to the internal loads. This way the battery meets the first rule of the expert system (absorbing the power excess) and part of the fourth rule (feeding the internal loads with its reserve). However, its interaction with the grid will depend on the battery particular profile.

To select a battery profile, the battery SOC is compared with two SOC thresholds, SOC_1^* and SOC_2^*, which, in return, depend on the energy price. The battery uses the first profile (charging) when its SOC is bellow both thresholds, the second profile when its SOC is between both thresholds and the third one when its SOC is above both of them. The lower SOC threshold is related to how cheap it is to buy energy from the grid: the cheaper the price, the higher the threshold is. The higher SOC threshold is related to how much can be gained by selling power to the grid: the higher the price, the lower the threshold is. Therefore, the battery will tend to sell energy when it is expensive, buy it when it cheap, and reserve it when it is about average, thus meeting the remaining rules of the expert system.

The dependency of the SOC thresholds with the energy price is parameterised using 4 optimisation variables: x_1, x_2, x_3 and x_4. Similar to the previously described method, the first optimisation variable, x_1, defines the averaging time window for the energy selling and buying prices. So, thd average price, P_{av}, is defined in (2), depending on the grid price, P_{grid}.

$$P_{av} = \frac{1}{x_1} \cdot \int_t^{t+x_1} P_{grid}\, dt \quad (2)$$

The remaining optimisation variables define two price margins, M_1 and M_2, as functions of P_{av}. M_1 represents the minimum margin for the battery to act at all, and M_2 represents the additional margin for the battery to act with all its capacity.

$$M_1 = x_2 \cdot P_{av} + x_3 \quad (3)$$

$$M_2 = x_4 \cdot P_{av} \quad (4)$$

It is worth noting that, since the grid prices for selling and buying power may differ, two values may correspond to each price margin. The margins calculated with the price for buying power from the grid are related to the first SOC threshold (SOC_1^*), while those calculated with the price for selling power to the grid are related to the second (SOC_2^*) threshold. When the grid buy price is higher than P_{av} minus M_1, grid power is considered to be not cheap enough, and the first threshold is set to 0%. On the contrary, when the buy price is lower than P_{av} minus M_1 and M_2, power is considered to be especially cheap, so the first threshold is set to 100%. When the price is between these values, a lineal interpolation is used.

$$SOC_1^* = \begin{cases} 0\%, & \text{if } P_{grid} \geq P_{av} - M_1, \\ 100\%, & \text{if } P_{grid} \leq P_{av} - M_1 - M_2, \\ \frac{P_{av} - P_{grid} - M_1}{M_2} \cdot 100\%, & \text{otherwise} \end{cases} \tag{5}$$

Similarly, when the grid sell price is lower than P_{av} plus M_1, the second threshold (SOC_2^*) is set to 100%: the price is too low to sell power. When the price is higher than P_{av} plus M_1 and M_2, the second threshold is set to 0%: the price is so high that it is acceptable to sell all the battery energy. Finally, for intermediate prices, a linear interpolation is used.

$$SOC_2^* = \begin{cases} 100\%, & \text{if } P_{grid} \leq P_{av} + M_1, \\ 0\%, & \text{if } P_{grid} \geq P_{av} + M_1 + M_2, \\ \frac{P_{av} + M_1 + M_2 - P_{grid}}{M_2} \cdot 100\%, & \text{otherwise} \end{cases} \tag{6}$$

Since the sell price can never be higher than the buy price at any given time, five possibilities appear as shown in Figure 5. Power can now be very cheap (A), somewhat cheap (B), average (C), somewhat expensive (D) or very expensive (E). The power plant will react differently to these five situations, with the consequent improvement in its energy management.

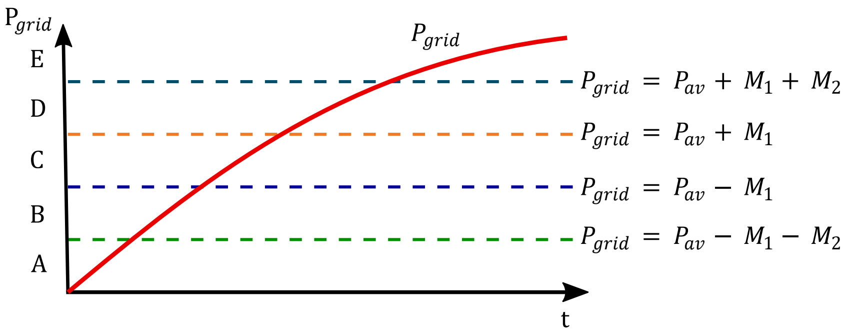

Figure 5. Grid pricing scheme as a function of average price and price margins.

2.4. Multi-Objective Sizing

When designing or upgrading a power plant it is important to consider the management strategy in order to correctly size the generation power and the storage energy to be installed. This is because beyond the management method and its quality, it is necessary to adjust it to the conditions of the market in which power plant participates and the own conditions of the plant.

For sizing and choose the appropriate sizes, a multi-objective optimisation is proposed. The motivation is double: (1) to take advantage of the Pareto frontier that results as a solution of a multi-objective optimisation, and (2) to maximise two objectives at the same time. In contrast to an optimisation in which a single objective is maximised, in a multi-objective optimisation multiple valid solutions are generated as a result of possible combinations of the optimisation parameters, which form the Pareto frontier.

A multi-objective optimisation makes it possible to evaluate the investments made in additional generation and storage in a more precise way. The two objectives to be maximised will be net present value (NPV) and internal rate of return (IRR), which will make it possible to find the most economically appropriate sizes. NPV is used to determine the viability of the investment and the benefits, while the IRR indicates the profitability of the investment in generation and storage. These indices are defined as:

$$NPV = -I_0 + \sum_{t=1}^{n} \frac{CF_t}{(1+k)^t} \tag{7}$$

$$-I_0 + \sum_{t=1}^{n} \frac{CF_t}{(1+IRR)^t} = 0 \tag{8}$$

where I_0 represents the total investment made in additional generation and ESS, n is the period analysed, k is the discount rate and CF is the annual cash flow generated by the investment made.

The main inputs to the sizing method must be data related to the market in which the plant will participate (prices and generation profile), data related to the cost of installing additional generation and storage, as well as the data required for the battery management method chosen (presented above). With these inputs, in addition to the parameters of the chosen method, the additional generation gen^{size} and storage bat^{size} are optimised in MW and MWh respectively. A diagram of this method can be seen in Figure 6.

Equation (9) shows the two objectives of sizing multi-objective optimisation.

$$\begin{aligned} \max_{gen^{size},bat^{size}} \quad & NPV \\ \max_{gen^{size},bat^{size}} \quad & IRR \end{aligned} \tag{9}$$

As mentioned above, a set of valid solutions, which forms the Pareto frontier, is obtained. This is interesting because it helps to make a better decision, since it offers more valid alternatives to the investor, who can choose the one that best satisfies his requirements (desired profitability, investment . . .), adjusting all the solution cases to the market and plant characteristics. The better the management method, better the economic results and integration of the storage, as it will profit more from the power plant usage. If a method is uncapable of making the storage system cost-effective, a battery investment may not be considered optimal and may be discarded in the sizing.

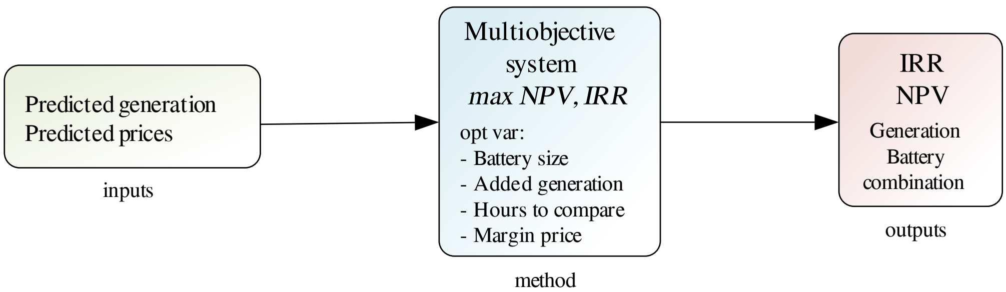

Figure 6. Input-output diagram multi-objective optimisation.

3. Test Data

The aforementioned methods are tested through simulations using real market price and generation data. In particular, the tests consist of the simulations that would be used to design an upgrade to an existing power plant. Initially, this power plant has 300 MW photovoltaic peak power installed, with no storage. According to its contract with the electrical grid, it may provide or receive up to 240 MW to/from the grid (this is the limit of the connection point). Different simulations are run to decide the best possible upgrade, with may include storage and/or additional PV generation.

In order for the simulations to be realistic, the annual generation data from PVGIS [43] has been used. An estimation of the annual generation in León, Guanajuato (Mexico) has been chosen for the study. Figure 7 shows this data.

Real market prices have also been employed for the test. These prices were obtained from the day-ahead market [44] of Mexico for the year 2019. As shown in Figure 8, selling prices are very variable, even within the same season, so the tests must consider the whole year (not just a few months). Nevertheless, some small simulations are run for only a few days in order to show the methods behaviour during the day.

Regarding the investment, Table 1 shows the cost data, including cost per MW of additional generation and the cost per MWh of storage. The cost of any land or space to place the additional generation is already included.

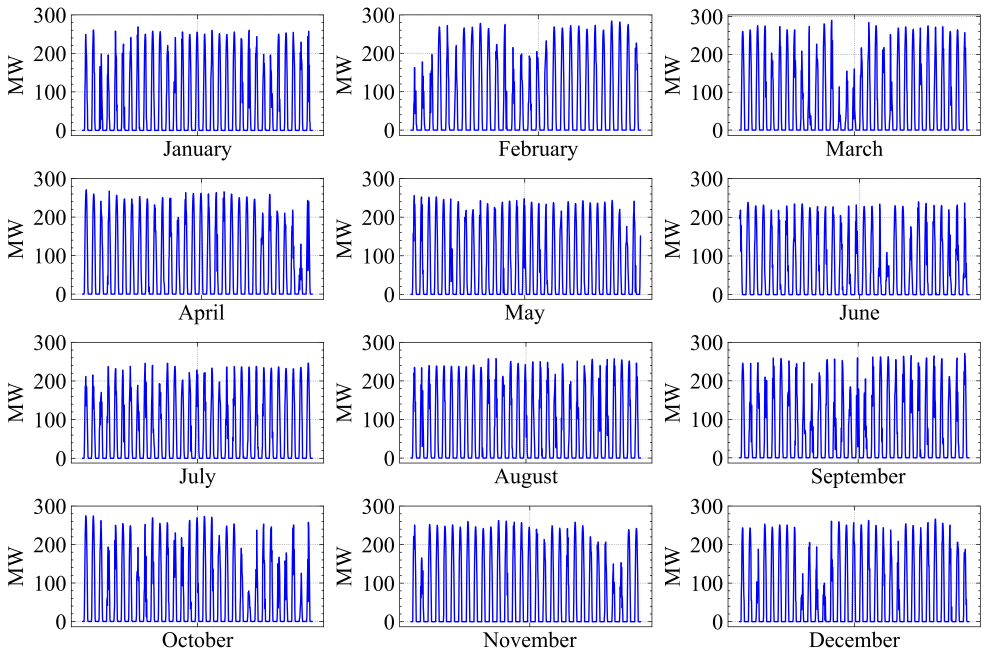

Figure 7. Annual photovoltaic generation in León, Guanajuato (Mexico) used for method testing.

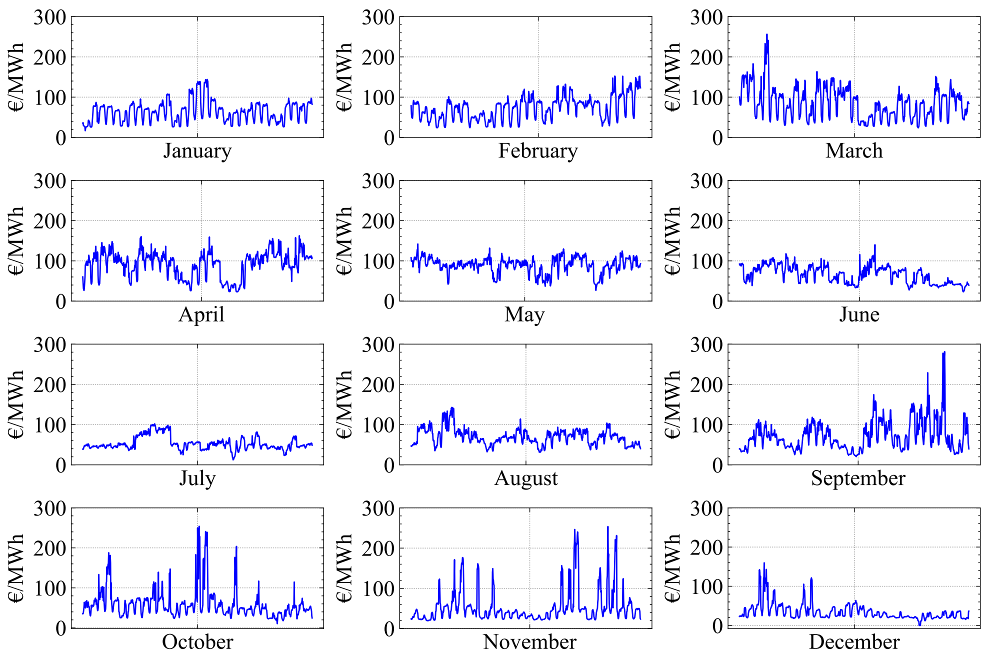

Figure 8. Annual day-ahead market prices for 2019 in Mexico used for testing methods.

Table 1. PV generation and battery costs.

Cost	Value
PV generation costs	632,500 €/MW
Battery cost	170,000 €/MWh
PCS cost	46,800 €/MWh
Engineering cost	35,000 €/MWh
Containers cost	30,000 €/MWh
EPC cost	14,000 €/MWh
Refurbished cost	125,000 €/MWh

For upgrade design, a 30-year period is analysed, with refurbishment on the 16th year. For the IRR, a 2% discount rate is assumed. It is assumed that all generated energy will be sold on the day-ahead market (limited by the 240 MW connection point). It is also assumed that the price of sale and purchase are equal. A 1-year simulation is performed and its result is considered to be approximately constant for the whole 30-year period. No ESS degradation is considered (although the refurbishment is still included) so that results of the different methods can be compared with ease. Additional simulations are run for only 15 days, in order to show the daily management of the methods in more detail.

4. Simulation and Results

This section presents the results of applying the methods described in Section 2 with the data indicated in Section 3 in two scenarios. On the first scenario, the daily management is detailed, while on the second one, a power plant expansion is designed for maximum profits in the long term.

4.1. Management

To see in detail the differences in daily management, methods are evaluated in some days of January. This month presents uniformity in prices and generation, making it a good month to compare results. The three management methods are tested for the first 15 days of January, with the second and third method being optimised for entire period (not day by day). Different combinations of additional generation and storage are tested with their respective profits shown in Table 2. The income of the original generation (without applying any methods) has been deducted. Since the table shows the daily profit, the investment cost is not considered.

Table 2. Summary table of the benefit obtained with the methods in the first 15 days of January.

Storage \ Generation	Method	50 MW	100 MW	150 MW	200 MW
25 MWh	Proposed	181,435.89 €	284,259.48 €	363,612.18 €	430,733.96 €
	Expert Opt	173,848.68 €	272,551.11 €	351,613.59 €	417,836.83 €
	Expert	166,150.08 €	264,617.73 €	344,043.69 €	411,097.68 €
50 MWh	Proposed	200,440.45 €	308,132.58 €	391,363.26 €	457,554.24 €
	Expert Opt	189,418.42 €	288,158.09 €	367,273.84 €	433,320.13 €
	Expert	173,108.54 €	273,019.45 €	354,085.77 €	420,165.98 €
75 MWh	Proposed	217,415.82 €	322,320.99 €	414,244.28 €	485,230.63 €
	Expert Opt	205,005.00 €	303,807.89 €	382,757.15 €	448,803.44 €
	Expert	182,831.97 €	281,711.76 €	365,051.73 €	430,032.63 €
100 MWh	Proposed	233,156.28 €	356,133.64 €	440,545.50 €	511,452.97 €
	Expert Opt	220,639.13 €	319,308.72 €	398,240.45 €	464,290.54 €
	Expert	192,887.85 €	293,311.60 €	373,138.86 €	439,876.02 €

Analysing these results, it can be seen that the proposed method obtains more profit in daily management in these 15 days for all combinations. It is observed that for the same added generation, as the installed storage size is larger, the difference between the methods becomes more evident. Therefore, the proposed AI method takes a better advantage of the ESS, making the investment more profitable.

Figure 9 shows the daily profits for the first 7 days of January for an additional generation of 100 MW, in which 25 MWh (a) and 75 MWh (b) of ESS are installed. For these cases, a daily optimisation is performed, calculating the parameters for each day, which may differ from the day to day result shown above. It is observed that, despite the difference in daily revenues due to the variation in generation and prices on those days, the differences between the management methods increase as the battery size gets larger, as previously discussed.

These results also reflect the influence of the parameters of the expert systems. The optimised expert system obtains better results than the non-optimised expert system, so optimising the window of comparison hours and the price margin is effective to obtain a higher profitability with the management. On the other hand, when comparing the optimised expert system with the proposed AI method, the latter generally performs significantly better.

The effect of the rigidity of the expert systems, even with the optimisation, can be observed for the 75 MWh size. On days 3 and 4, the optimised expert method obtains results similar to the proposed method, while for the rest of days the differences are significant. So the optimised expert system does not adapt so well to all types of days as the proposed AI method does, even when its parameters are optimised.

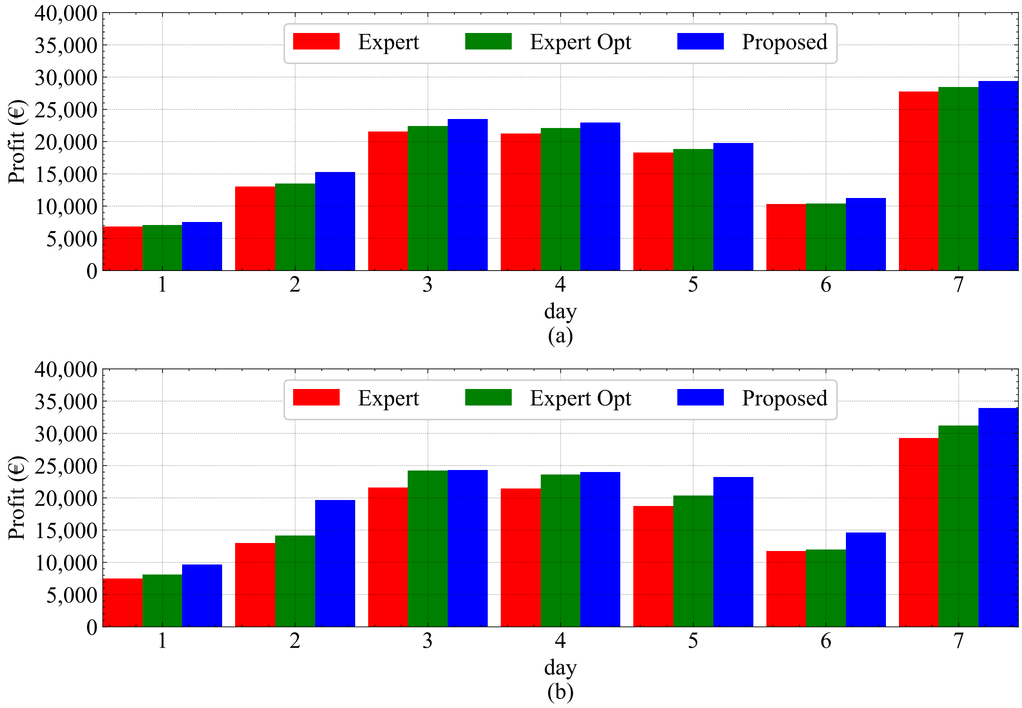

Figure 9. Comparison of daily management for case with 100 MW of added generation with 25 MWh of storage (**a**) 75 MWh of storage (**b**).

4.2. Sizing

As shown from the previous results, the proposed AI method is more adaptable and behaves better than the other two. Thus, the sizing tool proposed in Section 2.4 is tested using this third management method. The NPV and IRR indices are chosen to obtain the set of solutions that represent the best investments using multi-objective particle swarm as previously mentioned. The sizing tool obtains the Pareto-optimal frontier, which represents the combinations of additional generation and storage investment that produce the highest NPV and IRR.

To see the differences with the expert and optimised expert systems, this frontier is taken as a reference, evaluating the same investment combinations with the different methods. Figure 10 shows the Pareto-frontier obtained with the proposed method. Results of the optimised and non-optimised expert systems are represented with the same combinations as in the proposed AI method.

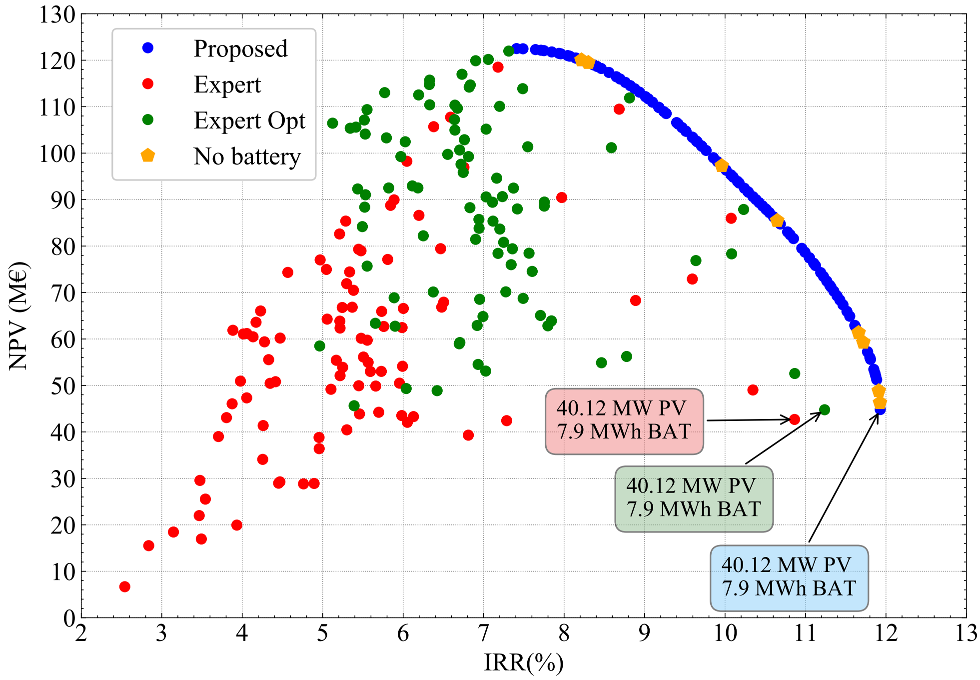

Figure 10. IRR vs. NPV for each combination of PV size and battery size using proposed method, expert system and optimised expert system for 30-year investment.

It can be seen how the expert systems rarely reach the Pareto frontier values obtained when using the proposed AI method. For example, the case when the investment consists of 7.9 MWh of storage and 40.12 MW of additional PV generation has been marked. It can be noted that the proposed method produces a result in the Pareto frontier, while both of the expert systems produce lower NPV and IRR. The optimised expert method produces a better result than the non-optimised one, but it is still far from the proposed AI method. It should be noted that the method also obtains combinations without adding battery (orange points). Such a combination would give the same result with all methods, since there is no battery management.

In Figure 11, results have been separated by the battery size. When battery sizes are smaller than 50 MWh, all systems obtain relatively close results despite their differences in complexity. For larger batteries, the proposed AI method is significantly better than the others, as previously shown. This demonstrates that the proposed AI method is most interesting for larger sizes of ESS. Table 3 summarizes these differences, where large additional generation sizes are not considered in order to see the influence of management methods more clearly. This is because with large additional generation sizes, the influence of management methods on economic indices may be distorted.

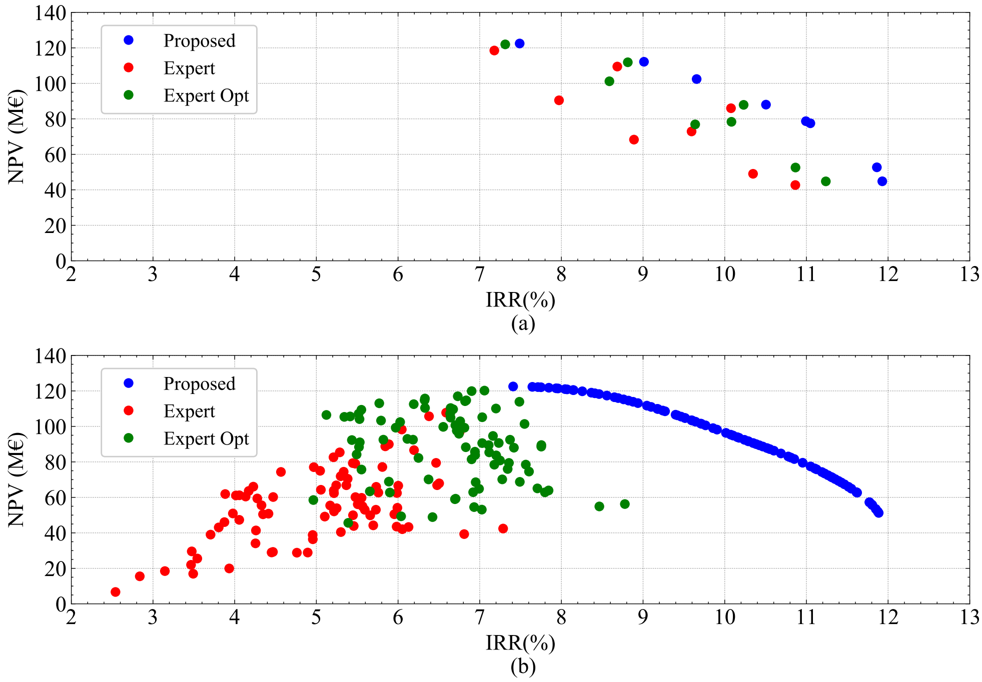

Figure 11. Thirty years' investment analysis for each combination, differentiating battery sizes under (**a**) and over (**b**) 50 MWh.

Table 3. Comparison of improvement of one method over another.

Combination		MO vs. ES		MO vs. ESO		ESO vs. ES	
Generation	**Storage**	**IRR (%)**	**NPV (%)**	**IRR (%)**	**NPV (%)**	**IRR (%)**	**NPV (%)**
40.12 MW	7.90 MWh	9.80	4.98	6.15	0.09	3.44	4.88
150 MW	10.55 MWh	3.76	2.46	2.25	0.25	1.48	2.21
60.78 MW	99.46 MWh	90.84	54.28	48.11	3.29	28.85	49.37
129.26 MW	108.93 MWh	47.17	31.80	26.06	3.27	16.75	27.62

In the case of batteries smaller than 50 MWh, the percentage of improvement between the methods does not reach 10%, but when the batteries are larger than 50 MWh, the improvement between the methods is very significant. As the size of the storage increases, so does the potential of the proposed AI method.

Focusing on the net present value, which calculates the money that an investment will generate in the future, eight combinations of additional generation and storage system are shown in Figure 12, also indicating its percentage of IRR. The most significant differences between methods arise in cases where the size of the battery to be installed is considerable compared to the additional generation. Although the optimised expert system substantially improves the expert, and approaches the values obtained by the proposed method, the difference is in millions of euros. This can be seen in the results: when 52.14 MW of additional generation and 59.50 MWh of storage are installed, the NPV difference between the proposed method and the optimised expert system is EUR 946,800. Or for the case of 60.78 MW of additional generation and 99.47 MWh of storage, where the difference is more significant: EUR 2,064,300.

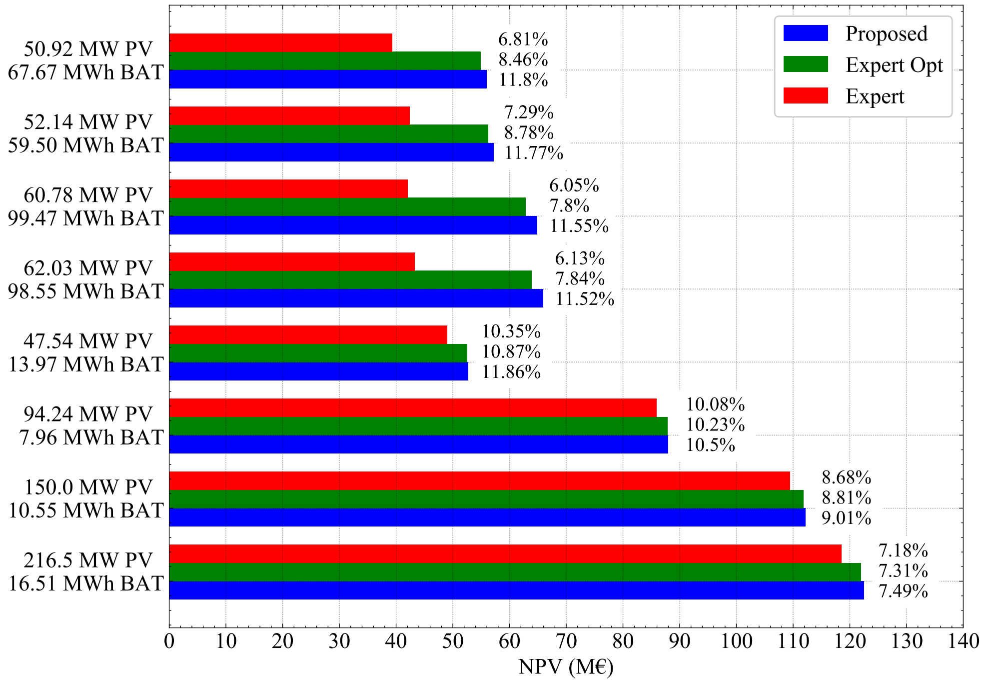

Figure 12. NPV results for four combination of battery sizes over 50 MWh and four combinations of battery sizes under 50 MWh.

5. Conclusions

A new energy management method based on price control has been proposed for hybrid power plants. This method uses the E-Broker algorithm and the particle swarm optimisation, along with a new parameterisation to control the behavior of the ESS. When compared with typical expert systems, it is shown to follow similar rules and still obtain more profits for the same power plant participating in the day-ahead market. In general, the profit difference (in favor of the proposed method) is greater as the ESS size increase. This makes the method a good management candidate as the quality of market batteries becomes better and their use increases.

In addition, a tool has been developed to search the best Pareto-optimal frontier between NPV and IRR when designing or expanding a hybrid power plant. This tool has shown good results when it uses the aforementioned management method. With this tools we expect to be making a contribution to development of power plants that rely on renewable energy sources, as well as bringing up more opportunities for business models based on these green energies. The proposed tools show that this type of power plant is profitable as long as the batteries are correctly exploited.

In our future work, we plan to expand our approach to the participation of hybrid plants and ESSs in several electricity markets simultaneously, in order to achieve even more benefits and to further promote the integration of renewable generation and storage.

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