Analysis of the potential for participation of hybrid renewable plants with storage in capacity markets

Javier Serrano González[1], Jesús Manuel Riquelme Santos[1], Juan Manuel Roldán Fernández[1], Jorge Cormane[2]
[1] University of Seville, Departamento de Ingeniería Eléctrica, Camino de los Descubrimientos S/N, Seville, Spain,
javierserrano@us.es, jsantos@us.es, jmroldan@us.es
[2] University of Brasilia – UnB, Faculdade UnB Gama, Brasilia, Brasil, jcormane@unb.br

***Abstract*— The present work undertakes the evaluation of the potential participation by hybrid renewable plants with storage in capacity markets. To this end, a realistic model has been developed for the evaluation of the hourly production of wind farms, taking into account real data on the renewable resource, as well as the evolution of prices in electricity spot markets to optimize battery management. This allows us to estimate the firmness coefficient (calculated as the precentage of hours per year that the committed capacity is able to provide) of the plant and, therefore, to estimate the potential participation of this type of plant in the capacity markets. The results obtained highlight the importance that storage systems coupled to a renewable plant can have in terms of market participation, even when the battery is managed with the objective of maximizing the benefits derived from participation in the energy markets.**

***Index Terms*-- capacity markets, degree of firmness of renewables, hybrid plants, solar energy, wind energy.**

I. INTRODUCTION

The energy transition toward decarbonized power systems has driven significant changes in the composition of generation resources. The large-scale integration of renewable energy sources characterized by their intermittency and dependence on weather conditions poses challenges to ensuring supply security and system stability. In this context, traditional electricity markets based solely on energy provision are often insufficient to deliver the economic signals required to maintain adequate and flexible generation capacity to meet demand under all circumstances.

The introduction of capacity markets emerges as a solution to address these limitations. These markets are designed to ensure that sufficient generation capacity is available, not only to cover the expected peak demand but also to manage system stress events.

Globally, various countries and regions have implemented capacity markets tailored to the specific needs of their power systems. In the United States, capacity markets play a crucial role in electricity markets managed by operators such as PJM, ISO New England or NYISO [1], [2]. These markets ensure adequate capacity through regular auctions where generators and demand-side resources compete for contracts that provide additional revenue in exchange for their availability during periods of peak demand.

In Europe, the reference capacity market is the mechanism in force in the United Kingdom, which was introduced in 2014 [3]. The UK system relies on annual auctions to secure contracts with resources that guarantee availability during system stress situations. In the UK Capacity Market, the "de-rating factor" plays a crucial role in determining the contribution of different resources to the system's reliability. This factor adjusts the rated capacity of a resource to reflect its expected availability during system stress events. For each technology type (including wind, solar, or battery storage) the de-rating factor is calculated based on historical performance data and statistical models that assess the likelihood of the resource being available. Thus, the application of de-rating factors ensures that payments in the Capacity Market are aligned with the actual reliability and contribution of resources.

The existing scientific literature on the participation of renewable plants in capacity markets is somewhat limited, although it is worth mentioning some works that undertake the analysis from a normative and regulatory point of view [5], [6]. Also noteworthy is the work done in [7] which examines the implementation of capacity mechanisms across Europe and their interactions with renewable energy sources. It highlights challenges such as the impact of renewable intermittency on system reliability and evaluates how different capacity mechanism designs can better support the integration of renewables while ensuring grid stability. Also of interest is the work carried out in [8] which analyzes how capacity markets can contribute to reliability in systems with high penetration of renewables. The study concludes that capacity markets are more effective than strategic reserves in ensuring reliability and reducing consumer costs.

This paper aims to analyze the possibility of participation by a hybrid renewable plant with storage in a capacity market with the same basic operating principles implemented in the

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United Kingdom. In particular, the approach is considered in the context of the Iberian electricity market through the analysis of a case study in Spain. In this regard, it should be noted that the regulatory context in Spain has not yet implemented a capacity market, although it is currently under development following similar characteristics to the system implemented in the UK. In particular, it is noteworthy that resources will also be remunerated based on the real potential of firm capacity contribution defined by firmness coefficients [4]

A novel approach is proposed to quantify the firm capacity contribution of renewable plants, including the potential enhancement provided by the integration of storage systems, which can significantly increase their participation in capacity mechanisms.

After this brief introduction, the rest of the paper is organized as follows: Section 2 introduces an overview of the implemented methodology, Section 3 provides the model of the hybrid renewable plant with storage, Section 4 presents the results obtained in the test cases, and finally, the conclusions are provided in Section 5.

II. METHODOLOGY OVERVIEW

This section briefly introduces an outline of the methodology implemented in this work. Fig. 1 shows schematically the different steps followed to obtain the estimation of the firmness coefficient by hybrid renewable plants with storage. For the calculation of the energy produced, historical series of meteorological data have been taken into consideration. These data have been fed into the wind farm production calculation models in order to obtain the energy output of these plants. On the other hand, for the management of the storage system, the generation outputs (with hourly profile) for the generation plants and, on the other hand, the hourly prices of the daily market observed in Spain during the year 2023, extracted from the Iberian market operator OMIE [9], have been taken into consideration. In this way, the battery management has been implemented taking into account two possible management approaches: (i) the battery can only be charged with energy coming from the wind farm and (ii) the battery can also participate in the price arbitrage by purchasing energy in the market. Once the optimal battery management strategy has been obtained for each of the proposed approaches, the firmness coefficient of the hybrid project has been evaluated by calculating the number of hours per year in which the project has the nominal capacity of the plant available. Note that the management of the battery has been focused on maximizing the revenues from participating in the energy markets (in this particular case the spot market), rather than maximizing its participation in the capacity market (whose strategy would be simply to keep the battery fully charged for as long as possible), which would make no sense since the potential revenues in the capacity markets are significantly lower than those that can be obtained by participating in other energy markets. In other words, it is assumed that the hybrid plant will optimize its participation in the energy markets and, subsidiarily, will have a certain potential for participation in the capacity markets, a potential that we intend to evaluate in this work.

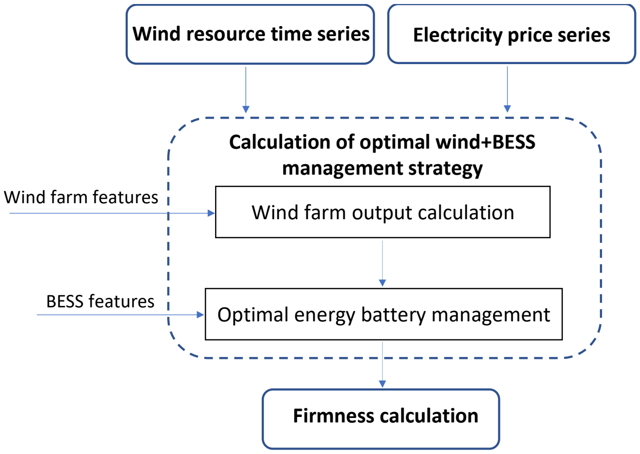

Figure 1. Overview of the implemented methodology

III. HYBRID PLANT MODEL

This section briefly introduces the models that have been implemented for the hybrid generation plant consisting of a wind farm plus storage system.

A. Wind farm energy output calculation

The calculation of the energy output of a wind farm is based on the application of the turbine's power curve, which defines the relationship between wind speed and the electrical power generated. To estimate the power output, hourly wind speed data from meteorological sources is used as input to the power curve, allowing the determination of the power generated by each turbine at every time step.

The total energy production of the wind farm over a given period is obtained by multiplying the power output of a single turbine by the total number of turbines (Nt) and integrating this power over time. This is done by summing the power generated at each hourly interval and multiplying by the duration of the time step. The energy calculation can be expressed as:

$$E = N_t \cdot \sum_{t=1}^{T} P(v_t) \cdot \Delta t \qquad (1)$$

where E is the total energy produced, N_t is the number of turbines in the wind farm, $\mathrm{P}(v_t)$ is the power output corresponding to the wind speed v_t at time t, and Δt represents the duration of each time interval, in this case, one hour.

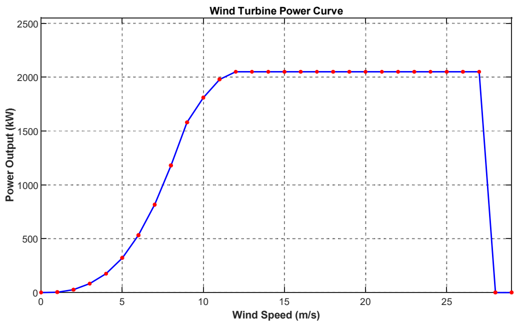

Figure 2. Power curve of the considered wind turbine model. Enercon E82/2000.

The considered wind turbine model in this work is the Enercon E82/2000, whose power curve is shown in Fig. 2.

B. Battery management strategy

The wind-battery hybrid system analyzed in this study is managed through an optimization-based approach aimed at maximizing the total revenues of the system, considering its participation in both energy and capacity markets. The operation of the battery is modeled using a *rolling horizon* optimization framework with a 24-hour time horizon. This approach enables continuous updating of operational decisions based on the evolving conditions of both market prices and wind power production, enhancing the system's ability to adapt to variability in supply and demand.

Three battery management strategies are considered to assess the impact of different operational policies. In the first strategy, the battery can be charged using both surplus wind energy and energy purchased from the market. This strategy seeks to maximize revenues through price arbitrage, exploiting price differentials between periods of low and high market prices. The second strategy restricts battery charging to surplus wind energy only, limiting arbitrage opportunities but optimizing the use of renewable resources. Finally, a scenario focused on maximizing the system's *firm capacity* is considered, where the state of charge is kept at the possibly highest level to ensure the highest availability of firm power. This latter strategy does not require an optimization algorithm, as it follows a static policy aimed at maintaining the battery's maximum state of charge.

The optimization problem is formulated to maximize the net revenues of the hybrid system, defined as the difference between the revenues from energy sales and the costs associated with purchasing energy from the market, when applicable. The model incorporates constraints to ensure the physical feasibility of the system, including the battery's energy balance, limits on charging and discharging power, the maximum storage capacity, and the availability of wind generation for direct charging. The charging and discharging processes are characterized by their respective efficiencies, denoted as η_c (charging efficiency) and η_d (discharging efficiency).

The battery's energy balance accounts for energy gains during charging, influenced by the charging efficiency, and energy losses during discharging, determined by the discharging efficiency. The battery can be charged from two sources: surplus wind power and electricity purchased from the market (P_{charge}). The discharged energy ($P_{discharge}$) is used to supply the market, complementing the direct sale of wind-generated electricity.

The objective function of the optimization problem aims to maximize the system's total revenues, defined as:

$$\max \sum_{t=1}^{T} (P_{sell,t} \cdot \pi_t - P_{charge,t} \cdot \pi_t) \tag{2}$$

where $P_{sell,t}$ represents the total power sold to the market at time *t*:

$$P_{sell,t} = P_{discharge,t} + P_{wind,t} \tag{3}$$

And π_t is the market price of electricity at time t. $P_{charge,t}$ is the power used to charge the battery.

The battery energy balance is governed by the following equation:

$$E_t = E_{t-1} + \eta_c \cdot P_{charge,t} - \frac{1}{\eta_d} P_{discharge,t} \tag{4}$$

where E_t is the state of charge of the battery at time *t*. η_c and η_d are the charging and discharging efficiencies, respectively.

Additionally, the optimization is subject to several constraints:

$$\begin{aligned} 0 &\le P_{charge,t} \le P_{max} \\ 0 &\le P_{\mathrm{discharge},t} \le P_{\max} \end{aligned} \tag{5}$$

$$0 \le E_t \le E_{max} \tag{6}$$

Where: $P_{\max}$ is the maximum charging or discharging power of the battery and $E_{\max}$ is the maximum storage capacity. Constraints (5) imply the maximum charge/discharge power of the battery, while constraint (6) stands for the maximum storage capacity of the BESS.

The optimization problem is solved using linear programming techniques, ensuring computational efficiency even for large datasets with high temporal resolution. This framework enables a comprehensive assessment of the battery's role in enhancing the economic performance of the hybrid system, as well as its contribution to grid reliability through firm capacity. The comparison of different operational strategies provides valuable insights for designing battery management policies that balance economic profitability with system reliability.

IV. TEST CASES

This section shows the results obtained in the case studies analyzed. The hybrid plant (wind plus storage system) consists of 10 wind turbines of the aforementioned model E82/2000, so the rated power of the wind farm is 20 MW. The wind farm is located at Latitude : 36° 25' 44" and Longitude : -5° 45' 42.4" and the historical wind data (2005-2023) has been collected from EMD-WRF Europe+ [10] by means WindPro software. The daily market prices corresponding to the Iberian market during the year 2023 have been considered [9] (for the sake of simplicity, this study assumes that the electricity prices observed during the selected year are repeated cyclically throughout the wind data period).

Regarding the storage system, different power ratings and capacities have been analyzed. For this purpose, a sweep has been performed by varying the nominal power of the battery depending on the power of the wind farm, from 0% (i.e. no storage) to 50% in 10% intervals. All this for 3 storage capacities: 1,h 2h and 4h. Likewise, as introduced above, two possible management strategies for the battery have been considered: (i) the battery can only be charged with energy coming from the wind farm (a situation that can occur in certain regulatory frameworks where the hybrid plant is considered as a generation plant and therefore cannot buy energy from the system) and (ii) the battery can be charged with energy coming from both wind farm and market so it can freely participate in price arbitrage.

Fig. 3 shows the results obtained for the described analysis, by means of the evolution of the firmness coefficient as a function of the battery power, expressed as a percentage of the wind farm's rated power. Blue circles correspond to the approach where the battery can only be charged with wind farm power and red squares correspond to the approach where it can also be charged with market power. The firmness coefficient represents the percentage of hours in which the system—comprising both the wind farm and the battery—is capable of delivering at least the nominal power of the wind farm.

As can be observed, in the absence of a battery, the wind farm firmness coefficient is 10.11%, due to the inherent variability of wind power. This indicates that the wind farm alone can meet its nominal capacity during only a limited fraction of the year. It can also be seen that for both scenarios (wind-only load and wind plus market load) the firmness coefficient is virtually the same (this is not the case for total plant revenues, as shown below). This is because the battery's contribution to system adequacy does not depend on the specific source of the energy used to charge it, but rather on its availability. Additionally, the battery's charging and discharging strategy does not depend on the origin of the energy, but rather on the arbitrage opportunities created by market price differences. This means that, for relatively moderate battery sizes, the solutions obtained under both strategies are virtually identical.

As battery power increases, the firmness coefficient improves. For a battery with a 1-hour storage capacity, the firmness coefficient rises from the above-mentioned 10.11% without a battery to 16.40% when the battery power equals 50% of the wind farm's nominal capacity. For larger storage capacities, the improvements are even more pronounced. With a 2-hour storage capacity, the firmness coefficient reaches around 17.75% when the battery power is 50% of the wind farm's nominal power. And when the storage capacity is further increased to 4 hours, the firmness coefficient approaches 19.80% for the same battery power level.

This appreciable increase as the power and storage capacity of the battery increases highlights the potential contribution that the battery has in providing firm power to the system, even when the battery is operated with the objective of maximizing revenue from the sale of energy in the markets. The results obtained also show some trends of interest. As expected, the higher the capacity of the battery, the higher its contribution to the firm capacity contribution to the system, since the battery

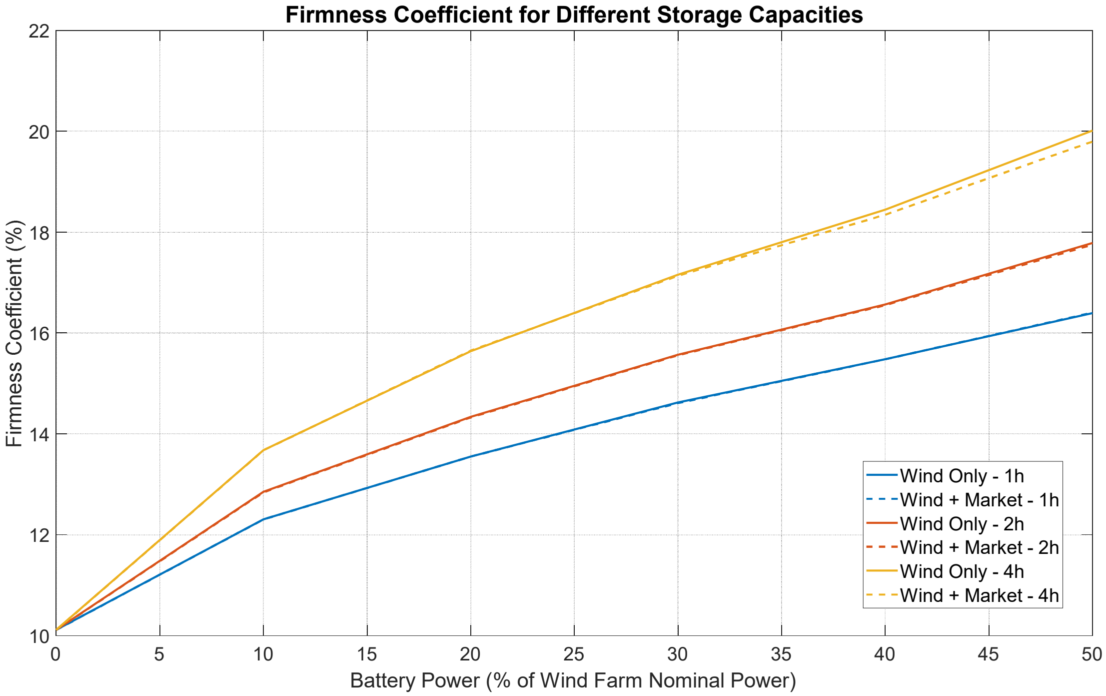

Figure 3. Firmness Coefficient for the analyzed test cases.

is able to maintain a higher level of load to optimize its participation in the price arbitrage.

Table I shows the economic results associated with the hybrid plant under study, particularly for a battery with a storage capacity of 2h, assuming that it can only be charged with energy from the market. Similarly, Table II shows the economic results for the approach in which it can be charged with energy from the market. In this analysis, a capacity market share price of €60/kW/year has been considered (taken on the basis of the latest results obtained in the UK capacity market, please note that this value has only been provided as a reference, as the final service price may vary depending on the specific outcomes of each auction). Accordingly, annual revenues from participation in the capacity market are computed by multiplying the service price, the committed capacity, and the firmness coefficient.

As expected, the total income increases progressively as the battery power increases. In the absence of a battery (0% power), the total annual income is 3.06 M€ (for both approaches). As the battery capacity is integrated into the system, total income increases, reaching an additional 0.54 M€ for the market charging approach (0.40 M€ for the wind only charging approach) for a battery with 50% of the wind farm's rated power. Regarding the income from participation in the capacity markets, it can be observed that it starts from a revenue of 0.121 M€ for the wind farm without storage system to 0.213 M€ for battery power equal to 50% of the rated power of the wind farm.

As can be seen, the revenues derived from participation in the capacity market are lower than those derived from the plant's main activity, i.e., the sale of energy. Nevertheless, these revenues are not negligible and should be taken into consideration when designing the optimal design of a hybrid renewable plant with a storage system. Even more so when increasing the size of the battery, the relative weight of the revenues in the capacity markets over the total revenues increases. That is, for the plant under study without storage, the share of capacity markets would be 3.9% of total revenues. However, the relative weight of revenues from capacity markets increases to 6.1% for battery power equal to the nominal power of the wind farm for the case in which the battery is only allowed to be charged with energy from the wind farm, while for the case in which it can be charged with energy from the market this percentage is 5.9%.

TABLE I. SUMMARY OF RESULTS WITH BATTERY OPTIMIZED FOR ARBITRAGE AND WIND-ONLY CHARGING (2H STORAGE).

Battery Power (% of WF Rated Power)	Total Income (M€)	Wind energy direct sale (M€)	Arbitrage Income (M€)	Capacity Income (M€)
0	3.056	2.935	0.000	0.121
10	3.168	2.856	0.158	0.154
20	3.254	2.789	0.293	0.172
30	3.329	2.729	0.414	0.187
40	3.395	2.675	0.521	0.199
50	3.460	2.623	0.623	0.213

TABLE II. SUMMARY OF RESULTS WITH BATTERY OPTIMIZED FOR ARBITRAGE AND WIND + MARKET CHARGING (2H STORAGE).

Battery Power (% of WF Rated Power)	Total Income (M€)	Wind energy direct sale (M€)	Arbitrage Income (M€)	Capacity Income (M€)
0	3.056	2.935	0.000	0.121
10	3.179	2.856	0.169	0.154
20	3.286	2.789	0.325	0.172
30	3.391	2.729	0.475	0.187
40	3.492	2.675	0.618	0.199
50	3.597	2.623	0.760	0.213

Finally, Tables III and IV show the revenues obtained by the plant as a function of the nominal power of the battery for a storage capacity of 2h under the assumption that the battery was operated to maximize the revenues derived from the participation in the capacity mechanism. From the results shown in the tables it can be deduced that, as expected, managing the battery to maximize the firmness coefficient results in lower total revenues than optimizing arbitrage. In practical terms this strategy translates into the battery management strategy, keeping at all times a minimum charge level equivalent to 1 hour of storage, while the remaining charge is used for price arbitrage. Under this mode of operation, a maximum firmness coefficient of 25.45% is achieved when the battery power is 50% of the nominal power of the wind farm.

TABLE III. SUMMARY OF RESULTS WITH BATTERY OPTIMIZED FOR FIRMNESS COEFFICIENT AND WIND-ONLY CHARGING (2H STORAGE).

Battery Power (% of WF Rated Power)	Total Income (M€)	Wind energy direct sale (M€)	Arbitrage Income (M€)	Capacity Income (M€)
0	3.056	2.935	0.000	0.121
10	3.171	2.892	0.087	0.192
20	3.248	2.853	0.167	0.228
30	3.313	2.816	0.241	0.255
40	3.371	2.782	0.311	0.278
50	3.432	2.750	0.376	0.305

TABLE IV. SUMMARY OF RESULTS WITH BATTERY OPTIMIZED FOR FIRMNESS COEFFICIENT AND WIND + MARKET CHARGING (2H STORAGE).

Battery Power (% of WF Rated Power)	Total Income (M€)	Wind energy direct sale (M€)	Arbitrage Income (M€)	Capacity Income (M€)
0	3.056	2.935	0.000	0.121
10	3.175	2.892	0.092	0.192
20	3.261	2.853	0.180	0.228
30	3.337	2.816	0.266	0.255
40	3.409	2.782	0.349	0.278
50	3.486	2.750	0.430	0.305

V. CONCLUSION

The research conducted in this study has highlighted the potential of hybrid renewable plants with storage systems to participate in capacity markets. The results show that the integration of storage enhances the firm capacity contribution of renewable plants. The firmness coefficient, which measures the ability of the plant to consistently deliver its nominal power, improves notably with increased battery power and storage capacity. This enhancement is particularly pronounced when the battery is allowed to participate in energy arbitrage within electricity markets. However, even when battery charging is restricted exclusively to renewable sources, storage systems contribute noticeably to the improvement of capacity firmness.

From an economic perspective, while revenues from capacity markets remain modest (as expected) compared to those from energy sales, their relevance increases as the storage system's size grows. The proportion of income derived from capacity markets rises with higher battery capacities, underscoring the importance of integrating both energy and capacity market participation into the design and operational optimization of hybrid renewable systems.

In conclusion, this paper has introduced a preliminary economic analysis of the potential for firmness contribution by a hybrid renewable plant through its possible participation in capacity markets. Although it is a theoretical approach (since revenues are calculated on the basis of the specific firmness coefficient that a given plant is able to provide during a time horizon of 1 hour and without considering potential penalties) the results obtained highlight the importance of considering the eventual participation in capacity mechanisms during the design and management phase.

Future work could extend this analysis by considering PV hybrid systems, assessing the correlation between stress events and renewable availability, incorporating storage costs, and evaluating the potential system-level impacts of large-scale deployment.

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