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Optimized Energy Management Strategy for Wind Plants with Storage in Energy and Reserve Markets

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Abstract. This paper addresses the joint operation of wind plants with energy storage systems in multiple markets to increase the value of wind energy from an economic and technical point of view. The development of an optimized energy management allows scheduling the wind generation in energy markets, as well as contributing to the system stability through the joint participation in frequency ancillary services. The market optimization maximizes market revenues considering overall storage costs, while avoiding energy imbalances and market penalties. Moreover, wind power fluctuations, forecast errors and real-time reserve requirements are controlled by the energy storage system and managed afterward through the participation in continuous intraday market. Furthermore, model predictive control approach enables a high compliance of reserve requirements and a huge reduction of energy imbalances in real-time operation. Different energy storage capacities are selected in order to evaluate their cost-effectiveness enhancing the wind plant operation under the considered study case.

1. Introduction

As a result of increasing penetration of wind energy in the electric power system, the uncertainty in wind energy forecast and the intermittency of power generation [1] could affect the grid stability.

Moreover, due to their power variability, wind plants (WP) have difficulties in participating and operating suitably under current electricity markets from a technical and economic point of view compared to traditional generators. However, Energy Storage Systems (ESS) are considered one of the key technologies [2], which enable more flexibility and controllability to their market operation [3], as well as the opportunity of providing ancillary services (e.g. frequency control). As a result, WP+ESS plants will participate in a more reliable and profitable way in electricity markets.

Until now, renewable energy sources (RES) participate mostly in energy markets. Firstly, ESS helps WP to deliver a steady output generation [4-5] for the Day-Ahead Market (DM), in which a certain hourly amount of energy is bidden beforehand and delivered later. In order to accommodate the wind production and their inherent forecast uncertainty, Intraday Market (IM) allows them to correct the DM scheduling, reduce large energy imbalances, and thus, maximize their market revenues [5-9].

The growth of variable renewable sources has increased the importance of efficient markets. For that reason, Continuous Intraday Market (CIM) was included in Spain since June 2018 through XBID project [11], which enables RES to manage and reschedule their generation each hour. While the Spanish IMs through six daily auctions is widely known and analyzed [8,10], recent studies take advantage of CIM in order to schedule industrial processes [12], make arbitrage [13], or operate a wind farm but incurring deliberately in energy imbalances when it is profitable [14]. Although some researches analyze the impact of the low liquidity in Nord Pool CIM [9,14,15], the current Spanish intraday trading volume through auction is relevant, around 20% of the total generation. Thus, the WP+ESS plant is supposed to participate in CIM with enough liquidity over time.

Furthermore, researches that are only limited to accommodate renewable energy or make arbitrage do not reflect the potential value of ESS with WP. With increasing renewable generation, large-scale wind farms and ESS could contribute to provide frequency ancillary services in the same way as conventional generators. In the case of Spain, the participation of RES in balancing services is allowed since 2017 [16]. In frequency ancillary markets, generators offer a power availability band the previous day in Spanish Secondary Reserve Market, known also as Frequency Restoration Reserve (FRR). In contrast to energy markets, FRR energy delivery requirements (known as, AGC dispatch signal) are uncertain until real-time operation. This issue has huge implications in their joint operation. Control techniques developed for energy markets or for conventional generation are not directly applicable for WP+ESS under ancillary market participation. Thus, the development of advanced Energy Management Strategies (EMS) is needed for their joint participation in multiple markets.

From the point of view of the system operator, the grid stability and reliability is improved by providing regulation control, while from the WP owner point of view, overall market profits increase. However, some authors do not consider the joint WP+ESS operation for FRR market [10], and thus, the WP do not participate actually in this ancillary service. Other authors show that the wind energy imbalances increase in case of FRR participation [10][17], which is contradictory with the objective of providing FRR. Regarding FRR capacity reservation, some strategies give priority of downward reserve bids (more advantageous for WP) [17], offer a small FRR band compared to the WP capacity [18], assure a low percentage of FRR compliance [19] or operate under the maximum available power [20]. After the operation, while some researches do not analyze clearly the level of FRR compliance [21], other analyses result in high reserve penalties [17-19], or otherwise, achieve a high technical FRR reliability because wind forecast errors are not really considered in the case study [18,20].

In order to fulfill the identified gaps from a global perspective, this paper presents a joint optimal scheduling and operation of DM, CIM and FRR markets in the Spanish market for a wind plant with ESS, similarly as the previous study carried out by the same research group for a solar plant with ESS [22]. Although the main objective of the proposed EMS is to maximize benefits while reducing overall system costs, energy imbalances and reserve penalties are almost reduced to zero, in order to guarantee high technical reliability regarding market scheduling and reserve requirements.

As well as the uncertainty in renewable generation forecast, the AGC dispatch signal at real-time is so variable and uncertain to be predicted that important implications arise for the optimization technique and, even more, on the real-time operation strategy that should be applied. While most researches address this problem from a non-deterministic approach, this paper proposes a mixed integer linear programming to calculate optimal market bids (energy schedule and reserve capacity bids in both directions according to the TSO requirements). Moreover, a model predictive approach enables making decisions closer to the real-time plant operation in order to accommodate wind forecast errors. Furthermore, there are other aspects that are hardly analyzed, such as ESS acquisition, degradation and replacement costs [17-21]. These costs should be analyzed together with market revenues in order to justify economically the installation of ESS with WPs.

This paper addresses the joint operation of WP+ESS in multiple markets to increase the value of wind energy from an economic and technical point of view. On the one hand, the market optimization maximizes WP+ESS market revenues while reduces energy imbalances and considers overall ESS costs. On the other hand, a high compliance of FRR is achieved thanks to the CIM participation and real-time operation based on a Model Predictive Control (MPC) approach in order to calculate the final grid output at each time step by following the AGC dispatch signal; and being aware of the current State Of Charge (SOC) of the ESS, the most recent wind forecast, and real generation.

2. Energy Management Strategy

In this section the proposed EMS to participate in the market is described. This strategy is divided into several blocks, as can be observed in Figure 1: scenario and market definition, optimization process, ESS degradation analysis, real-time operation and techno-economic analysis.

In the scenario definition, main design and operation variables are defined, such as: wind generation profile, energy storage capacity, market prices data, investment, operation and maintenance costs of wind plant and storage system, several operating conditions and other design parameters.

The electricity market design for this study is based on the Iberian electricity market, composed by:

- Day-ahead Market (DM): This market is the main energy trading market to meet demand of the following day. In Iberian Market, the gate closure is at 12:00 of the day before and hourly energy products are remunerated at marginal price (€/MWh) through an auction.
- Continuous Intraday Market (CIM): This market allows updating the scheduling generation in DM with a closer closure time. In this study, CIM market will be modeled because hourly re-scheduling greatly improves forecast accuracy and reduces energy deviations. CIM energy bids at pay-as-bid price should be matched at least one hour before the delivery hour.
- Imbalance settlement (IB): In Spanish framework, two-price system is established for imbalance settlement. This financial settlement mechanism, calculated after the operation, aims to charge and/or pay power plants for the energy imbalances from DM+CIM schedule.
- Frequency Restoration Reserve (FRR): The auction, at 17:30 of the day before, consists of a price for capacity reservation (€/MW) and two prices for energy product in real-time operation (known as AGC signal) (€/MWh), concerning to upward and downward energy products respectively.

MPC is applied for the analysed horizon, with a time step of 15 minutes ($\Delta t = 0.25$). Each sample corresponds with the subscripts k. In this study, the simulation period is one year, although the optimization only covers is carried out independently for each day.

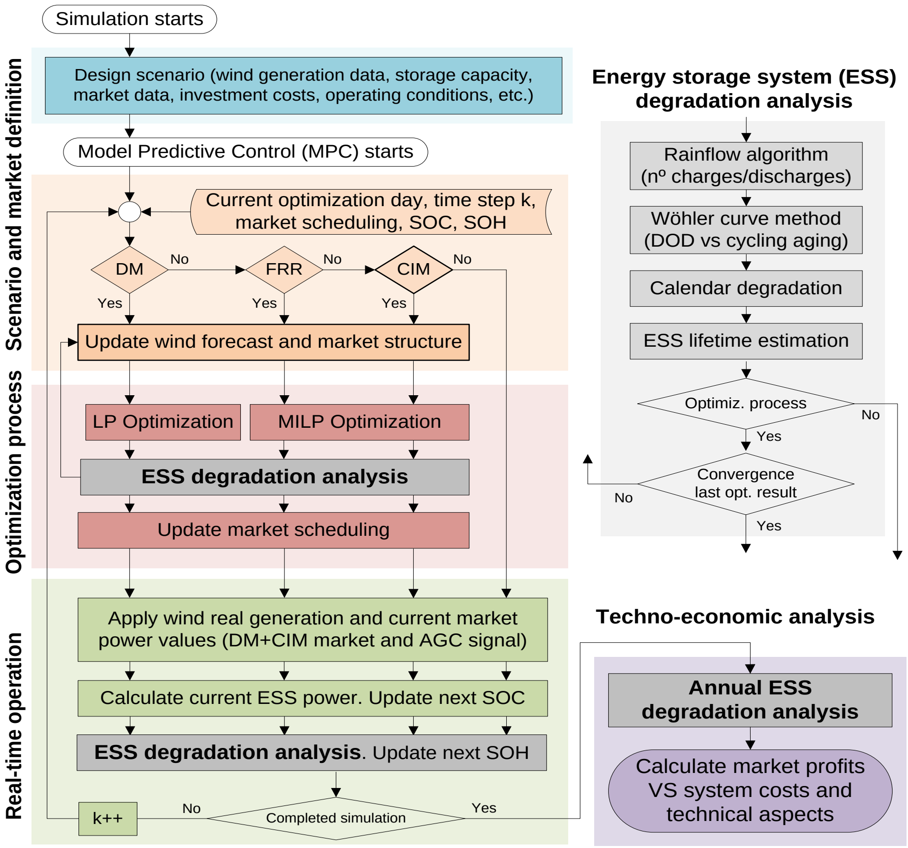


Figure 1. Proposed Energy Management Strategy.

After that, a market evaluation decides whether optimal market bids to DM, FRR or CIM can be calculated, or otherwise, real-time operation for next time step should be directly calculated.

Matlab software was used to model the entire EMS and carry out the simulation. In particular, *linprog* and *intlinprog* functions have been applied to calculate the optimal market operation. For DM optimization, a simplified linear model (LP) is applied, as described in [21], focused on DM profit maximization, including day-ahead generation forecast and hourly mean prices. By the time of FRR auction, the generation forecast improves and real daily DM prices are published. Taking advantage of this current information, a more complex objective function is maximized, through a Mix-Integer Linear Programming (MILP) optimization, described in (1). The first term considers converter and other installation costs (c^{MW}), battery system costs (c^{MWh}), converter power (P^{conv}), nominal ESS capacity (C^{ESS}) and their expected lifetime ($life^{conv}, life^{ESS}$). The second term controls the final daily energy value (E_{kend}^{ESS}) at the middle of the ESS capacity, increasing their weight in the objective function by the multiplier *M*. The third term calculates the hourly DM+CIM schedule (P_h^{mkt}) including estimated CIM prices (hourly prices to be highly matched under the pay-as-bid market process). The fourth and fifth terms minimize positive and negative energy imbalances (P_k^{imb+}, P_k^{imb-}) as much as possible, and only incurring them if the ESS is not able to operate and control the wind generation. The last three terms are related to the profits for hourly FRR capacity reservation band (P_h^{band}) and average upward/downward energy products, with their associated market prices (λ).

Apart from optimal market schedule, optimal daily ESS power and energy profiles (P_k^{ESS}, E_k^{ESS}) are calculated according to the operating limits and technical constraints including in the model.

$$max\begin{bmatrix} -(c^{MW}\cdot P^{conv}\,/life^{conv}+c^{ESS}\cdot C^{ESS}/life^{ESS})/365\ +M^3\cdot E_{kend}^{ESS} \\ +\Sigma_h\big(\,\lambda_h^{mkt}\cdot P_h^{mkt}\big)-M\cdot\Delta t\cdot\Sigma_k(\lambda_h^{imb+}\cdot P_k^{imb+}+\lambda_h^{imb-}\cdot P_k^{imb-}) \\ +\Sigma_h(\lambda_h^{band}\cdot P_h^{band}+\lambda_h^{uw}\cdot\bar{E}_h^{uw}-\lambda_h^{dw}\cdot\bar{E}_h^{dw}) \end{bmatrix}\ \forall k,h \tag{1}$$

In real-time operation, ESS energy profile (E_k^{ESS}) varies from the optimal value, in order to fulfill the most recent market schedule and AGC power signal (P_k^{AGC}), taking into account real wind generation (WP_k^{real}). Due to these unpredictable changes, optimal WP+ESS plant operation is recalculated in each successive CIM taking into account previous energy deviations thanks to MPC approach, in order to maintain the state of charge (SOC_k^{ESS}) within the operating limits (5-95%) as well as reducing energy imbalances and FRR penalties almost to zero, as discussed in Section 3.

Due to MPC approach, the first values of the market optimization are applied to calculate the final grid output (P_k^{grid}), the charge and discharge power (P_k^{ESS}) and the current state of charge (SOC_k^{ESS}) at each sample k, according to (2)-(3). The ESS operation differs from the optimal calculated one, because real wind generation (WP_k^{real}) and real-time AGC power signal (P_k^{AGC}) are finally applied.

$$P_k^{ESS}=WP_k^{real}-P_k^{grid}\ =\ WP_k^{real}-\big[\,P_k^{mkt}+P_k^{imb+}+P_k^{imb-}+P_k^{AGC}\,\big]\ \forall k=1 \tag{2}$$

$$SOC_k^{ESS}=[E_{k-1}^{ESS}+\Delta t\cdot(P_k^{ESS}\cdot(u_k\cdot\mu_{ch}+(1-u_k)/\mu_{dch})]\,/\,C^{ESS}\quad u_k=\{0,1\};\ \forall k=1 \tag{3}$$

After each market optimization and at the end of each day, an ESS degradation analysis is carried out. In regard to cycling degradation, Wöhler curve-based ageing models are applied to evaluate the degradation of the ESS regarding to the number of cycles at a certain Depth of Discharge (DOD). Secondly, a theoretical calendar ageing is added. And finally, the lifetime of the ESS ($life^{ESS}$) is calculated based on both aging models and this term is updated in the objective function.

Finally, an annual ESS degradation analysis is conducted. Moreover, annual market profits are calculated, and annualized WP+ESS costs are calculated in order to assess the profitability of the proposed WP+ESS plant. Furthermore, other technical aspects are analyzed, such as, the traded energy, the level of FRR compliance by following P_k^{AGC} and the Full Equivalent Cycles (FECs).

3. Techno-economic results

The proposed EMS of the WP+ESS plant was validated for one year in different cost scenarios shown in Table 1. This EMS is applied for an annual wind generation profile based on [23], with available day-ahead and intraday updated forecasts. This profile was scaled for a WP of 30 MW resulting in 2230 Equivalent Full-Load Hours which match properly with a great location in Spain. An ESS capacity between 0.21 and 0.54 $\mathrm{MWh_{ESS}}$ / $\mathrm{MW_{WP}}$ is considered for the sensitivity analysis. Spanish market prices for 2017 were used for this study case, downloaded from the Spanish system operator website [24]. Investment costs of WP are considered in €/MW [25]. Investment costs of the ESS [26-28] are considered based in energy and power terms: investment energy-related term (in €/MWh), investment power-related term (€/MW) and replacement energy term according to the number of replacements needed (n) during the lifetime of the WP, whose value will be reduced.

The joint operation of a single day is shown in Figure 2. As can be observed, DM schedule is calculated considering the DM forecast. During the day, an evaluation of the current SOC, AGC signal required up to that time, most recent updated forecast and expected CIM prices is made. Based on this real-time information, the MILP optimization recalculates the optimal DM+CIM schedule for current conditions according to the objective function in eq. (1). For this particular day, the ESS is not fully charged and discharged and it is able to control the grid output at all times. Therefore, output power (P_k^{grid}) is equal to DM+CIM scheduling plus the AGC signal required for FRR markets. The power difference between P_k^{grid} and WP_k^{real} is provided by the ESS, according to eq. (2)-(3).

In order to evaluate the profitability of the WP+ESS, different energy storage capacities have been selected to compare their annual market benefits and annualized net profits (market benefits minus the annualized WP+ESS costs according to Table 1). Figure 3 summarizes all these economic results, in which the BC corresponds to annualized net profits of a WP without ESS participating in DM+CIM market under WP costs (1.25 mill.€/MW) reported in [25].

Table 1. WP+ESS costs for different cost scenarios.

WP+ESS costs	Base Case (BC)	CS1	CS2
WP investment costs (mill. €/MW)	1.25	1	0.75
ESS inv. energy costs (mill. €/MWh)	0.4	0.3	0.2
ESS inv. power costs (mill. €/MW)	0.5	0.4	0.3
ESS replacement costs (mill.€/MWh)	$\Sigma_{\mathrm{r=1}}^{\mathrm{n}}\, c_{ESS}(1)\cdot[1-\left(0.8\cdot \mathrm{e}^{-0.11\cdot \mathrm{yr(r)}}+0.13\cdot \mathrm{e}^{0.017\cdot \mathrm{yr(r)}}\right)]$		

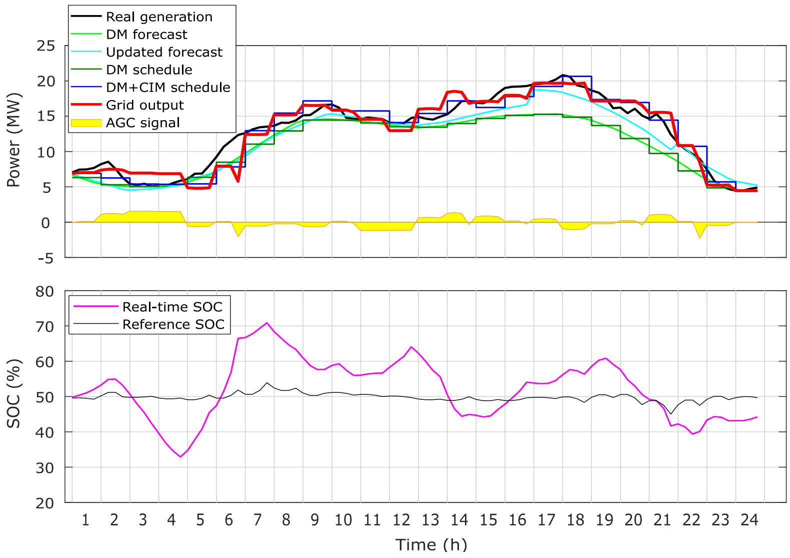


Figure 2. WP+ESS operation of a single day (30 MW and 0.54 MWh/MW).

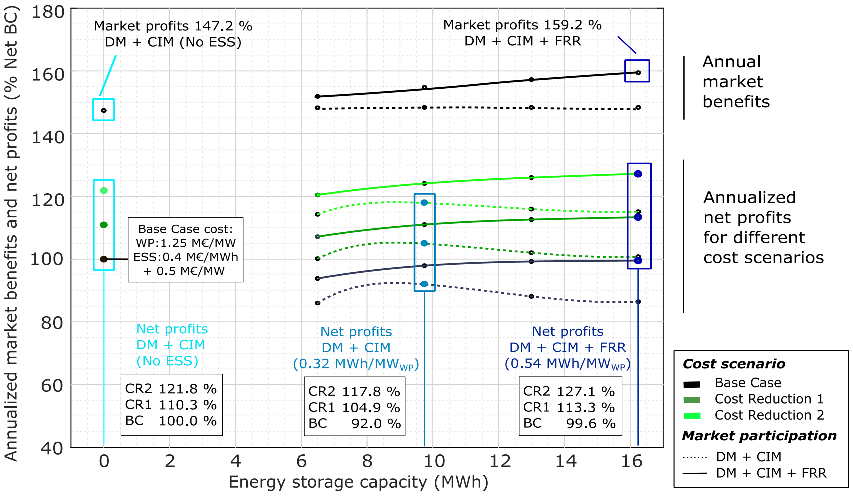


Figure 3. Annualized market profits and net profits (%) for a WP of 30 MW, considering different energy storage capacities (without ESS and 0.21-0.54 MWh/MW), considering two market participations (DM+CIM and DM+CIM+FRR) and three cost scenarios (CS).

On the one hand, the profitability of the WP+ESS under current cost scenario will be analyzed. Based on a 100% of net profits for the BC, additional costs of ESS for the DM+CIM participation are higher than annual market benefits obtained from the reduction of annual energy imbalances costs. For the optimal ESS sizing (0.32 MWh/MW, 9.75 MWh), net profits for this market participation (black dotted curve) are reduced 8% respect to the BC without ESS. In case of FRR participation, the optimal ESS capacity increases up to 0.54 MWh/MW (16.25 MWh). Net profits with this ESS sizing (99.6%) reach nearly the BC without ESS (100%), because annual market profits increase by 12% thanks to the proportional increment of capacity reservation in the FRR auction.

However, the Spanish WPs nowadays participate mainly in IM auctions every 4/6 hours, and therefore, their energy imbalances costs are quite higher than the ones obtained in this analysis. Thus, their current net profits could be less than the obtained ones with a DM+CIM+FRR participation.

On the other hand, if a reduction of considered WP and ESS costs (green curves), the economic results show that the joint operation of a WP+ESS will be more profitable than a WP without ESS when FRR is contemplated. In order to assure a more valuable option than without ESS, the minimum ESS capacity that should be installed will be 10 MWh in case of CR1 scenario and 7.5 MWh in case of CR2 scenario. The trends reveal that the best ESS capacity would be 16.25 MWh.

Focusing on all terms that composed net profits, they could be divided into benefits and/or costs related to: DM, CIM, imbalances, FRR band availability, upward AGC signal, downward AGC signal, AGC penalty, WP investment, ESS energy term (investment and replacements) and ESS power term.

The three optimal choices drawn from Figure 3 are compared below. As can be concluded from Figure 4, the usage of CIM increases when ESS is installed, because wind forecast errors are absorbed by the ESS, and then, this energy is shifted in the coming hours through higher CIM bids. Moreover, positive and negative imbalances terms are reduced hugely. Especially, energy imbalances are practically zero for DM+CIM+FRR participation with an ESS of 16.25 MWh.

Moreover, the FRR participation increases benefits by 10.65% for band availability, 5.22% for upward AGC signal, -2.66% for downward AGC signal and -0.006% for AGC penalty. On the contrary, ESS investment and replacement costs increase annualized costs by 7.57% for energy terms plus 4.88% for power terms, according to the third WP+ESS plant (darker bar) in Figure 4.

Annual traded energy with respect to the annual wind generation is analyzed in Figure 5, with similar conclusions drawn from Figure 4. As can be observed, the energy traded in DM corresponds mostly to the DM forecast, and the SOC initial values. Regarding energy imbalances, they are reduced significantly as the ESS sizing increases. Furthermore, the CIM participation increases in order to

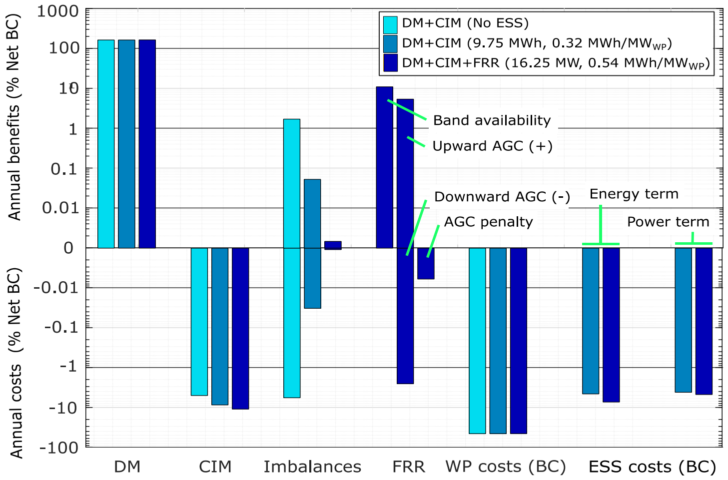
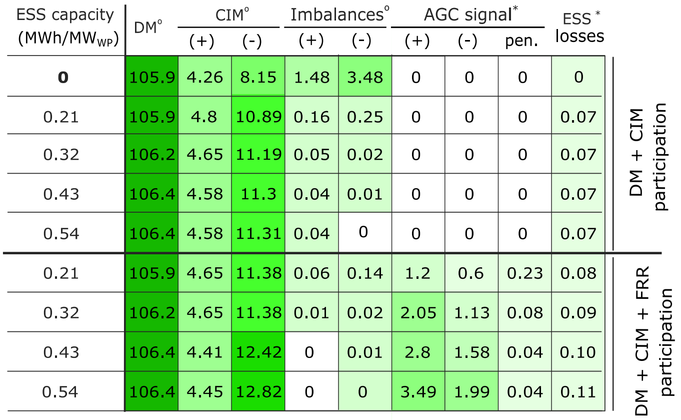


Figure 4. Annual benefits and costs of the three optimal plants under the Base Case cost scenario: 1) DM+CIM without ESS, 2) DM+CIM with 0.32 MWh/MW, 3) DM+CIM+FRR with 0.54 MWh/MW.



ESS capacity (MWh/MW$_{WP}$)	DM°	CIM°		Imbalances°		AGC signal*			ESS* losses	
		(+)	(-)	(+)	(-)	(+)	(-)	pen.		
0	105.9	4.26	8.15	1.48	3.48	0	0	0	0	DM + CIM participation
0.21	105.9	4.8	10.89	0.16	0.25	0	0	0	0.07	
0.32	106.2	4.65	11.19	0.05	0.02	0	0	0	0.07	
0.43	106.4	4.58	11.3	0.04	0.01	0	0	0	0.07	
0.54	106.4	4.58	11.31	0.04	0	0	0	0	0.07	
0.21	105.9	4.65	11.38	0.06	0.14	1.2	0.6	0.23	0.08	DM + CIM + FRR participation
0.32	106.2	4.65	11.38	0.01	0.02	2.05	1.13	0.08	0.09	
0.43	106.4	4.41	12.42	0	0.01	2.8	1.58	0.04	0.10	
0.54	106.4	4.45	12.82	0	0	3.49	1.99	0.04	0.11	

Resolution: ° Hourly net value, * For all simulation steps

Figure 5. Annual traded energy with respect to the annual wind generation (%)

manage hourly net imbalances from forecast errors, and real-time AGC power signal. Concerning FRR service, the hourly available FRR band and the energy delivered through the AGC signal increase proportionally to the ESS capacity, because the maximum hourly band is limited up to 20% of the C^{ESS}. As can be observed, AGC penalties are also reduced in energy terms when more ESS capacity is installed. Finally, ESS losses are calculated based on the ESS power profile applying the ESS efficiency considering all the conversion stages related to the energy storage system.

Other technical aspects that should be discussed are related to the ESS operation and the level of compliance of FRR service. Regarding annual Full Equivalent Cycles, FECs are reduced when ESS size is larger. In case of FRR participation, annual FECs increase due to a more demanding operation in order to follow AGC signal in real-time operation. Thus, annual FECs result from 501 FECs (0.21 MWh/MW) to 281 FECs (0.54 MWh/MW). According to these annual FECs, the lifetime of the ESS could be estimated between 8.6 years -181 FECs- and 13.3 years -501 FECs-, by applying Wöhler curve method and limiting the calendar lifetime up to 15 years. This means that one or two ESS replacements will be made during the WP lifetime depending of the ESS sizing.

Finally, the technical reliability of FRR participation is worth analyzing. Other studies are not focused on this parameter, while other ones address it [17-19] but not to the point that the power quality standards need. The developed EMS enables a huge reduction of energy imbalances and

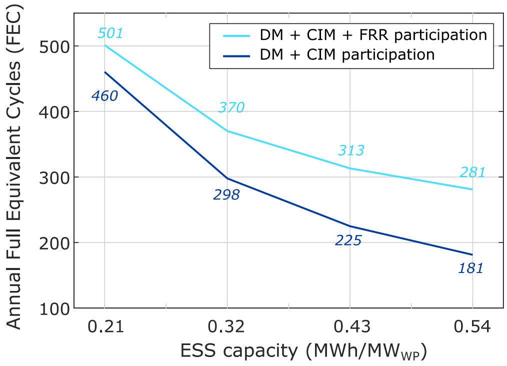


Figure 6. Annual Full Equivalent Cycles for each market participation and ESS capacity.

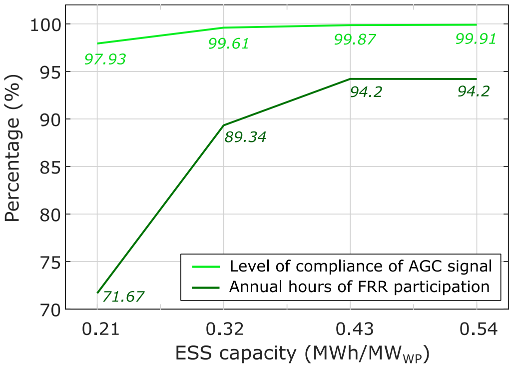


Figure 7. Level of compliance of AGC signal and annual hours of FRR participation.

achieves a high technical reliability of upward and downward FRR needs (from 97.9 % up to 99.9%).

Moreover, the daily number of hours of FRR participation increase with the ESS size, taking into account that an hourly minimum band must be 1 MW and a maximum band is limited up to 20% of the ESS capacity. Moreover, the WP+ESS plant participates daily a maximum of 23 hours, because the last hour is destined by design to manage the final daily SOC at the middle value. Thus, the mean daily hours increase from 17.2 h (with 6.5 MWh) to 22.6 h (with 13.25 MWh).

4. Conclusion

As can be concluded from the above results, this optimal EMS addresses the wind integration challenge to a great extent in the grid and in the electricity market. Through a MILP optimization, the daily DM+CIM schedule and hourly bands for FRR service are calculated in order to maximize the overall market benefits, taking into account the lifetime of the ESS and their associated costs. Moreover, the implementation of MPC approach enables the avoidance of annual energy imbalances and achieves a high technical reliability of FRR needs (up to 99.9%) with an ESS sizing of 0.54MWh per MW of wind power capacity installed for the study case. This analysis calculates the ESS degradation according to the annual resultant operation of the ESS.

This fact results in less annual Full Equivalent Cycles for higher ESS sizing and only one ESS replacement in the twelfth year. Therefore, the additional increase in market benefits due to the FRR participation results in more annualized net profits, compensating the incremental ESS costs. In the considered scenarios, under a light reduction of these ESS costs (corresponding to the CR1 or CR2), the joint operation of a WP+ESS plant could be more profitable than a WP without ESS. These obtained economic results are simulated and validated based on Spanish market framework and market prices of 2017, and under no feed-in-tariff scheme. Therefore, this EMS enables a high replicability to evaluate the WP+ESS cost-effectiveness under other markets, prices and wind profiles.

Acknowledgments

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