Participation of wind power producers in day-ahead and balancing markets: An overview and a simulation-based study

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At present, a harmonized pan-European electricity market (EM) is a close reality. While in day-ahead markets (DAMs) the harmonization is at an advanced stage, in balancing markets (BMs) still exist some challenging issues, notably the remuneration of imbalances: some countries have simple and clear methods, but others consider complex methods that are not appealing to the participation of variable renewable energy (VRE). The participation of VRE in BMs is technically feasible, although with some restrictions to guarantee security and stability. Thus the economic attractiveness of these markets should be increased in order to enable full integration of VRE without feed-in-tariffs or other incentives. This article presents an overview of EMs, focusing on European BMs, and also investigates the benefits of the participation of wind power producers (WPPs) in BMs at both economic and technical levels. In particular, the article presents a new strategy allowing WPPs to bid in BMs. It also presents a study involving four scenarios, where WPPs participate in: (a) the DAM (baseline scenario), (b) the DAM and the automatic-activated frequency restoration reserve market, (c) the DAM and the manually activated FRR (mFRR) market, and (d) the DAM and a 15-min mFRR market. The simulations are performed with the agent-based system MATREM (for Multi-Agent TRading in EMs). For the last scenario, the results indicate an increase around 6% in the wind energy value to the market, a decrease of 12% in the total reserve used, and a decrease around 16% in the costs from the BM.

This article is categorized under:
- Wind Power > Systems and Infrastructure
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KEYWORDS
agent-based system, balancing markets, simulation-based study, strategic bidding, wind power producers

1 INTRODUCTION

The share of variable renewable energy (VRE) in power supply systems is progressively increasing, while the share of conventional generation is decreasing. To ensure that the power supply continue functioning reliably and in a cost-effective way, electricity markets (EMs) should be adapted to this new paradigm (e.g., Lopes & Coelho, 2018a). Contrary to conventional generation, appropriately designed to control the power output, VRE units are nondispatchable and dependent of stochastic weather conditions. Since these conditions can be forecasted, the possible contributions from VRE can be considered schedulable, although with uncertainties associated with forecast errors. In order to minimize such uncertainties, the input of VRE should be scheduled as close as possible to real-time operation.
The current EMs were not designed to receive high shares of VRE, and thus should be analyzed and adjusted to deal with the variability of stochastic sources, in order to avoid the payment of balancing services, typically at high costs (Holttinen et al., 2012). The harmonization of European EMs, which is already progressing, should be promoted to minimize costs and ensure fair conditions to market participants (Stoerring, 2016). In 2017, the European Commission (EC) presented a new proposal for regulating the European Internal Market of Electricity (EC, 2017a).

Regarding the day-ahead markets (DAMs), the next step of the harmonization is probably to shorten the trading periods (EC, 2014). Also, sloping schedules (instead of flat) could be used to avoid the need of balancing reserves (Brauns et al., 2014). And a major challenge for the design of future DAMs is to hedge tail risks, ensuring a power capacity adequacy. Existing or new market products can serve as an example for this purpose. In the intraday markets (IDMs), there are still some issues to be addressed in order to achieve a full harmonization, namely the time unit (between 15 min and 1 hr), the gate closure (between 5 min and 3 hr), the market coupling (only possible in few countries) and the trading type (continuous or not) (ACER, 2017).

For balancing markets1 (BMs), a pan-European harmonization is still in its infancy. Currently, only Norway, Sweden, Finland, and Denmark have a common manually activated frequency restoration reserve (mFRR) market. This lack of harmonization is due to the importance of BMs for a secure and stable operation of the National electricity grids, the necessity of interventions by transmission system operators (TSOs), and also because of the differences between the adopted schemes for procuring balancing energy in both automatic-activated FRR (aFRR) and mFRR markets in Europe (Morch et al., 2016). The European Network of Transmission System Operators for Electricity (ENTSO-E) has already elaborated a definition of product requirements and a set of rules for a cross-border market for BMs. However, it is necessary to uniform some aspects, such as bidding times, tendering and remuneration rules, and minimum bid sizes (EC, 2017a; ENTSO-E, 2014).

There is a growing literature on the participation of VRE in BMs. Such participation may increase the economic value of wind2 and decrease both the market prices and the needs of BMs (e.g., Mills & Wiser, 2014). In this way, and although with some restrictions, Spain (Martín-Martínez, Lorenzo-Bonache, Honrubia-Escribano, Cañas-Carretón, & Gómez-Lázaro, 2018), Germany (Ocker & Ehrhart, 2017), and Denmark (Sorknaes, Andersen, Tang, & Strøm, 2013) have already allowed the participation of wind power producers (WPPs) in the mFRR market.

The next sections present an overview of the participation of VRE in BMs, analyze the technical feasibility of the participation of WPPs in BMs, and propose a new strategy for WPPs bidding in BMs. Additionally, they present a simulation-based study on the participation of WPPs in both the DAM and the BM and discuss the results obtained.

2 | EUROPEAN ELECTRICITY MARKETS: CHARACTERISTICS AND RULES

This section describes some key features of the main European markets and some important aspects related to the evolution of the European EMs toward a pan-European market.

2.1 | Day-ahead and IDM

With the harmonization, the European DAMs close at 12:00 p.m. (CET time), 12–37 hr before the physical delivery. The trading is based on an implicit auction, where price and quantity are calculated during day \((d)\) before the day of operation \((d + 1)\), using a hybrid algorithm called Euphemia (Sleisz, Sores, & Raisz, 2014). The auction is based on simple and complex bids from producers and consumers, and takes into account physical constraints of cross-zonal capacity (Frontier Economics, 2007). By setting prices and quantities for each bidding zone, the auction also defines the schedules between bidding zones. TSOs rely on the market clearing results to plan the day of operation. IDMs may involve auctions close to real-time (2–3 hr), or operate continuously, typically using the pay-as-bid as the pricing method.

2.2 | Balancing markets

The deviations from the schedules of DAMs and IDMs need to be compensated in BMs, involving the payment of imbalance prices (or penalties). Clearly, the process for determining imbalance prices differs from market to market, varying from a simple and clear method (in the Nordic countries) to a complex method (in Portugal and Germany) (e.g., Holttinen et al., 2016). To envisage a pan-European BM, with clear rules for all power producers, where WPPs pay for their deviations, a clear and general method should be adopted (Morch et al., 2016).3

In most European power systems, the frequency reserves are classified as follows (EC, 2017b):

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1. Balance markets
2. Wind power
3. References
Frequency controlled reserve (FCR) or primary control reserve; aFRR, secondary reserve or fast active disturbance reserve; and mFRR, tertiary reserve or slow active disturbance reserve.

The control reserve services are mandatory and imposed by ENTSO-E. Operationally, each TSO has the responsibility of guaranteeing the power reserve values for these services within the control zone, based on ENTSO-E requirements. Table 1 summarizes the most important characteristics of the three types of control reserve. FCR is the first to be activated, after grid disturbances, incidents, or imbalances between production and consumption, that results in a frequency deviation in relation to the programmed value (50 Hz for the European grid). It should be activated up to 15 s (maximum) and the disturbances need to be controlled in seconds (normally 30 s). FCR is a mandatory and non-remunerated system service for all generators connected to the grid, or that influence it, and who have technical capability for a fast response. The allocated generators need to provide 5% of their nominal power in stable conditions. Currently, this service is mainly supported by hydropower generation (Hirth & Ziegenhagen, 2015).

aFRR should be activated up to 30 s (maximum), taking up to 15 min to be finalized, replacing FCR. It also restores the grid frequency to the programmed value. Taking into account the programmed size of aFRR (power band), the TSO defines the needs for every hour.

mFRR is primarily used to free up and/or complement aFRR. The TSO is responsible to activate this reserve, which allows to solve long-term active-power deviations, by implying changes in the following (ACER, 2017): (a) generation or load on a contractual market or regulatory basis (depending on the different schemes used for procuring balancing energy activated from mFRR) and (b) the generation/load schedule. It should be fully activated within 15 min and can continue active for a long period of time (hours), freeing up the FCR and aFRR. TSOs define the needs of mFRR (capacity) based on the deviations that both FCR and aFRR cannot deal with.

In the aFRR and mFRR products, TSOs typically define schedules for blocks of 15 min. In the corresponding markets, an auction for every hour of the day (or blocks of various hours) is carried out, and the technically capable generators are allowed to make bids. The auction criterion aims to determine the lowest capacity price (aFRR market) and the lowest energy price (mFRR market), based on marginal pricing, pay-as-bid or other pricing methods.

### TABLE 1 Comparison of the most typical types of balancing control options

| Key characteristics | FCR | aFRR | mFRR |
|---------------------|-----|------|------|
| Target              | Frequency | Area control error and frequency | Current and expected level of aFRR activation |
| Minimum offer       | ±1 MW | 5 MW | 5 MW |
| Activation          | Decentralized via frequency measurement | Centralized (TSO); IT* signal (automatic gain control) | Centralized (TSO); phone/IT* signal |
| Activation speed    | 15 s | 30 s | 15 min |
| Response time       | 30 s | 15 min or less; direct | Hours or less; direct or scheduled |
| Typical suppliers   | Synchronized generators, (large consumers) | Synchronized generators, stand-by hydro plants, large consumers | Synchronized and fast-starting stand-by generators, large consumers |
| System              | ENTSO-E | ENTSO-E and balancing area | ENTSO-E and balancing area |
| Reserved capacity   | 3,000 MW (Europe) | Determined by national TSOs | Determined by national TSOs |

*IT (Information Technology).

3 | PARTICIPATION OF WIND POWER IN BMS

This section discusses the participation of WPPs in BMs. It analyses the operational capabilities of WPPs to support the frequency support provision. Also, it describes the current status of key European countries in relation to that participation.

3.1 | Operational capability: Analysis and discussion

Currently, WPPs respond to curtailment requests of TSOs according to the ramp rates given in the Network Codes of each TSO. As an example, consider the following possibilities of active power curtailment (EirGrid, 2013):

- Germany, with a ramp rate of 10% of grid connection capacity per minute.
- Ireland, with a ramp rate of 1–30 MW per minute.
- Nordic Grid Code, with a ramp rate of 10% of the rated power per minute.
- Denmark, with a ramp rate of 10–100% of the rated power per minute.
Accordingly, various control methods can be used to provide very fast responses. Notice that such responses are limited by the rate of changing the thresholds of reference power (the electrical torque, which is typically 0.4–0.6 p.u., according to the wind turbine size and type) (Walling, Gursoy, & English, 2011). Furthermore, as discussed by Attya, Domínguez-García, and Anaya-Lara (2017), the different time responses from each control method may have a strong impact on the dynamics of the power system frequency.

There are four key approaches involving different control methods to secure a power surge (overpower) from a wind turbine during frequency deviations (Attya et al., 2017): (a) the kinetic energy extraction, (b) the over-speeding, (c) the balance de-loading, and (d) the delta-de-loading.

Despite the existence of different approaches, the capability of WPPs to provide balancing services is strongly related to the accuracy of wind power forecasts (Mørch et al., 2016). Also, it is clear that WPPs should meet set-points as precisely as possible, and also react to changes of set-point as quickly as possible. Therefore, in the new paradigm of WPPs participating in BMs, WPPs may need to follow a schedule (involving all energy traded in both spot and bilateral markets). They should be able to respond to short-run variations of the schedules requested by TSOs. Brauns et al. (2014) showed that WPPs can accomplish schedules. The authors performed a test where a particular WPP reduces around 70% of the optimal production to comply with a specific schedule, taking about 15 s to accomplish it. This situation leads to a reduction of market prices, but also to a large quantity of wasted energy concerning the available resources. So, to avoid wasting energy, WPPs should submit aggregated bids in BMs, as in Spain (Martín-Martínez et al., 2018), or consider bids aggregated with conventional generation, as in Denmark (Energinet, 2017), or even provide a maximum of 70% of their installed capacity for downward regulation, as in Germany (50Hertz, 2016).

Martín-Martínez et al. (2018) concluded that the provision of upward regulation can be possible in case of forecast errors, when the real-time expected production is higher than the performed bids, or also where VPPs perform voluntary bids below forecasts. This can also be possible by overloading wind turbines, that is, by forcing their inertia moment to generate extra energy (Shang, Hu, Yuan, & Chi, 2017). However, in case of wind falls, WPPs may not be able to guarantee the security of the system and need to perform aggregated bids with conventional generation (Energinet, 2017).

Over the long-term, when VRE and conventional generation follow the same rules, unit commitment and aggregation should be important aspects to avoid the payment of penalties. The analysis of some prominent studies about these topics follows.

Banshwar, Sharma, Sood, and Shrivastava (2017a) demonstrated how VRE can participate in BMs in a test system with seven different generators (thermal, hydro, wind, and PV). The authors considered a sequential clearing of spot markets and BMs, concluding that the integration of VRE results in cost savings and feasible solutions in both markets. Banshwar, Sharma, Sood, and Shrivastava (2017b) presented a review about the participation of VRE in ancillary services, concluding that WPPs are technically competitive in providing services like operating reserves, regulation, and voltage support, but have difficulties to provide other services, such as “load following” and “black start”.

Hansen, Altin, and Iov (2016) tested the support of aggregated WPPs to temporary frequency response (inertial response and FCR), and to power oscillation damping (damps of the low-frequency oscillations), concluding that WPPs exhibit technical capabilities to provide such services. However, in situations involving high shares of wind power, the frequency is potentially degraded, and WPPs need to be supported by conventional generation.

Regarding the economic and welfare benefits, the participation of VRE in BMs was studied by an increasing number of researchers. For instance, Kiviliouma et al. (2014) studied the benefits for Portugal and Spain, Ireland, and Europe (EU-28 plus Norway and Switzerland), by considering three scenarios involving different levels of VRE share: scenario A (32%), scenario B (42%), and scenario C (50%). For Portugal and Spain, the benefits—that is, the decrease in annual costs—range between 1% in scenario A and 8% in scenario C. For Ireland the benefits range between 8% and 12%. For Europe, the benefits range between 1 and 6%. For the particular case of scenario B, the results for Portugal and Spain indicate the following shares of VRE: 5.4% in upward FCR, 90% in downward FCR, and 12.5% in aFRR. For Europe, the shares of VRE are as follows: 4% in upward FCR, 34% in downward FCR, and 12% in aFRR. Accordingly, for Portugal and Spain, 42% of VRE share can be considered appropriate (to a certain extent) to surpass the downward needs of FCR, while in Europe such share can be considered insufficient. EC (2016) also analyzed the reduction of the total reserve costs in the European Union (EU-28) by considering solar and other renewable energy sources, reaching a reduction of 6% in the cost of BMs.

To conclude our analysis of the literature, it is worth noting that most researchers are addressing important issues associated with the participation of VRE in BMs (e.g., Fernandes, Frias, & Reneses, 2016). However, the majority of them focus on the reduction of the costs of the system and the share of VRE in BMs. In this work, we also focus on the following four key dependent variables: the value of wind energy to the market, the system imbalances, the costs associated with BMs, and the total cost of the system.
3.2 | Current status of key European countries

In 2016, Spain has become pioneer in relation to the participation of WPPs in BMs, by allowing the participation of aggregated WPPs in both the mFRR market and the imbalance management (IM) (Fernandes et al., 2016). In 2017, more than 50% of the Spanish WPPs may participate in these two markets, with a share of 6% for downward regulation, 2.6% for upward regulation, and 0.7% for the IM (Martín-Martínez et al., 2018).

In Germany, two wind farms (86 MW of installed capacity) were prequalified to provide up to 70% of their installed capacity to the downward mFRR market (50Hertz, 2016). Hirth and Ziegenhagen (2015) estimated that WPPs may surpass 90% of the German downward regulation needs, in case they participate in BMs only. However, this result is reduced to 10%, in case WPPs participate in both the DAM and BMs. Papaefthymiou et al. (2015) studied the impact of alternative market designs in cost savings, using real data from 2013, and considering that German offshore WPPs may participate in the downward mFRR market. In a reference scenario (corresponding to 0.6 GW of installed capacity), such participation can bring cost savings of 0.7%. In other two scenarios, specifically a scenario of 11 GW (approved capacity) and a scenario of 30 GW (capacity to be approved), the cost savings were 20 and 18%, respectively. The improvements (in relation to the reference scenario) are as follows: (a) a cost saving around 49%, in case of no reaction of markets to the new offshore WPPs and (b) a cost saving of 33% (30 GW scenario), in case of the implementation of weekend tenders of offshore wind. A change of the product time, from 4 hr to 1 hr, is only beneficial for large shares of offshore wind power. In relation to the reference scenario, higher feed-in-tariffs are not beneficial for a very high installed capacity of offshore WPPs (30 GW). Also, an increase in the capacity procurement brings lower benefits. Lorenz and Gerbaulet (2017) simulated the participation of WPPs in the aFRR and mFRR markets in the German electricity system of 2025. The authors concluded that the costs of BMs can be reduced in 40% (in case of a wind power share of 10% in both the aFRR and the downward mFRR).

Denmark has also allowed the participation of WPPs in the downward mFRR market. However, WPPs need to submit bids together with conventional generation to guarantee the supply, when wind turbines are unable to deliver the required performance, due to failing wind (EMD, 2012; Sorknaes et al., 2013). EMD (2012) and Sorknaes et al. (2013) performed tests where WPPs with an installed capacity of 21 MW can make bids for downward regulation in Denmark (on February 14, 2012, at 0:00 p.m.). The results of the former study indicated an increase in the wind energy value of 173%, while for the latter study such increase was 196%. Also, the latter study involved the offer of downward regulation by WPPs during the first 9 months of 2010, resulting in an increase of 8.5% in the wind energy value. Skytte and Bobo (2018) studied the different degrees of active participation of a WPP with 15 MW in both the Danish day-ahead and BMs, during the year 2014, by considering four scenarios: (a) a single-stage offering strategy (reference scenario, where the participation in the DAM is based on wind power forecasts only), (b) a single-stage offering strategy (bids based on both wind power forecasts and prices of BMs), (c) a two-stage offering strategy (strategic bidding on both the DAM and BMs), and (d) a deterministic two-stage offering strategy (bids based on both perfect information of production and market prices). The authors concluded that the strategic bidding of WPPs increases the wind power imbalances in relation to the bids in the DAM, but also increases the wind energy value in relation to the reference scenario, namely 1.5% (second scenario), 4.5% (third scenario), and 7.5% (fourth scenario).

Great Britain allowed WPPs to participate in two curtailment products (a balancing service different from BMs): “Manage Constraint” and “Rebalance System,” receiving 40% more money to cut energy than to produce it (National Grid, 2018). In Ireland, WPPs can participate in similar products: “Constraints” and “Curtailments.” In Denmark, Germany, Italy, Portugal, and Spain, WPPs can also be compensated for curtailments (WindEurope, 2016). In Belgium, a study for the specific case of the downward aFRR market obtained a reliability above 90% (WindVision et al., 2015).

4 | STRATEGIC BIDDING IN BMs

WPPs can adopt a strategy that optimizes the use of wind power, increasing their revenue and avoiding large quantities of wasted energy. Bidding the deviations from the DAM commitments in the mFRR market at 0 €/MWh (for “upward regulation”), and the DAM price (for “downward regulation”), receiving/paying the clearing price, may represent an adequate solution to avoid the payment of penalties. However, WPPs can probably obtain a better remuneration by considering the aFRR market, namely by bidding their short-run capacity at 0 €/MW and receiving the market price, despite a higher probability to waste more energy or even to slightly decrease imbalances. 5

The resulting strategy is based on the optimal use of the resources of WPPs, with the goal of being the first to buy or sell in a market base (as in the DAM). So, in case of large deviations from the DAM schedule, it can be favorable to bid deviations in the mFRR market. This behavior consists in a nonstrategic provision of regulating power (WPPs only benefit from better production forecasts, not from market price forecasts), the second degree of the active participation of WPPs in the markets (e.g., Skytte & Bobo, 2018). WPPs can only make bids in BMs if they maintain a stable operation (i.e., keep a stable
power requested by TSOs). In other words, WPPs can only make bids if they deviate in a specific direction during a particular hour, for the specific case of the mFRR market (and in case of up deviations, for the aFRR market as well). Furthermore, they may bid either the lowest 15-min deviation (for the case of up deviations) or a higher deviation (for the mFRR market only). This option is similar to the German case, where WPPs are limited to offer a maximum of 70% of their installed capacity to downward regulation (50Hertz, 2016). For a possible 15-min mFRR market, WPPs do not need to address such issues, since their production uncertainty decreases with a reduction of the market time unit, increasing their potential to support BMs (see Figure 1).

5 WIND POWER PARTICIPATION IN BMs: A SIMULATION-BASED STUDY

This section begins by presenting an overview of the MATREM system. Next, it describes a study aiming at investigating the operation of WPPs to satisfy the needs of BMs. The simulations involve the DAM as well as the aFRR and mFRR markets. The section closes by presenting and discussing the experimental results in detail.

5.1 MATREM: An agent-based simulation tool for electricity markets

MATREM (for Multi-Agent TRading in Electricity Markets) allows the user to conduct a wide range of simulations regarding the behavior of EMs under a variety of conditions (Lopes, 2018; Lopes & Coelho, 2018b). In each simulation, different agents are used to capture the heterogeneity of restructured markets, notably generating companies, retailers, aggregators, large and small consumers, market operators, and system operators (e.g., Algarvio et al., 2016; Lopes, Algarvio, & Santana, 2017). The agents are essentially computer systems capable of flexible action and able to interact with other agents to meet their design objectives. A graphical interface allows the user to specify and monitor all simulations.

MATREM supports a DAM and a shorter-term market known as IDM. Supply bids and demand offers are aggregated to find a clearing price at which supply and demand are equal (e.g., Lopes et al., 2017; Lopes & Algarvio, 2018). MATREM is also able to simulate BMs. The system operator defines the needs of these markets and the agents may submit orders to buy or sell energy.

5.2 Methodology and data

The study involves the simulation of both the daily Iberian market prices and the BM prices during the period 2009–2010. In this period, 31 representative days are statistically selected based on a K-medoids clustering algorithm (Park & Jun, 2009).
Specifically, the clustering algorithm is used to identify the representative wind power daily profiles based on the observed data. For each representative day, the algorithm is then applied to identify typical daily forecast errors from the bids of the DAM (Ramos, Duarte, Soares, Vale, & Duarte, 2012).

The average share of wind power in Portugal was 16% during the period of the study. The following sources of data are considered in the analysis: (a) hourly prices and quantities submitted to the daily Iberian market (OMIE, 2018), (b) hourly prices and quantities submitted to the Portuguese BM (data reported by REN, the Portuguese electrical grid), (c) hourly requirements of aFRR and mFRR, and (d) hourly imbalances and prices of the imbalances (REN, 2018).

The analysis is carried out using the MATREM system. The agents are 20 producers (representing the supply-side) and four retailers (representing the demand-side). Several key features of the producer agents are shown in Table 2, including the maximum capacity of producer P1, the wind aggregator of WPPs, and its bid price (to submit to the simulated DAM). The wind power generation data was achieved from a set of eight distributed WPPs situated in Portugal (involving the installed capacity of 249 MW, around 10% of the Portuguese installed capacity). To get meaningful results, the data is scaled to 2,490 MW (of installed capacity), by multiplying all values by a constant factor. The forecasts (time horizon from 18 to 42 hr) are obtained by using the K-nearest neighbor methodology (Couto, Rodrigues, Costa, Silva, & Estanqueiro, 2016). The normalized root mean square error of the forecasts is around 17%.

The study accounts for the statistical distribution of seven typical power profiles:

- Profile 1: 68 occurrences (9.5%).
- Profile 2: 93 occurrences (13.1%).
- Profile 3: 63 occurrences (8.8%).
- Profile 4: 74 occurrences (10.4%).
- Profile 5: 165 occurrences (23.1%).
- Profile 6: 124 occurrences (17.3%).
- Profile 7: 128 occurrences (17.9%).

Each profile involves three to six typical deviation patterns (forecast errors) in relation to the bids submitted to the DAM, resulting in 31 representative days (see Figure 2).

The daily Iberian market and the Portuguese BM are simulated by using the MATREM system. Due to interconnection constraints observed in the electricity transactions between Portugal and Spain, in the hours that the clearing point results in a violation of such constraints, a market splitting mechanism is considered, meaning that the DAM is simulated for Portugal only.

Due to technical reasons in the Portuguese aFRR market, every producer needs to bid half of their upward capacity as downward capacity. Since aFRR is more requested for upward regulation, the system requirements for upward capacity are twice the requirements for downward capacity. Also, we consider that agents P1, and P10 to P14 submit bids to the BM. The biding process of agent P1 involves basically the following three steps (see also Figure 1):

1. Submission of (forecast) bids to the DAM, individually for each WPP_i.
2. Determination of the expected 15-min deviations of each WPP_i.
3. For each WPPᵢ, submission of bids to the BM (only for WPPs that maintain a stable power).

Figures 3 and 4 present an example for a particular day of operation (April 8, 2010), placing emphasis on WPP₁. In particular, Figure 3 depicts the bids submitted to the DAM and the sum of the expected individual deviations. Figure 4 depicts the 15-min deviations. In Figure 4a, there are no bids to the aFRR and mFRR markets, while for the 15-min mFRR market the four pairs of the type (power, price) are as follows: (−7.1, 35), (8.3, 0), (21.3, 0), (124.1, 0). In Figure 4b, the bids are the lowest deviation (99.9 MW) for the mFRR market and a power band between −49.9 and 99.9 MW for the aFRR market, with a
price equal to 0 €/MWh, while for the 15-min mFRR market the quantity submitted is exactly the 15-min deviations of each 15-min block with a price equal to 0 €/MWh. In Figure 4c, the bids are the highest deviation (−67.2 MW) for the mFRR market with a price equal to the DAM price (43.0 €/MWh). There is no bid to the aFRR market and the power bids for the 15-min mFRR market are the 15-min deviations with a price of 43.0 €/MWh (the DAM Price).

For each hour of every representative day, all technically capable agents can participate in both the DAM and the BM. The study involves four scenarios:

- **Baseline scenario**: agent P₁ participates in the DAM only.
- **Scenario A**: P₁ participates in both the DAM and the aFRR market.
- **Scenario B**: P₁ participates in both the DAM and the mFRR market.
- **Scenario C**: P₁ participates in both the DAM and a 15-min mFRR market.

### 5.3 Iberian market simulations—Results and discussion

Table 3 presents the simulation results from the point of view of WPPs, that is, by taking into account the following variables: (a) the wind energy value, (b) imbalances, and (c) penalties and costs with imbalances.

The DAM results are similar for all simulations performed. For each scenario, the main differences are related with the following: (a) BM results in terms of costs and quantity, (b) the remuneration of WPPs from the market, (c) costs with deviations of WPPs, and (d) deviations of WPPs.

Table 3 shows that bidding in a 15-min mFRR market leads to better results for WPPs, which indicates that reducing the market time unit (from 1-hr to 15-min) and the gate closure (to a time closer to real-time) is beneficial. In particular, allowing WPP agents to bid in the BM leads to an increase of the wind energy value between 2.18 and 5.76% (for scenarios B and C, respectively). Also, the wind power deviations decrease between 3.8 and 14.4% (in scenarios A and C, respectively).

Table 4 presents the simulation results from the point of view of the BM, that is, by taking into account the following variables: (a) the quantity exchanged, (b) the reserve direction, (c) costs, (d) balancing needs, and (e) the share of wind power. The reduction of the imbalances of WPPs leads to a reduction of the costs of the BM up to 15.9% (in scenario C). The percentage of wind power that satisfies the band needs of aFRR is 24.8%, resulting in a reduction of the cost of the aFRR band around 15%. The use of 15-min bids (considered in Scenario C) leads to an increase of the wind energy value in the market, due to a reduction in both the deviations of WPPs and the penalties, as well as a decrease of the clearing-prices of BMs. A reasonable share of wind power in the mFRR (less than 18% for upward regulation and 16% for downward regulation), and also a moderate share in the aFRR band (24.8%), lead to a reduction of the costs of these markets.

### Table 3  Simulation results from the point of view of wind power producers: Average values of the key variables under evaluation (per day) considering both the DAM and the BM

| Variable                                | Scenario |
|-----------------------------------------|----------|
| Wind energy value (€/MWh)              | Baseline | A   | B   | C   |
| Total imbalances of WPPs (GWh/day)     | 8.70     | 8.37 | 8.26 | 7.45 |
| Losses due to imbalances of WPPs (k€/day) | 133.15  | 127.19 | 127.35 | 113.62 |
| WPPs Levelized costs of penalties (€/day) | 7.24    | 6.95 | 6.87 | 5.93 |
| Penalties paid by WPPs (€/MWh)         | 13.43    | 13.35 | 13.37 | 12.97 |
The results also highlight that a share of wind power of 16% in the power system is still far from satisfying the needs of the BM (a maximum of 24.8% share in the aFRR band). However, the remuneration is lower when compared with the remuneration from a case involving no deviations of WPPs (Algarvio, Couto, Lopes, Estanqueiro, & Santana, 2017). Overall, Table 4 shows that bidding in a 15-min mFRR market leads to better results.

From the point of view of the TSO, the participation of WPPs in BMs can bring the following positive impacts: (a) a reduction in the use of reserves due to a decrease in the wind power deviations, (b) a reduction in the costs of the BM due to the bids of WPPs at zero euros (for upward regulation) and the DAM price (for downward regulation), which leads to a decrease in the clearing prices of upward regulation (and also an increase in the prices of downward regulation), and (c) a short-run upgrade information about WPPs real-time (expected) schedules.

6 | CONCLUSION

This article analyzed the participation of WPPs in BMs. Specifically, the article presented a simulation-based study to evaluate the participation of WPPs in both the DAM and the BM. The study involves four scenarios: baseline scenario (participation of WPPs in the DAM only), scenario A (participation of WPPs in both the DAM and the aFRR market), scenario B (participation of WPPs in both the DAM and the mFRR market), and scenario C (participation of WPPs in both the DAM and the mFRR market, with a reduction of the time unit of the mFRR market from 1 hr to 15 min).

The main results indicate that scenario C is the best one. We highlight the following (for scenario C in relation to the baseline scenario):

- An increase of 5.8% in the wind energy value to the market.
- A reduction of 14.4% in the imbalances.
- A decrease around 16% in the costs of the BM.

Overall, the results highlight that the participation of WPPs in the BM benefit the power system at both technical and economic levels, by increasing the wind energy value to the market and reducing imbalances. Such participation can contribute to a possible new paradigm, where WPPs may be active players in EMs, without needing FITs or other incentives to be economically viable. In such a paradigm, VRE will take more responsibility, by being able to provide a full range of grid support services. However, to obtain all possible benefits, and as indicated by other authors (e.g., González-Aparicio & Zucker, 2015; Holttinen, 2012; Lopes & Coelho, 2018a), new elements of market design may be needed (e.g., a market time unit of 15 min, instead of 1 hr).

Finally, we note that the approach discussed in this work, as well as other existing approaches (such as aggregation or postponing the day-ahead gate closure), may result in a power system more attractive for investment in VRE without FITs (or others incentives). Since wind power has zero or near-zero marginal cost, its participation in BMs is important at an economic level (to reduce the costs of BMs), and also at a technical level (both to control the production of WPPs and to reduce the imbalances of the system).

6.1 | Future work: Analysis of key aspects

The new proposal of the European Community (EC, 2017a) includes legislation for a gate closure of EMs closer to real-time operation, balance responsibility for renewable energy sources, aggregation of bids, reduction of the market time unit up to 15 min in 2025, and the participation of VRE in BMs.
This article considered individual bids of WPPs in BMs, a situation similar to the German case, with non-strategic provision of regulating power. It also considered a gate closure of 15 min ahead and bids performed for products of either 1 hr and 15 min. Accordingly, some important aspects for future work are as follows:

1. Strategic bidding in DAMs, intra-day markets and BMs.
2. The possibility of aggregated bids in BMs.
3. A gate-closure of BMs between 1 hr and 5 min ahead of real-time operation.
4. A market time unit lower than 15 min for BMs.
5. New BM products adapted to wind power.

Some notes about these five aspects follows. Skytte and Bobo (2018) verified that a gradual increase in the active participation of WPPs in markets, results in high wind energy values. WPPs can perform strategic bids in spot and BMs taking into account wind power forecasts and expected values of market prices. An increase in the wind energy value is important to have profitable investments (e.g., in new wind turbines).

Bids of aggregated WPPs are typically advantageous to minimize forecast errors. As noted earlier, this is the solution adopted in Spain for the participation of WPPs in the mFRR market (Martín-Martínez et al., 2018). It can also be considered a good solution to increase the efficiency of the participation of WPPs in BMs, namely by reducing imbalances (and consequently the penalties to pay) and the wasted energy (in case of meeting set-points). However, a potential better solution consists of allowing aggregated bids of WPPs and conventional generation in BMs (as performed in Denmark, for the downward mFRR market only).

A gate closure of BMs close to real-time operation is an important element of market design to accommodate the participation of WPPs in BMs (e.g., Algarvio, Couto, Lopes, Estanqueiro, & Santana, 2016; Holttinen et al., 2016). Also, Papaefthymiou et al. (2015) verified that shortening the length of the downward mFRR product from 4 hr to 1 hr in Germany, for large share levels of wind power, may contribute to a cost saving of 18%. Clearly, a gate closure close to real-time operation and short products are important elements of market design that can improve wind power forecasts and the value of wind energy.

A market time unit up to 15 min to BMs (instead of 1 hr) may also be considered an important element of market design as we try systematically to note throughout this article. In fact, balance products need to be fully activated in 15 min and imbalance costs are also calculated for periods of 15 min (EC, 2017a, 2017b). This measure also benefit WPPs, since they have less volatility in shorter time periods, which can be verified by the difference of almost three times in the reduction of imbalances in scenarios B (5%) and C (14.4%) of our study.

Overall, we are confident that the participation of WPPs in BMs is (and will be) an important feature of future markets, which can be largely improved by considering the five aspects just outlined.

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CONFLICT OF INTEREST
The authors have declared no conflicts of interest for this article.

ENDNOTES
\(^1\)The term “balancing market” is used in a broad sense, refereeing to the automatic-activated and manually-activated frequency restoration reserve markets.
\(^2\)Mills and Wiser (2014) classify the economic value of wind as the sum of four variables: the market value of energy, the capacity value, the forecast error and the ancillary services value.
\(^3\)ENTSO-E presents the legislation about the imbalances settlements (ENTSO-E, 2014). In particular, Article 62 defines that each TSO shall settle all imbalances with each Balance Responsible Party (BRP) pursuant to Article 60. Furthermore, each TSO shall settle each Imbalance Settlement Period pursuant to Article 21, against the appropriate imbalance price (pursuant to Article 61). Article 60 defines several aspects involved in the determination of imbalances, including the final position, the allocated volumes, and the imbalance adjustment for each BRP and for each imbalance settlement period and area. Article
21 defines the targets for imbalance settlement. Article 61 considers that each TSO defines rules to calculate the imbalance price to be paid by the BRP to the TSO.

4The European Union before Brexit (i.e., including the United Kingdom).

5In this work, we consider that WPPs submit up-regulation orders at 0 €/MWh, thus entering at the bottom of the curve. Also, WPPs submit down-regulation orders at the DAM price, entering at the top of the curve.

6To simulate the daily Iberian market prices, there is a need to define the software agents that participate in the (simulated) day-ahead market incorporated into the MATREM system. For simplicity, and after a careful examination of the operation of MIBEL, we consider that the electricity supply industry is represented by 20 software agents and the demand for electrical energy involves four agents. This simplification allows us to perform computer simulations as close to the reality as possible, while overcoming the computational complexity resulting from considering a larger number of agents.

7Agent P₁ results from the aggregation of eight WPPs (agents P₂ to P₉) situated in the center of Portugal (henceforth, for simplicity, each wind power producer is also referred to as WPPᵢ, i = 1,...,8).

8Notice that the submission of aggregated bids to the Iberian DAM and to the Portuguese balancing market is currently not allowed.

9For clarity of exposition, and since the agent P₁ is the most import for this work, we describe only its bidding process.

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