Wind offering in energy and reserve markets

T Soares[1a], P Pinson[2a], H Morais[3b]

[a]Technical University of Denmark, Elektrovej B. 329A, 2800 Kgs. Lyngby, Denmark
[b]Polytechnic Institute of Porto, Porto, Portugal

[1]tiasoar@elektro.dtu.dk, [2]ppin@elektro.dtu.dk, [3]hugvm@isep.ipp.pt

Abstract. The increasing penetration of wind generation in power systems to fulfil the ambitious European targets will make wind power producers to play an even more important role in the future power system. Wind power producers are being incentivized to participate in reserve markets to increase their revenue, since currently wind turbine/farm technologies allow them to provide ancillary services. Thus, wind power producers are to develop offering strategies for participation in both energy and reserve markets, accounting for market rules, while ensuring optimal revenue. We consider a proportional offering strategy to optimally decide upon participation in both markets by maximizing expected revenue from day-ahead decisions while accounting for estimated regulation costs for failing to provide the services. An evaluation of considering the same proportional splitting of energy and reserve in both day-ahead and balancing market is performed. A set of numerical examples illustrate the behavior of such strategy. An important conclusion is that the optimal split of the available wind power between energy and reserve strongly depends upon prices and penalties on both market trading floors.

1. Introduction

In last two decades electricity markets have been evolving in different ways with the aim to improve the competition among the different players without compromising the required reliability and stability in the electric system. In this scope, electricity markets are composed by different market stages for different commodities. Besides the energy commodity traded in energy auctions, there are ancillary services commodities (usually traded in reserve markets) that are used by power system operators to ensure proper levels of reliability, stability and security in the power system.

With the continuous introduction of wind generation in the electricity market, the behavior of electricity market participants has been changing. Currently, multiple methodologies for optimizing the strategic behavior of wind power producers (WPP) in the energy market have been proposed, accounting for expected costs from the balancing market [1–8]. Part of this work has been conducted based on the assumption that the strategic behavior of wind power plants does not have a significant impact on the market equilibrium, thereby, assuming price-taker behavior, i.e. the WPP does not exert market power [1–5]. In an opposite direction, several works exist, claiming that WPP may have a significant impact in the market equilibrium, and somehow may exert market power – yielding a price-maker assumption [6–8].

Nevertheless, wind power generators are now able to provide ancillary services, such as frequency and voltage control [9]. Namely, wind power plants can control active power injection in a few seconds; injecting/consuming reactive power while maintaining proper voltage levels, as well as providing virtual inertia to the system [10–12]. Thus, new business models may emerge, stimulating

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

the willingness of wind power producers to participate and take advantage of reserve markets to increase their profit, as detailed in [13–15]. A analytical approach based on probabilistic forecast for wind power participating in the energy and reserve market is proposed in [13,14]. In [13], a simplistic strategy for splitting the available wind power in energy and reserve is applied, while [14] uses two different control strategies (proportional and constant wind power control) for WPP to participate in both energy and reserve markets.

We place ourselves under the proportional control strategy used in [14], contributing with a new stochastic methodology that maximizes the expected revenue of the WPPs in the day-ahead energy market and in the reserve market, while accounting for expected costs from failing to provide the energy and reserve products at the balancing stage. Besides that, this work contributes with a new perspective of facing the lead time of the WPP between the day-ahead and balancing stage by considering that energy and reserve bids submitted in the day-ahead market by the WPPs can be changed in the balancing market, i.e. the use of more accurate forecast of the wind power production in the balancing stage reduces the deviation between the power production committed in day-ahead stage and the effective production during the energy delivery. This may allow WPPs to bid in both market stages with more precise information about their wind power production, thereby, reducing expected energy and reserve costs in the balancing market. The results show that allowing a change in the proportionality of energy and reserve between day-ahead and balancing market, improves the expected revenues of the WPP, as well as, reduces the expected power deviation between the day-ahead and the energy delivery.

The paper is structured as follows. Section 2 describes the market structure for wind power producers participating in energy and reserve markets. Section 3 presents the detailed mathematical formulation of the optimal offering strategy for wind power producers. Section 4 numerically evaluates the offering strategy in expectation under different prices and penalties schemes that may occur in the market. Section 5 assembles the most important conclusions.

2. Wind power in electricity markets

2.1. Day-ahead and balancing participation

Currently, wind power producers can participate in the wholesale market by submitting their power bids (usually, their expected production) in the day-ahead market. The uncertainty of the wind power production is usually mitigated through the balancing market (the last mechanism for correcting the system and market participant imbalances), where the deviations of the wind power producers (the difference between their day-ahead market bids and the expected power production close to real-time) may induce some penalties for the wind power producers by failing to provide their day-ahead bids (either in deficit or surplus of power production) [16,17].

In that context, the expected costs to the wind power producers depend on the energy imbalance of the power system and of the difference between the sell and the delivered energy by the WPP. Furthermore, two different penalty mechanisms (one-price settlement and two-price settlement) can be applied depending on the characteristics and of the market rules [18,19]. For instance, the two-price system is assumed in the balancing mechanism in Denmark [20].

In what concerns the price bids of wind power plants in the day-ahead market, usually, WPPs places their power bids in the market at zero price or even negative price. This behavior depends on the internal rules of each market, as well as, on the different incentive schemes that wind power producers are submitted in each country. For instance, in Denmark, wind power producers are remunerated based on a scheme that lies on a combination of market participation (negative prices are allowed in NordPool) plus a premium [14]. In Portugal, similar schemes have been followed, yet most of wind power producers are still under fixed feed-in tariffs [21]. Besides, the Iberian market does not allow for negative bids [22,23].

2.2. Energy and reserve markets model

WPPs are willing to provide some ancillary services, since in their perspective, providing reserve (even with uncertainty and under high penalties when failing to provide the service) can somehow increase their revenue. Thus, the development of a methodology for wind power participation in energy and reserve markets at the day-ahead market, while accounting with expected costs in the balancing market is proposed and illustrated in Figure 1. The energy and reserve markets assume different characteristics, so different considerations are taken. On the one hand, wind energy bids submitted in the day-ahead market should account for potential imbalance situations and their asymmetric penalties. On the other hand, bids submitted in the reserve market should take into account the possibility to fail in providing the service.

Nevertheless, this model allows WPPs to submit bids into the energy and reserve market at day-ahead stage, following a proportional strategy for the split of the available power into energy and reserve (a share parameter is obtained by the split between energy and reserve). The bidding strategy for the day-ahead market assumes an expected energy market price, while the reserve market participation strategy takes into account the capacity reserve price.

At the balancing stage, expected costs for energy and reserve deviations are considered. On the one hand, expected costs for energy surplus or deficit of the WPP are considered. In contrast, reserve costs are only accounted for deficit of reserve, since the reserve surplus is not detrimental to the system. Additionally, this models assumes that the share parameter (split between energy and reserve) at the balancing stage can assume a different value from the one used for the day-ahead market decision. Thus, WPPs have the opportunity to reduce some energy or reserve deviations, thereby, increasing its expected revenue.

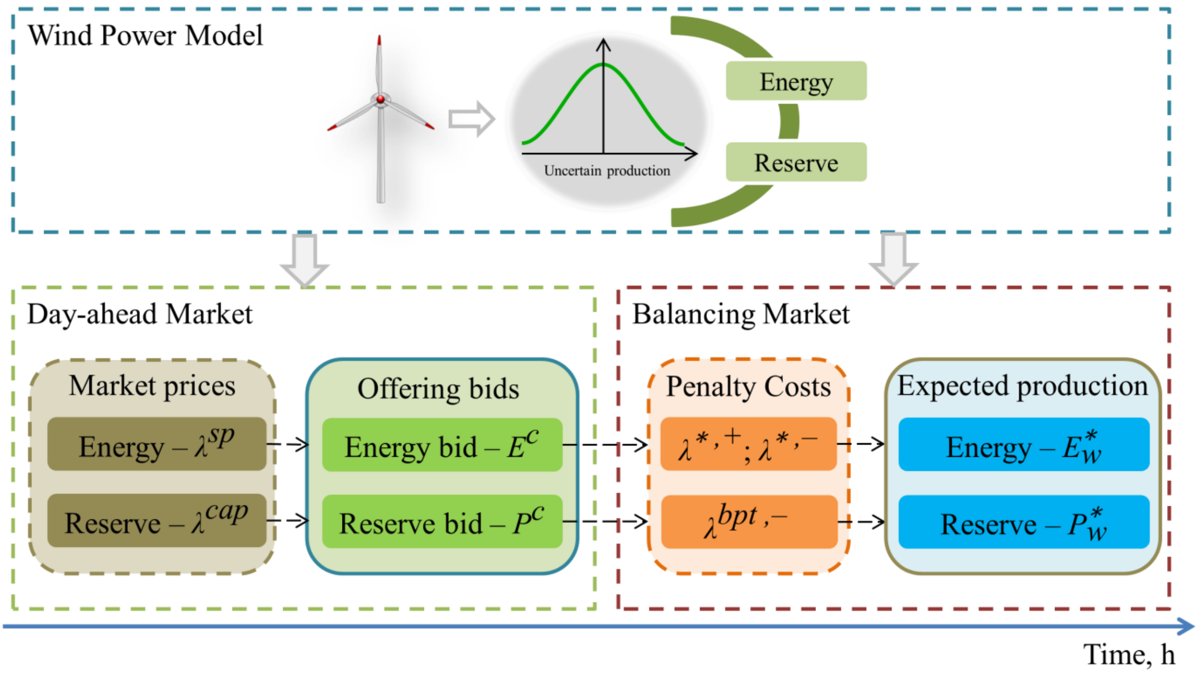

Figure 1. Wind power participation model in the energy and reserve market.

2.3. Wind power control to provide energy and reserve

Currently, wind power plants have developed several ways of active power control to provide energy and reserve, thereby, ensuring the stability of the power system. The use of these controls has been required by the system operators in different countries with high penetration of wind power, thereby, updating the grid-codes with new active power controls methodologies. System operators may require the use of such controls in cases of excess of wind power, to decrease congestion or even just for reserve provision. In this context, four methods for active power control of wind power for providing energy and reserve are described in detail.

2.3.1. Proportional wind control. This control mechanism consists in the proportional split of the available active power in energy and reserve, as illustrated in Figure 2. In terms of market strategy, the proportional wind offering strategy is used to define the share of energy E^c and reserve P^c to be submitted in the market [14,24], where Q is the total power bid and α^c the strategy parameter controlling the share of energy and reserve bids at day-ahead stage, which varies between 0 and 1.

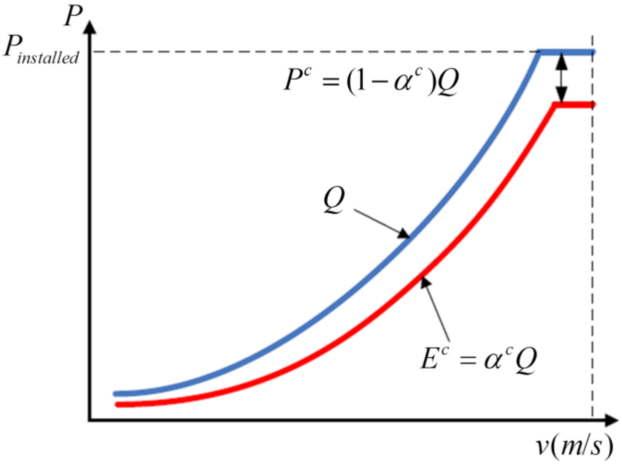

Figure 2. Proportional wind offering strategy (reproduced with authorization from [24]). The blue line Q stands for the available wind power production, while the red curve E^c comprises the energy part of Q to offer in the energy market. The reserve bid P^c to offer in the reserve market is equal to area between the blue and red curve. α^c is the proportional share parameter that splits the available wind power into energy and reserve assuming a value between 0 and 1.

2.3.2. Constant wind control. The constant wind power consists in a constant curtailment of energy in case that the expected forecast is bigger than a specified level of wind power (Figure 3) [14,24]. The strategy, reserves a fixed amount of power reserve to face system imbalances. The remaining active power is dispatched for the energy service. In this control, wind power plant has a fixed amount of power reserve for ancillary services, when the wind power available is above of a certain percentage X% of the installed wind power. Otherwise, the available wind power is offered to the energy market.

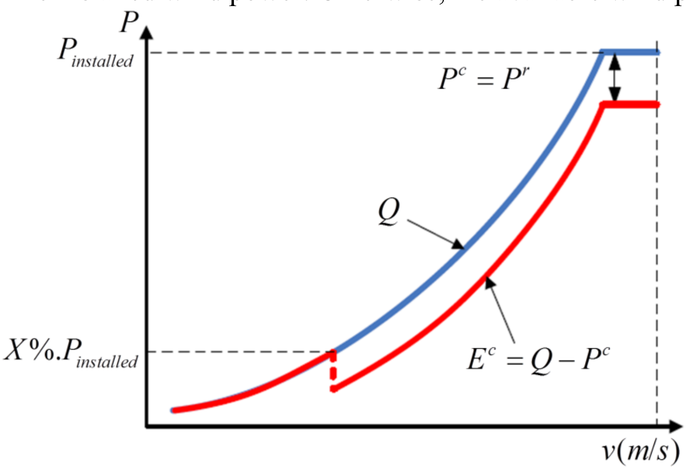

Figure 3. Constant wind offering strategy (reproduced with authorization from [24]). The blue line Q stands for the available wind power production, while the red curve E^c is the remaining part of Q to offer in the energy market assuming a certain fixed amount of reserve P^c.

2.3.3. ΔP control. This control is similar to the constant wind power control. The control curtails a certain and fixed amount of the maximum available power in function of the system operator requirements [15,25,26]. The biggest difference between the ΔP control and the constant control is the use of a minimum threshold (X% of the installed wind power) in the constant control to allocate part of the available wind power as power reserve.

2.3.4. Output cap. The output cap is an active power control for wind turbines establishing a maximum level of active power that can be provided to the energy service [15]. In cases of the available wind power higher than the output cap, the power that exceeds the output cap is curtailed by the wind turbine. Thus, system operator can require low levels of output cap to decrease the variability of the wind power production. However in the WPP standpoint, this control most likely reserves a significant part of the available energy to power reserve, which may result in a small but somehow constant provision of the energy service.

3. Wind offering methodology

3.1. General optimization framework

A methodology for the optimal offering of a WPP in energy and reserve markets at the day-ahead stage, while accounting for the expected penalties in the balancing market is proposed. A two-stage stochastic approach is used to optimize the revenue *R* for a given WPP, and is expressed as

$$\underset{Q,\alpha^c,\alpha_w^*}{Maximize}\ R = \lambda^{cap}P^c + \sum_{w\in\Omega}\pi_w\left[\lambda^{sp}E_w^* - T_w^* - W_w^*\right] \tag{1}$$

where λ^{cap} is the capacity price for primary reserve allocation, P^c is the reserve contracted (offered) in the day-ahead market, λ^{sp} is the spot price, E_w^* is the delivered energy in scenario *w*, T_w^* is the regulation costs from the regulation market, and W_w^* is the penalty cost for wind power plant failing to provide the scheduled reserve.

Additionally, it is assumed that the WPP acts as a price-taker. Thus, the market prices and penalties are independent of the WPP production. Then, the regulation costs from the regulation market can be defined as

$$T_w^* = \begin{cases} \lambda^{*,+}\left(E_w^* - E^c\right), & E_w^* - E^c \geq 0 \\ -\lambda^{*,-}\left(E_w^* - E^c\right), & E_w^* - E^c < 0 \end{cases} \tag{2}$$

where (E_w^*- E^c) is the difference between the delivered energy E_w^* and the amount of energy offered at day-ahead market E^c. The variables $\lambda^{*,+}$ and $\lambda^{*,-}$ are the regulation unit costs for positive and negative deviations, respectively,

$$\begin{aligned} \lambda^{*,+} &= \lambda^{sp} - \lambda^{c,+} \\ \lambda^{*,-} &= \lambda^{c,-} - \lambda^{sp} \end{aligned} \tag{3}$$

where $\lambda^{c,+}$ is the unit down-regulation price for being long, while $\lambda^{c,-}$ is the up-regulation price for being short. In addition, a two-price settlement rule (as in NordPool) is assumed [1]. Thus, when the power system imbalance is negative, there is a need for downward regulation (energy surplus), which is given by

$$\begin{aligned} \lambda^{c,+} &\leq \lambda^{sp} \\ \lambda^{c,-} &= \lambda^{sp} \end{aligned} \tag{4}$$

On the other hand, when the power system imbalance is positive, there is a need for upward regulation so the prices and penalties hold that

$$\begin{aligned} \lambda^{c,+} &= \lambda^{sp} \\ \lambda^{c,-} &\geq \lambda^{sp} \end{aligned} \tag{5}$$

The penalty costs for reserve imbalance is given by

$$W_w^* = \begin{cases} \lambda^{bpt,+}\left(P_w^* - P^c\right), & P_w^* - P^c \geq 0 \\ -\lambda^{bpt,-}\left(P_w^* - P^c\right), & P_w^* - P^c < 0 \end{cases} \tag{6}$$

where (P_w^*- P^c) is the reserve power imbalance between the deployed level of reserve P_w^* in real-time and the reserve offered, $\lambda^{bpt,+}$ is a unit penalty when wind producer generates more power than the contracted (surplus), and $\lambda^{bpt,-}$ is the unit penalty cost when the WPP generate less than contracted. These are given by

$$\begin{aligned} \lambda^{bpt,+} &= \lambda^{cap} - \lambda^{pt,+} \\ \lambda^{bpt,-} &= \lambda^{pt,-} - \lambda^{cap} \end{aligned} \tag{7}$$

hence $\lambda^{pt,+}=0$ since (extra) positive reserve is not detrimental to the system's reliability. $\lambda^{pt,-}$ is the penalty for negative reserve imbalance, weighted by the probability that reserve is needed.

3.2. Proportional wind offering strategy

In this work and by simplicity, the proportional wind offering strategy is applied for splitting the available wind power for energy and reserve, as illustrated in Figure 2. The objective function is subject to the following constraints regarding the proportional strategy split of energy and reserve. The proportional wind offering strategy is used to define the share of energy E^c and reserve P^c to be submitted in the market [14,24].

$$E^c = \alpha^c Q \tag{8}$$

$$P^c = (1-\alpha^c)Q \tag{9}$$

$$1 \leq Q \leq E^{\max} \tag{10}$$

Under some support schemes, the WPPs are required to participate in the day-ahead market, thereby, the bounds of the total power bid Q reflects the minimum power bid to participate in the market (1 MW in most of electricity markets) and the installed capacity of the WPP.

Equations (11) and (12) concerns the wind offering strategy under the balancing power market

$$E_w^* = \alpha_w^* E_w^{obs} \qquad ,\forall w \in \Omega \tag{11}$$

$$P_w^* = (1-\alpha_w^*) E_w^{obs} \qquad ,\forall w \in \Omega \tag{12}$$

where E_W^{obs} donates the eventually observed wind power production, composed by energy E_W^* and reserve P_W^* share actually available. α_W^* is the strategy parameter for the splitting in real-time operation.

3.3. Fixed and relaxed approach of wind strategic split in day-ahead and balancing market

Under the fixed approach (problem with "non-anticipativity" constraints), it is assumed that the share of energy and reserve established in the balancing stage cannot be different from the day-ahead stage. This ensures that perfect information on real-time cannot be used to change the share of energy and reserve decided on the first-stage problem, thereby avoiding the decision process to play with full degree of freedom. Equation (13) represents the "non-anticipativity" constraint of the wind offering problem.

$$\alpha_w^* = \alpha^c \qquad ,\forall w \in \Omega \tag{13}$$

On the other hand, a simplification of the proportional strategy in the stochastic problem can be performed, assuming that the wind power producer can change the share of energy and reserve in both day-ahead and balancing stages (relaxed approach). This means that the wind power producer can adjust the share of energy and reserve in real-time, accordingly with the expected power production in each scenario *w*. Thus, the WPP can improve their revenue by changing their bid according with better information of their production when closer to real-time operation. The mathematical formulation for that case relies on equations (1) to (12).

The wind power producer problem presented here has been modelled as two-stage stochastic approach in GAMS [27] modelling language and carried out with CONOPT [28] as a NLP solver on an Intel Core i5 2.70 GHz processor with 8 GB RAM.

4. Evaluation of offering strategies

A wind power plant with 15 MW of installed power is considered. The wind total bid offer is subjected to a minimum amount of power to participate in the markets. Currently, electricity markets settle 1 MW as the minimum power for the bidding process. A set of 100 wind power scenarios for a single period presented in [29], has been considered for evaluating the proposed methodology. It is assumed that all the scenarios have equal probability.

The evaluation of the proposed strategy is performed according with a set of prices and penalty costs combination allowing us to test the behavior of the strategy for different assumptions, such as $\alpha_w^*=\alpha^c$ and allowing that α_w^* can be free (i.e., α_w^* can be equal or different of α^c) – stochastic approach with and without "non-anticipativity" constraint.

4.1. Normal operation

Under normal operation in the electricity market, adequate price signals for wind participate in both energy and reserve markets should be ensured. In this scope, the capacity price in the day-ahead market should be higher than the spot price ($\lambda^{cap} \geq \lambda^{sp}$). Besides that, the reserve penalties in the balancing stage for failing to provide the bid offered in the day-ahead stage should be higher than the penalty for failing to provide the energy ($\lambda^{bpt,-} \geq \lambda^{*,-}$), since for the power system is much worse a unit failing to provide reserve rather than energy.

Thus, the prices for energy and reserve, and the unit penalty costs for up and down deviations under normal operation for the power system (our base case) are presented in Table 1.

Table 1. Prices and penalty costs in energy and reserve market for base case.

Energy	Price (€/MWh)	Reserve	Price (€/MW)
λ^{sp}	40	λ^{cap}	41
$\lambda^{c,+}$	30	$\lambda^{bpt,+}$	0
$\lambda^{c,-}$	50	$\lambda^{pt,-}$	96

Under the normal operation case, it is expected that both strategies may behave differently, since the allocation of the available energy to one of the markets is not straightforward. One can expect the strategy with fixed share parameter base their decision with the information available in the day-ahead stage, while the approach with the flexible share parameter may use the better information of the balancing stage to reduce expected costs. Figure 4 illustrates the energy market participation for both stochastic approaches with standard and flexible share parameter relationships between day-ahead and balancing market. The standard approach chooses to participate only in the energy market, since the gain from participating in the reserve market is not much higher than participating in energy-only, and account with a high penalty when failing to provide the offered power reserve (risk adverse behavior). In contrast, the flexible approach (without "non-anticipativity" constraint) presents a different behavior (closer to the risk neutral), since participating in both energy and reserve markets. The participation in both energy and reserve can in one way give flexibility to the wind power producer to increase the expected revenue while taking the risk of getting penalties from failing to provide energy and reserve. Thus, for lower levels of available wind power (until wind available power equal to P^c, as can be seen in Figure 5) it is allocated all the available power to the reserve market (E^*=0, in Figure 4), where the penalty for failing is higher.

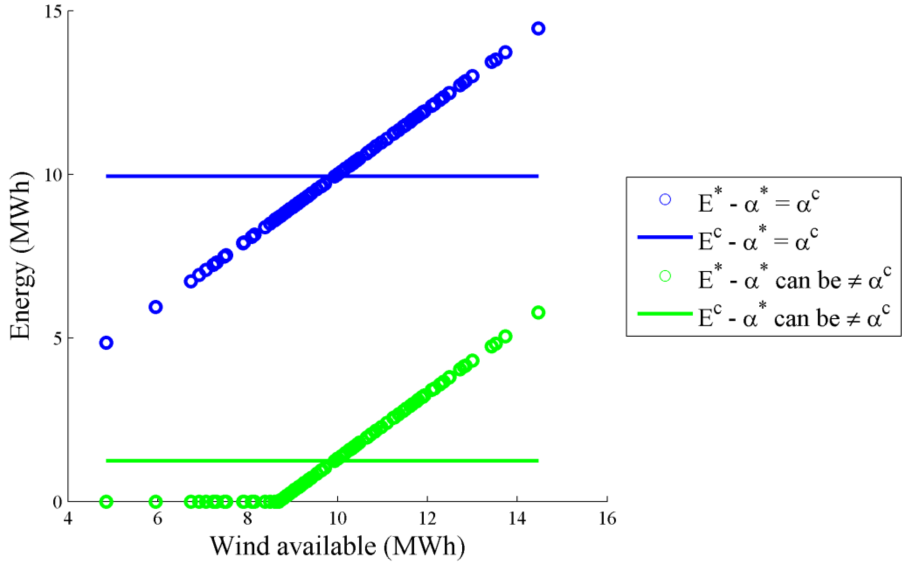

Figure 4. Energy bid in the day-ahead (E^c) and balancing stage (E^*) for both approaches under the normal operation case.

The reserve bids in day-ahead and balancing stage for both strategies are shown in Figure 5.

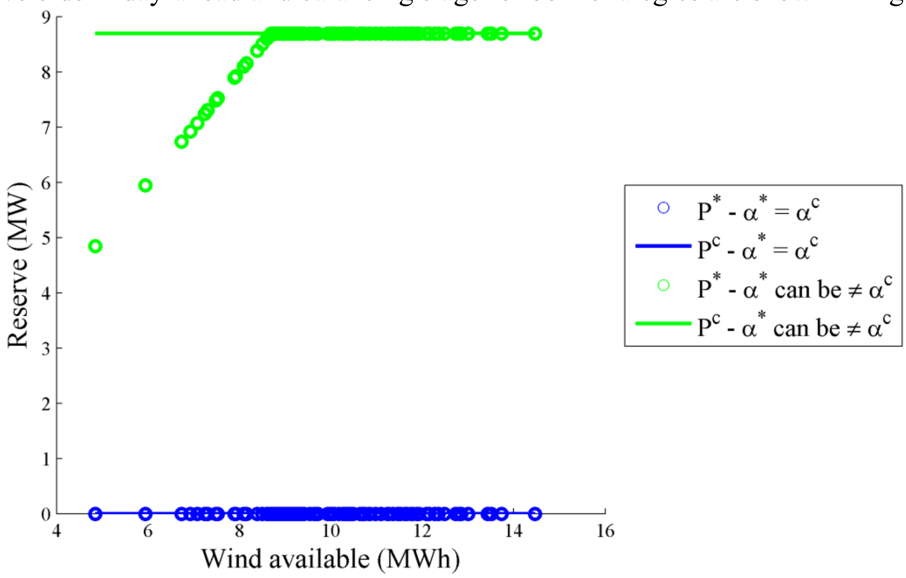

Figure 5. Reserve bid in the day-ahead (P^c) and balancing stage (P^*) for both approaches under the normal operation case.

Moreover, the expected revenue that the WPPs may achieve by participating in energy and reserve market with different behavior of the share between energy and reserve in day-ahead and balancing market is 387 € and 395 €, respectively. In this case, the opportunity to change the energy and reserve share in the balancing market improves the revenue of the WPPs about 2%.

4.2. Special operation – single market participation

In cases of occur different schemes of prices and penalties, the participation in the market behaves differently, as expected. For instance, in cases where the capacity price is higher than the spot price ($\lambda^{cap} \geq \lambda^{sp}$) and the reserve penalty lower than the energy penalty ($\lambda^{bpt,-} \leq \lambda^{*,-}$), both strategies fully offers in the reserve only market. In this case, make total sense to offer only in the reserve market since there is no gain on participating in the energy market.

On the opposite case, when the capacity price is lower than the spot price ($\lambda^{cap} \leq \lambda^{sp}$) and the reserve penalty is higher than the energy penalty ($\lambda^{bpt,-} \geq \lambda^{*,-}$), both strategies assumes the same behavior by participating in the energy only market. One can notice that participating in the energy market will results in higher revenues in the day-ahead market and less expected costs in the balancing stage.

Both special cases implies a logical participation in a single market, however, these cases are unlikely to happen in future electricity markets with competitive integration of wind power generation in the reserve market.

5. Conclusions

With the introduction of new business models where the WPPs can provide energy and reserve bids in the day-ahead market while accounting for the expected cost from the balancing market, new strategic bidding for WPPs is crucial to increase their profit.

This work presents two ways for WPPs to submit their bids in the energy and reserve markets based on the assumption of WPP behaving as a price-taker. One of the approaches considers fixed share of energy and reserve in the stochastic general problem, i.e. the share parameter in both day-ahead and balancing stages remains the same. The other approach sets the share parameter to be free between the day-ahead and balancing stages. Although the strategy with flexible share parameter can increase the revenue of the WPP, this requires a certain level of perfect information of the balancing stage, since the “non-anticipativity” constraint between first and second stage of the problem is not applicable in this case. However, this strategy allows the WPP to change their bids in the market when getting close to the market closure gate, where information of its available production is more reliable.

Notwithstanding, future electricity market may face some changes on this topic, since new behavior and market opportunities for WPPs may influence the market design and mechanisms specially in reserve markets. On the one hand, system operators can require some guarantees from the WPPs, controlling somehow the level of uncertainty in the reserve product and maintaining proper levels of system reliability. On the other hand, market operators must develop mechanisms to ensure a fair participation of all type of market participants in both energy and reserve products and avoiding market power. Pushing decisions close to real-time is of the most interest of WPPs, since it will improve the quality of their decisions and to some extent reduce the lead time effect between the day-ahead decisions and the energy and services delivered.

References

[1] Pinson P, Chevallier C and Kariniotakis G N 2007 Trading wind generation from short-term probabilistic forecasts of wind power *IEEE Trans. Power Syst.* **22** 1148–56

[2] Dent C J, Bialek J W and Hobbs B F 2011 Opportunity cost bidding by wind generators in forward markets: analytical results *IEEE Trans. Power Syst.* **26** 1600–8

[3] Morales J M, Conejo A J and Pérez-ruiz J 2010 Short-term trading for a wind power producer *IEEE Trans. Power Syst.* **25** 554–64

[4] Matevosyan J and Söder L 2006 Minimization of imbalance cost trading wind power on the short-term power market *IEEE Trans. Power Syst.* **21** 1396–404

[5] Botterud A, Zhou Z, Wang J, Bessa R J, Keko H, Sumaili J and Miranda V 2012 Wind Power Trading under Uncertainty in LMP Markets *IEEE Trans. Power Syst.* **27** 894–903

[6] Baringo L and Conejo A J 2013 Strategic offering for a wind power producer *IEEE Trans. Power Syst.* **28** 4645–54
[7] Zugno M, Morales J M, Pinson P, Madsen H and Sets A 2013 Pool strategy of a price-maker wind power producer *IEEE Trans. Power Syst.* **28** 3440–50
[8] Kazempour S J and Zareipour H 2014 Equilibria in an oligopolistic market with wind power production *IEEE Trans. Power Syst.* **29** 686–97
[9] Ela E, Kirby B, Navid N and Smith J C 2012 Effective ancillary services market designs on high wind power penetration systems *IEEE Power and Energy Society General Meeting* (San Diego, California) pp 1–8
[10] Nock D, Krishnan V and McCalley J D 2014 Dispatching intermittent wind resources for ancillary services via wind control and its impact on power system economics *Renew. Energy* **71** 396–400
[11] Zeni L, Rudolph A J, Münster-Swendsen J, Margaris I, Hansen A D and Sørensen P 2013 Virtual inertia for variable speed wind turbines *Wind Energy* **16** 1225–39
[12] Michalke G and Hansen A D 2013 Grid support capabilities of wind turbines *Handbook of Wind Power Systems* ed M P Pardalos, S Rebennack, F M V Pereira, A N Iliadis and V Pappu (Berlin, Heidelberg: Springer Berlin Heidelberg) pp 569–90
[13] Liang J, Grijalva S and Harley R G 2011 Increased wind revenue and system security by trading wind power in energy and regulation reserve markets *IEEE Trans. Sustain. Energy* **2** 340–7
[14] Soares T, Pinson P, Jensen T V. and Morais H 2016 Optimal offering strategies for wind power in energy and primary reserve markets *IEEE Trans. Sustain. Energy* **7** 1–10
[15] Roald L, Misra S, Backhaus S, Chertkov M and Andersson G 2016 Optimal power flow with wind power control and limited expected risk of overloads *19th Power systems computation Conf.* (Genoa) pp 1–7
[16] Krohn S, Morthorst P E and Awerbuch S 2009 The economics of wind energy *EWEA - Eur. Wind Energy Assoc.* 1–155
[17] Skytte K 1999 The regulating power market on the Nordic Power Exchange Nord Pool: an econometric analysis *Energy Econ.* **21** 295–308
[18] Conejo A J, Carrión M and Morales J M 2010 *Decision making under uncertainty in electricity markets* ed F S Hillier, C C Price and S F Austin (Springer US)
[19] Vandezande L, Meeus L, Belmans R, Saguan M and Glachant J-M 2010 Well-functioning balancing markets: A prerequisite for wind power integration *Energy Policy* **38** 3146–54
[20] Energinet.dk 2008 *Regulation C2 : The balancing market and balance settlement*
[21] PLMJ 2014 Renewable Energies - 2013 Legislative changes in the sector *Energy Nat. Resour. - PLMJ* **4** 1–4
[22] Singh S N and Erlich I 2008 Strategies for wind power trading in competitive electricity markets *IEEE Trans. Energy Convers.* **23** 249–56
[23] MIBEL 2009 *Description of the operation of the MIBEL*
[24] Wang Y, Bayem H, Giralt-Devant M, Silva V, Guillaud X and Francois B 2015 Methods for assessing available wind primary power reserve *IEEE Trans. Sustain. Energy* **6** 272–80
[25] Energinet.dk 2015 *Technical regulation 3.2.5 for wind power plants with a power output above 11 kW*
[26] EirGrid 2015 *EirGrid Grid Code, version 6*
[27] Rosenthal R 2008 *GAMS – a user's guide* (Washington, DC: GAMS Development Corporation)
[28] Drud A 1996 *CONOPT: a system for large scale nonlinear optimization*
[29] Bukhsh W A, Zhang C and Pinson P Data for stochastic multiperiod opf problems https://sites.google.com/site/datasmopf/