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# Strategies for Wind Power Trading in Sequential Short-Term Electricity Markets

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**Abstract**—In several countries, independent wind power producers have the possibility to participate in short-term electricity markets for trading their production. However, the limited predictability of the wind resource may lead to differences between produced and contracted energy, thus generating energy imbalances. This may result in the payment of imbalance penalties, which leads to a reduction of the competitiveness of wind power generation. This paper develops a methodology, suitable for independent wind power producers, that permits them to participate in an efficient way simultaneously in several sequential electricity markets, namely day-ahead and intraday markets. The considered intraday market takes place through a continuous trading mechanism. The imbalance cost reduction related to the adjustment participation in the intraday market is assessed using a real-world test case.

## I. INTRODUCTION

**W**IND power is the fastest growing renewable electricity generating technology. For instance, the target for the next decades aims at obtaining a high share of wind power in electricity generation in Europe [1]. To make such developments possible, one of the present challenges is to increase the integration of wind power in the new electricity market context. Nowadays, independent wind power producers have the possibility to participate in electricity markets for trading wind power production. More precisely, these producers may be allowed to participate in several sequential short-term electricity markets, such as day-ahead and adjustment markets [2] [3].

For participating in a short-term electricity market, a decision has to be made about the amount of energy to bid [4]. The decision has to be made a given amount of time prior to the actual delivery, with imperfect knowledge about the future power generation. At the delivery time, differences between contracted and produced energy (constituting energy imbalances) may lead to the payment of penalties [5]. The wind power producer is exposed to such penalties due to the variable nature of the wind resource as well as to the limited predictability of wind production. As a consequence, the decision about the amount of energy to bid is based on short-term wind power prediction tools that give an estimate of the future power generation [6].

In the state of the art, advanced trading strategies have been proposed for bidding in the day-ahead market in order to reduce the imbalance penalties. A stochastic programming method is proposed in [7] for generating optimal wind power production bids for a day-ahead power market. The estimation of the uncertainty associated to the wind power forecast is used in [8] for deriving optimal bidding strategies for participating in the day-ahead electricity market. The risk related to the imbalance penalties for the independent power producer has been considered in [9] where a strategy based on utility risk assessment is proposed. A mean-risk approach is proposed by the authors in [10], where the risk is measured through the conditional value at risk.

Participation in the intraday market can be done through the use more accurate wind power forecasts for bidding and, as a consequence, it may potentially reduce the risk related to imbalance penalties. More accurate wind power forecasts result from considering the updates that can be made available in time closer to the energy delivery. The benefits from the participation in the intraday market have been verified in [11] for the Spanish market. For the NordPool market, the possibility to reduce imbalance penalties through the intraday market participation has been studied in [12].

The present work proposes a decision making method for the optimal participation of independent wind power producers in day-ahead and intraday electricity markets. The participation in the intraday market is considered as a way for the wind power producer to reduce the imbalance penalties resulting from the participation in the corresponding day-ahead market. The considered intraday market takes place through a continuous trading mechanism. The benefits of the proposed methodology are demonstrated using real-world data of wind power generation as well as of electricity market prices.

## II. GENERAL DESCRIPTION OF THE PROBLEM

### A. Electricity Markets

Electricity markets are usually complex due the amount of energy trading possibilities they offer, to their rules, and to the way they operate, which is usually market-specific. In this work, the wind power

producer is supposed to participate in both the day-ahead and intraday markets.

1) *The Day-Ahead Market:* Day-ahead electricity market generally takes place through power exchange session [2]. Each session has a gate opening and gate closing time as well as a fixing time. The time delivery scope is the 24 hours of the following day. Participants in day-ahead markets have to submit their quantity-price bid during the period between the gate opening and the gate closing time. The energy contracts for each participants and the system price are determined by *marginal pricing*; all bids are aggregated to form a curve for purchases and a curve for sales for each of the 24 hours of the day following the gate closure time. The point at which the two curves intersect within each hour determines the system price, also called *spot price*, which in turn establishes the trading result for each participant for that hour. For markets including different regions, regional spot market prices are derived from system prices taking into account transmission bottlenecks [13].

2) *The Intraday Market:* An intraday market is defined here as a market which gives the possibility for transactions between market parties between the day-ahead market gate closing time and the final notification. This notification is the last moment in time where a market party is allowed to change the energy program which will form the basis of the imbalance calculation [14].

From the independent power producer's point of view, the goal for participating in an intraday market is related to the need for additional trade and a change of position after the day-ahead market gate closing time. More precisely, market parties may want to cover for open positions for reducing the imbalance risk.

During the intraday market period, trade can take place through several different mechanisms such as Over The Counter (OTC), power exchange sessions or continuous trading [14]. The intraday market mechanism considered in the present study is a continuous trading one. Trading takes place in a central exchange where standard products are traded on a *first come first serve* basis: the first matching offer to a bid (or vice versa) is rewarded and fixed into two bilateral transactions between the seller and the buyer. Such a pricing mechanism is denoted as *pay as bid pricing*.

Figure 1 describes the example of a combined participation in the Elspot and Elbas markets from NordPool in Denmark. Bids in the Elspot are proposed before the gate closure time at 12 : 00 the day before the delivery. The Elbas intraday market takes place through a power exchange continuous trading mechanism. In the example, bids in the Elbas market are proposed in the central exchange 6 hours before the delivery time.

## B. The Independent Wind Power Producer

The considered independent wind power producer is supposed to participate in the electricity market in order to sell its power production. In the present study, the bids proposed by the wind power producer for both the day-ahead and intraday markets are only selling, and not buying bids. The possibility to propose buying bids in the intraday market is not considered.

The wind power producer is assumed to be balance-responsible. It is thus liable to pay penalties for the energy imbalances it generates according to the market rules. In the present study, an energy imbalance is defined as the difference between the energy delivered by the wind power producer and the sum of the energy contracted in the day-ahead and intraday markets.

The total capacity of the wind farm is considered to be small enough so that its owner does not possess sufficient market power. In addition, the day-ahead market is considered to be competitive and composed of a relatively high number of market participants. In such a case, in the electricity market context, the wind power producer is considered to be a *price taker*.

## III. MARKET MODELS

This section describes the bidding model for the day-ahead and intraday markets, as well the market settlement model for the same markets. The subscript 0 refers to the day-ahead market, while the subscript 1 will refer to the intraday market.  $B_0$  and  $C_0$  are relative to the day-ahead market bid and contract, respectively. Similarly,  $B_1$  and  $C_1$  are relative to the intraday market bid and contract, respectively.

### A. Day-Ahead Market Model

Following the assumptions regarding the independent wind power producer in section II-B, the proposed quantity-price bids for the day-ahead market are assumed to be price independent bids, at bid price  $\pi^{B_0}$  equal to zero. In the present work, the bid energy quantity  $E_{T_i}^{B_0}$  for the delivery period  $T_i$  is determined using the most recent update of the wind power forecast  $\hat{P}_{t_c+k/t_c}^{WF}$ , available at time  $t_c$ :

$$\mathcal{B}_{T_i}^0 : \begin{cases} \Pi_{T_i}^{B_0} = 0 \\ E_{T_i}^{B_0} = \hat{P}_{t_c+k/t_c}^{WF} \times \Delta t \end{cases} \quad (1)$$

where  $\mathcal{B}_{T_i}^0$  constitutes the bid in the day-ahead market for the period  $T_i$ . The index  $k$  is the horizon, also called look-ahead time of the prediction; it is selected so that the prediction  $\hat{P}_{t_c+k/t_c}^{WF}$  corresponds to the prediction of the mean wind power production for the time period  $T_i$ . The symbol  $\Delta t$  is the market time step, also called Program Time Unit (PTU). It corresponds to the length of the period  $T_i$ .

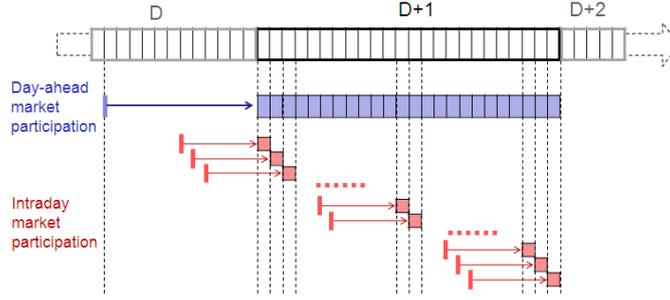


Fig. 1: Example of a combined participation in the Elspot and Elbas markets (NordPool). Bids in the Elbas market are proposed 6 hours before the delivery time.

At the market settlement, the wind power producer bid is always accepted as a consequence to the price taker hypothesis at zero price. The system price is determined by the other participants' bids and the energy contract equals the energy bid. Thus:

$$Contract_{T_i}^0 : \begin{cases} \Pi_{T_i}^{C_0} = \Pi_{T_i}^{C_0 market} \\ E_{T_i}^{C_0} = E_{T_i}^{B_0} \end{cases} \quad (2)$$

where  $Contract_{T_i}^0$  constitutes the day-ahead market contract for the period  $T_i$ .

### B. Intraday Market Model

The considered intraday market is based on a continuous trading mechanism. Contrary to the case of day-ahead market participation, the bid is not always accepted. A trade occurs when the selling and buying bids match. The contract price  $\Pi_{T_i}^{C_1}$  then equals the bid price  $\Pi_{T_i}^{B_1}$ , which results from the *pay as bid pricing*. The contracted energy quantity in the intraday market depends on the buying bids of the other participants.

Modeling the trading mechanism which gives the contracted energy from the bid energy quantity is necessary for simulating and evaluating the bidding strategies. Here, we propose to model the contracted energy quantity  $E_{T_i}^{C_1}$  as a proportion of the bid energy quantity  $E_{T_i}^{B_1}$ . This proportion is expressed by a coefficient  $\alpha$ , and models the bid acceptance:

$$Contract_{T_i}^1 : \begin{cases} \Pi_{T_i}^{C_1} = \Pi_{T_i}^{B_1} \\ E_{T_i}^{C_1} = \alpha \times E_{T_i}^{B_1} \end{cases} \quad (3)$$

The energy traded in the intraday market for a given delivery period can be traded during the period when the intraday market is open, at different price. The available public information from the market operator for the intraday trading prices consists of the minimum, the maximum and the mean of the price of the energy traded for each delivery time period. The minimum, mean and maximum of the trading price  $\Pi_{T_i}^1$  inform about the distribution of this trading price for each delivery period  $T_i$ . Here, the

intraday trading price  $\Pi_{T_i}^1$  distribution is modeled as a triangular distribution using the minimum, mean and maximum prices which are public data. An example is shown in the upper plot of [Figure 2](#).

The proposed market settlement model consists in modeling the proportion of accepted energy by the probability of having the bid accepted for a given bid price. Since a trade occurs when the selling and buying bids match, an estimation of the probability of having the bid accepted for a given bid price can be the probability of having the bid price  $\Pi_{T_i}^{B_1}$  inferior to the trading price  $\Pi_{T_i}^1$ . This is illustrated in the lower part of [Figure 2](#). Such an estimation of the  $\alpha$  proportion only considers the bid price to determine whether the bid is accepted or not, and does not consider neither the market liquidity nor the time when the intraday bid is proposed.

$$\begin{aligned} \alpha &= prob(\Pi_{T_i}^{B_1} < \Pi_{T_i}^1) \\ &= 1 - prob(\Pi_{T_i}^1 \leq \Pi_{T_i}^{B_1}) \\ &= 1 - F_{\Pi_{T_i}^1}(\Pi_{T_i}^{B_1}) \end{aligned} \quad (4)$$

where  $F_{\Pi_{T_i}^1}$  is the cumulated distribution function of the trading price  $\Pi^1$  for the delivery period  $T_i$ .

The quantity-price bid for the intraday market results from a decision making method which aims at reducing the imbalance penalties paid by the wind power producer. Such a method is formulated in the next section [IV-C](#) after having derived the expression of the imbalance penalties.

## IV. FORMULATION OF THE INTRADAY MARKET BIDDING PROBLEM

### A. Imbalance Penalty Model

The Transmission System Operator (TSO) is responsible for maintaining the physical balance between production and consumption. As mentioned in section [II-B](#), the wind power producer is assumed to be a balance responsible entity which is thus paying a market imbalance price for any contribution to the global system imbalance. This section describes why energy imbalances may lead to economical risk for the wind power producer. The proposed model is the extension of the regulation market model

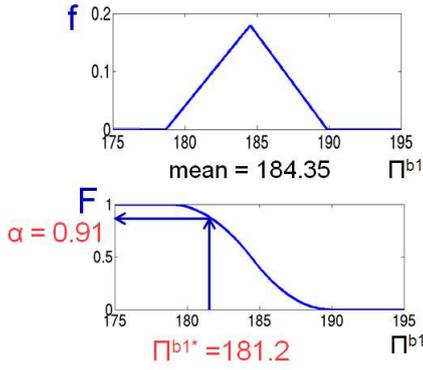


Fig. 2: Upper: Example of modeling the intraday trading price through a triangular distribution. Lower: Example of the estimation of the  $\alpha$  proportion in the Elbas intraday market (NordPool) the 11/04/2004 at 11.00 AM (prices in DKK/MWh).

presented by the authors in [10] for the participation in the day-ahead market only.

1) *Participation only in the Day-Ahead Market:*

In general terms, for a given delivery period  $T_i$ , the revenue  $R_{T_i}$  of a power producer participating in a day-ahead market with a contracted energy  $E_{T_i}^{C_0}$  can be written as the income from the day-ahead contract reduced by the imbalance penalties:

$$R_{T_i} = E_{T_i}^{C_0} \times \Pi_{T_i}^{C_0} - \text{Imb.Pen.} \quad (5)$$

Such revenue can be reformulated as the combination of the income from selling the actual wind generation  $\tilde{E}_{T_i}$  at the spot price  $\Pi_{T_i}^{C_0}$ , minus the cost  $\delta_{T_i}(\tilde{E}_{T_i})$  associated to the energy imbalance that results from the power generation  $\tilde{E}_{T_i}$ :

$$R_{T_i} = \tilde{E}_{T_i} \times \Pi_{T_i}^{C_0} - \delta_{T_i}(\tilde{E}_{T_i}) \quad (6)$$

where the imbalance penalty function  $\delta_{T_i}$  is defined as:

$$\delta_{T_i}(\tilde{E}_{T_i}) = \begin{cases} (\tilde{E}_{T_i} - E_{T_i}^{C_0}) \times (\Pi_{T_i}^{C_0} - \Pi_{T_i}^+), & \tilde{E}_{T_i} > E_{T_i}^{C_0} \\ (\tilde{E}_{T_i} - E_{T_i}^{C_0}) \times (\Pi_{T_i}^{C_0} - \Pi_{T_i}^-), & \tilde{E}_{T_i} \leq E_{T_i}^{C_0} \end{cases} \quad (7)$$

where  $\Pi_{T_i}^-$  and  $\Pi_{T_i}^+$  are the regulation prices for negative and positive imbalance, respectively, for the delivery period  $T_i$ . The energy imbalance is in that case the difference  $(\tilde{E}_{T_i} - E_{T_i}^{C_0})$ .

The determination of the regulation prices varies according to the considered market. In our case (i.e.: NordPool [15]) it is the result of the regulation market, where actors with power reserves place bids for fast production increase or decrease. The regulation price for negative imbalance is greater or equal to the spot price ( $\Pi_{T_i}^- \geq \Pi_{T_i}^{C_0}$ ) and the

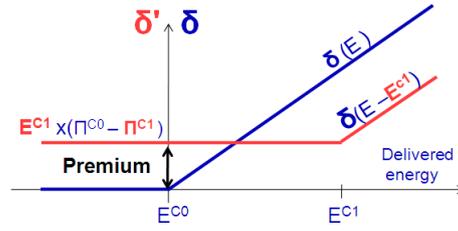


Fig. 3: Modification of the imbalance penalty function.

regulation price for positive imbalance is lower or equal to the spot price ( $\Pi_{T_i}^+ \leq \Pi_{T_i}^{C_0}$ ), so that the imbalance cost function  $\delta$  is generally an increasing function of the absolute energy imbalance. Such a mechanism encourages market participants to have their energy contract as close as possible to their energy delivery.

2) *Combined Participation in the Day-Ahead and Intraday Markets:*

For a given delivery period  $T_i$ , the revenue  $R_{T_i}$  of a power producer participating in a day-ahead market with a contracted energy  $E_{T_i}^{C_0}$ , as well as in the intraday market with a contracted energy  $E_{T_i}^{C_1}$  can be written as the sum of income from both the day-ahead and intraday contracts reduced by the imbalance penalties:

$$R_{T_i} = E_{T_i}^{C_0} \times \Pi_{T_i}^{C_0} + E_{T_i}^{C_1} \times \Pi_{T_i}^{C_1} - \text{Imb.Pen.} \quad (8)$$

In a similar way to the previous section, such revenue can be reformulated as a combination of the income from selling the actual wind generation at the spot price, reduced by penalties related to the energy imbalances. A new imbalance penalty function  $\delta'_{T_i}$  is then derived:

$$R_{T_i} = \tilde{E}_{T_i} \times \Pi_{T_i}^{C_0} - \delta'_{T_i}(\tilde{E}_{T_i}) \quad (9)$$

with

$$\delta'_{T_i}(\tilde{E}_{T_i}) = E_{T_i}^{C_1} \times (\Pi_{T_i}^{C_0} - \Pi_{T_i}^{C_1}) + \delta_{T_i}(\tilde{E}_{T_i} - E_{T_i}^{C_1}) \quad (10)$$

where  $\delta_{T_i}$  is the imbalance penalty function defined in Equation 7. In the proposed model, the participation in the intraday market is considered as a modification of the imbalance penalization mechanism.

This is illustrated in Figure 3 which plots the imbalance penalty functions  $\delta$  relative to the participation in the day-ahead market and  $\delta'$  relative to the participation in the day-ahead and intraday markets. In order to simplify the mathematical expressions, the period  $T_i$  in the index is neglected hereafter in Figure 3. The represented balancing mechanism corresponds the one used in the NordPool area, where balance responsible actors are only penalized for their imbalance if this is opposite to the regulation

measure taken by the TSO. In the specific example in the figure, the TSO is down-regulating. When participating only in the day-ahead market, the imbalance penalty function is  $\delta$  and only positive imbalances are linearly penalized according to Equation 7 for the case of positive imbalance. When participating in both the day-ahead and intraday markets, the imbalance penalty function becomes  $\delta'$ , derived in Equation 10. The first term  $E^{C_1} \times (\Pi^{C_0} - \Pi^{B_1})$  of  $\delta'$  is represented as a constant cost added to the  $\delta$  function. The second term  $\delta(\hat{E} - E^{C_1})$  corresponds to a variable change of the  $\delta$  function, which is represented as a shift by  $E^{C_1}$ .

Participating in the intraday market in order to reduce the imbalance penalties can be further interpreted in Figure 3 as getting the red  $\delta'$  curve lower than the blue  $\delta$  curve. The constant cost can be interpreted as the *premium* to pay in order to reduce the imbalance penalties. Two parameters determine the position of the curve  $\delta'$  relatively to the  $\delta$  curve:  $E^{C_1}$  and  $\Pi^{C_1}$ .

### B. The Decision Making Problem

The imbalance penalty for the intraday market participation is formulated in Equation 10 as a function  $\delta'_{T_i}$  of the delivered energy  $\hat{E}_{T_i}$ . The imbalance penalty is derived only after the energy delivery since it is based on the comparison between the delivered energy and the contracted energy.

The present work proposes a decision making method for the optimal quantity-price bid for the intraday market, in order to reduce the imbalance penalties paid by the wind power producer. The participation in the intraday market takes place before the energy delivery and the imbalance settlement, and, consequently, neither the future delivered wind energy nor the imbalance price are known when making the decision. It is thus necessary to first estimate the imbalance penalty related to a given intraday bid. When making a decision about intraday bid, focus is given to the influence of the intraday bid energy and price on the resulting imbalance penalty. The imbalance penalty is formulated as a function of the intraday bid energy and price, by combining Equation 10 and the intraday market settlement model in Equation 3:

$$\begin{aligned} \delta'_{T_i}(E_{T_i}^{B_1}, \Pi_{T_i}^{B_1}) = & \\ & \hat{\alpha}_{T_i} \times E_{T_i}^{B_1} \times (\Pi_{T_i}^{C_0} - \Pi_{T_i}^{B_1}) + \\ & \hat{\delta}_{T_i}(\hat{E}_{T_i} - \hat{\alpha}_{T_i} \times E_{T_i}^{B_1}) \end{aligned} \quad (11)$$

where  $\hat{\alpha}_{T_i}$  is the estimated proportion of contracted energy,  $\hat{\delta}_{T_i}$  is the estimated imbalance penalty function and  $\hat{E}_{T_i}$  is the estimated wind power production for the period  $T_i$ . When participating in the intraday market, the wind power producer is supposed to have already participated in the corresponding day-ahead market. Consequently, the day-ahead contract energy  $E_{T_i}^{C_0}$  and price  $\Pi_{T_i}^{C_0}$  are known.

The decision making problem about the intraday bid which minimizes the estimated imbalance penalty can then be formulated as the following optimization problem:

$$\begin{aligned} & [E_{T_i}^{B_1*}, \Pi_{T_i}^{B_1*}] \\ = & \arg \min_{[E_{T_i}^{B_1}, \Pi_{T_i}^{B_1}]} \delta'_{T_i}(E_{T_i}^{B_1}, \Pi_{T_i}^{B_1}) \quad (12) \\ = & \arg \min_{[E_{T_i}^{B_1}, \Pi_{T_i}^{B_1}]} (\hat{\alpha}_{T_i} \times E_{T_i}^{B_1} \times (\Pi_{T_i}^{C_0} - \Pi_{T_i}^{B_1}) \\ & + \hat{\delta}_{T_i}(\hat{E}_{T_i} - \hat{\alpha}_{T_i} \times E_{T_i}^{B_1})) \end{aligned}$$

### C. Proposed Approach

The optimization problem formulated in Equation 12 is based on market price forecasts. First, the  $\alpha$  parameter model is based on the intraday price distribution as described in Equation 4. Consequently, estimating  $\alpha$  relies on the estimation of the intraday market price distribution. Similarly, Equation 7 shows that estimations of the regulation and spot prices are necessary for estimating the imbalance cost function. However, market price prediction is not a trivial task. Market prices are highly volatile and hardly predictable as they may exhibit a feature of spikes in trajectories, as described in [16]. Consequently, the results from the general decision-making problem might be sensitive to the price forecast errors.

The proposed approach consists in bidding in the intraday market in order to *adjust* the contracted production using updated wind power forecasts. Consequently, the intraday bid quantity equals the difference between the estimated delivered energy  $\hat{E}_{T_i}$  during  $T_i$  and the energy contracted in the day-ahead market  $E_{T_i}^{C_0}$  for the same period. The quantity bid is positive since the wind power producer is assumed to participate in the electricity market only with selling (offer) bid as explained in section II-B.

$$E_{T_i}^{B_1} = \begin{cases} \hat{E}_{T_i} - E_{T_i}^{C_0}, & \hat{E}_{T_i} > E_{T_i}^{C_0} \\ 0, & \hat{E}_{T_i} \leq E_{T_i}^{C_0} \end{cases} \quad (13)$$

The estimated delivered energy  $\hat{E}_{T_i}$  is determined using the most recent update of the wind power forecast available when bidding:  $\hat{E}_{T_i} = \hat{P}_{T_i}^{WF} \times \Delta t$ .

For the considered intraday market, the contract price equals the bid price. The bid price  $\Pi_{T_i}^{B_1}$  thus determines the premium cost  $E_{T_i}^{C_1} \times (\Pi_{T_i}^{C_0} - \Pi_{T_i}^{B_1})$ . The higher is the bid price, the lower will be the premium. However, the bid price also determines the proportion of contracted energy  $\alpha_{T_i}$ , according to Equation 4. The higher the bid price, the lower will be the probability to have the bid accepted.

The proposed bid quantity derived in Equation 13 focuses on the reduction of the positive but not

the negative imbalance penalties. When considering the definition of  $\delta'$  in Equation 10 and the positive imbalance case in the definition of  $\delta$  in Equation 7, two values of  $\Pi^{B_1}$  can be noted:

- if  $\Pi^{B_1} = \Pi^{C_0}$ , the premium is null. Furthermore, in the case of perfect prediction of the wind power,  $E^{B_1} = \tilde{E} - E^{C_0}$  and consequently  $\delta(\tilde{E} - E^{C_1}) = 0$  if the bid is accepted. The imbalance penalty is reduced to 0 after the intraday market participation:  $\delta'(E^{C_1}) = 0$ .
- if  $\Pi^{B_1} = \Pi^+$ , then the imbalance penalty is unchanged after the intraday market participation:  $\delta(E^{C_1}) = \delta'(E^{C_1})$ .

If  $\Pi^{B_1} = \Pi^{C_0}$ , the  $\alpha$  proportion will be lower than if  $\Pi^{B_1} = \Pi^+$ , since the regulation price for positive imbalance  $\Pi^+$  is lower than the spot price  $\Pi^{C_0}$ .

Finally, in order to analyze the influence of the intraday bid price on the reduction of imbalance penalties, we propose to formulate the intraday bid price as:

$$\Pi_{T_i}^{B_1} = \hat{\Pi}_{T_i}^+ + \beta \times \left( \Pi_{T_i}^{C_0} - \hat{\Pi}_{T_i}^+ \right), \quad \beta \in [-0.2, 1.2] \quad (14)$$

where  $\hat{\Pi}_{T_i}^+$  is the estimated regulation price for positive imbalance available when participating in the intraday market.

## V. SIMULATION METHODOLOGY

### A. Overall Description

As shown in Figure 4, wind power measures and Numerical Weather Predictions (NWP) are used by the wind power forecasting module to produce Wind Power (WP) forecasts. Such forecasts are used as input for bidding in the day-ahead market, according to Equation 1. The day-ahead contract results from the market settlement model detailed in Equation 2. To make the intraday bid, we take into account the day-ahead contract, updated wind power forecasts as well as the estimated regulation price. The model proposed for the intraday bidding is the one explained in the previous section IV-C. The intraday market settlement based on the  $\alpha$  proportion of accepted energy, given in Equation 4, is used to derive the intraday contract.

The market evaluation consists in the quantification of the global outcome of the simulations resulting from the utilization of the proposed method. Such outcome includes the revenue, the penalties and the energy imbalances associated to the participation of the considered wind power producer in the day-ahead and intraday markets.

### B. Wind Power Forecasts

Forecasts of wind power are used as input to both the day-ahead and intraday market participations. In this work, such forecasts were obtained using a state-of-the-art statistical model described in [17]. This model aims to represent the relationship

between the wind speed forecasts and the power output of the wind farm. This approach is often referred as *power curve modeling*. Here, the power curve is modeled by a piecewise least squares linear fitting of the wind-speed to power relation.

The forecasts used for the intraday market are updated forecasts, produced using as recent as possible wind power measurements as well as updated Numerical Weather Predictions (NWP). The errors of these updated forecasts are normally lower than the errors of the forecasts used for the day-ahead market participation.

### C. Regulation Price Forecasts

The proposed intraday bid approach uses estimations of regulation price for positive imbalance as inputs. A first estimation of such regulation price can be obtained by taking the mean value for a period of time preceding the case study. This basic forecasting approach will be denoted hereafter as the *Realistic* case. The case where a perfect knowledge of the regulation prices is also considered in this work for assessing the sensibility of the results regarding the regulation price forecasts. This case is denoted as *Perfect* case. Advanced regulation price forecast models can be found in [18].

## VI. CASE STUDY

### A. Description of the Case Study

In this study, we considered a 18 MW wind farm located in the North West of Denmark. Results are presented and analyzed for the participation of this wind farm in the NordPool day-ahead and intraday electricity markets during the period between the 1<sup>st</sup> of January 2002 and the 31<sup>st</sup> of March 2002 [15].

To produce the wind power forecasts, Hirlam Numerical Weather Predictions (NWPs) were used as well as measured wind power from the years 2000 and 2001 as learning and testing sets, respectively. The Hirlam NWPs are updated every 12 hours.

In NordPool, the contracts for the coming day are traded on the day-ahead market, named Elspot. The Elspot gate closure time is at 12:00 *pm* (local time) of the preceding day. Hence, we used the last available wind power forecasts (11:00 *am* of the same day) as input to day-ahead market participation module. Forecast horizons were selected in order to get the forecasts for the next day.

The corresponding intraday market is the Elbas market which takes place through a continuous trading mechanism. For the present work, intraday bids are proposed 6 hours before the delivery period. Regarding the balancing settlement, balance responsible actors are only penalized for their imbalance if these are opposite to the regulation measure taken by the TSO. The interested reader may refer to [15] for obtaining further information on NordPool market rules.

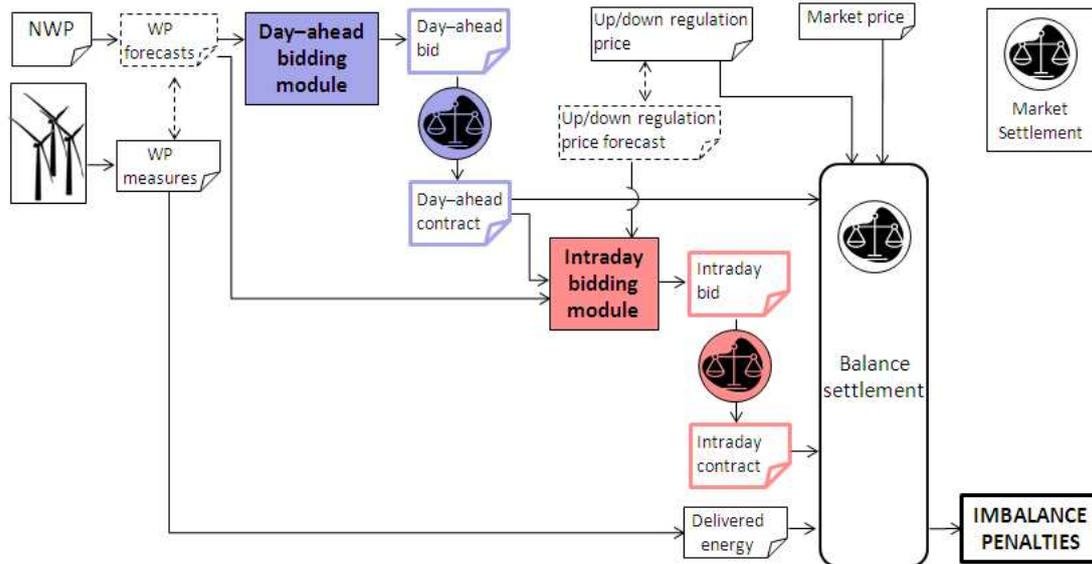


Fig. 4: Schematic representation of the overall simulation for the combined participation in the day-ahead and intraday markets.

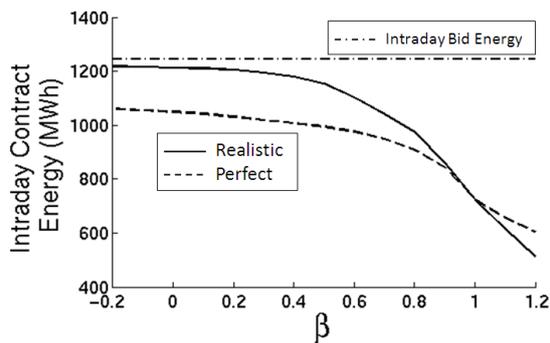


Fig. 5: Influence of the intraday bid price parameter  $\beta$  on the intraday contract energy.

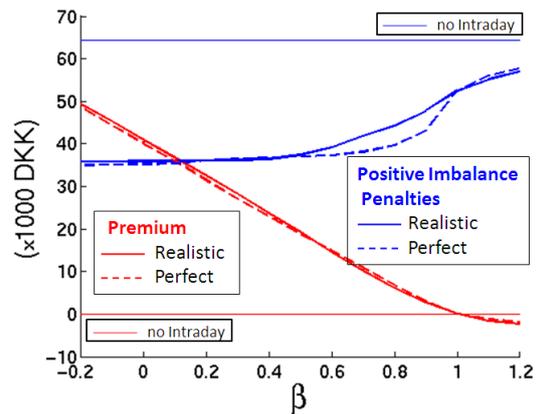


Fig. 6: Influence of the intraday bid price parameter  $\beta$  on the premium and on the positive imbalance penalties.

### B. Results and Discussion

The aim of this section is to assess the reduction of imbalance penalties when the proposed approach for the combined participation in the day-ahead and intraday markets is used. The analysis focuses on the influence of the decision making parameter  $\beta$  on the imbalance penalties.

Figure 5 describes the influence of the intraday bid price parameter  $\beta$  on the intraday contract energy. The horizontal line shows the intraday bid energy which is independent from the parameter  $\beta$ . The ratio between the contracted energy and the bid energy represents the  $\alpha$  proportion. The simulation shows that increasing the bid price (through the  $\beta$  parameter) decreases the  $\alpha$  proportion of contracted energy, for both the realistic and the perfect prediction cases.

Figure 6 describes the consequences of the variation of the intraday contracted energy showed in Figure 5, on the premium and on the positive imbalance penalties, which are derived in Equation 10. The

horizontal red and blue lines represent the positive imbalance penalties and the premium when there is no participation in the intraday market. When the  $\beta$  parameter increases, the intraday bid price increases and the intraday contracted energy decreases, which decreases the premium as shown with the red curves. At the same time, the decrease of the intraday contracted energy leads to an increase of the positive imbalance penalties. These analyses are valid for both the realistic and the perfect prediction cases.

Finally, Figure 7 describes the consequences of the variation of the premium and the positive imbalance penalty shown in Figure 6, on the imbalance penalties and on the market revenue. The market revenue is normalized by the revenue that would be obtained without imbalance penalties or with perfect prediction of wind power. The light horizontal line

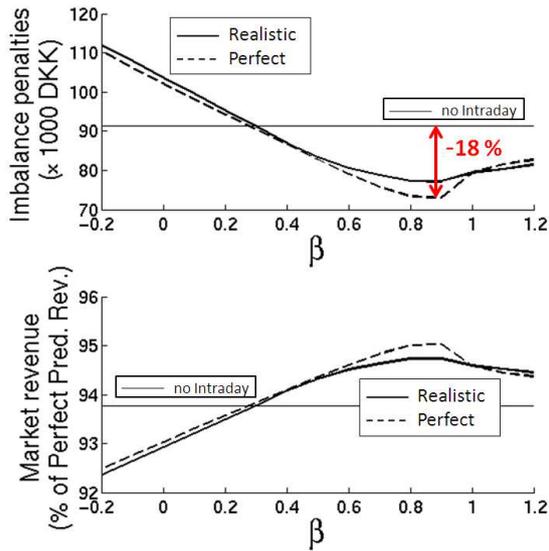


Fig. 7: Influence of the intraday bid price parameter  $\beta$  on the imbalance penalties and on the market revenue.

represents the case when there is no participation in the intraday market: the market revenue is then nearly 94% of the perfect prediction revenue.

For  $\beta \leq 0.3$ , the imbalance penalties resulting from the combined participation in the day-ahead and intraday markets are greater than the ones relative to participating only in the day-ahead market (no intraday). This is explained by the high premium. For  $\beta > 0.3$ , the participation in the intraday market reduces the imbalance costs.

For  $-0.2 \leq \beta \leq 0.9$ , the imbalance costs decrease when  $\beta$  increases. This is explained by the premium decrease and the slight positive imbalance cost increase in Figure 6. The imbalance penalties are minimum when  $\beta$  is close to 0.9; they are then reduced by approximately 16% in the realistic case and 18% in the perfect case. The market revenue is then increased by 1% to nearly 95% of the perfect prediction revenue.

## VII. CONCLUSIONS AND FURTHER WORK

In this study, a novel method for an efficient combined participation of wind farm operators into both the day-ahead and intraday markets is proposed. The participation in an intraday market is formulated as a hedging method which aims to reduce the imbalance penalties.

The method was presented in detail and applied to a realistic test case, where real-world measured data and forecast obtained by a state-of-the-art wind power forecasting model are used. The present case study shows that the participation in the intraday market can reduce the imbalance penalties by up to 18%. The obtained results demonstrated a low sensibility of the results to the regulation price forecasts.

A model for the settlement of continuous trading market is proposed. This model is based on the available data of market prices; further work should consider the market liquidity. The influence of the time when the intraday bid is proposed should be considered as well.

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