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Risk-Constrained Offering Strategy of Wind Power Producers Considering Intraday Demand Response Exchange

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***Abstract*—This paper proposes a comprehensive stochastic decision making model for wind power producers' (WPPs) participation in a competitive market. The presented model incorporates three trading floors: 1) day-ahead; 2) intraday; and 3) balancing markets. An efficient integration of intraday markets allows market players to react to the latest information (e.g., more accurate wind forecast). Creating a platform that allows demand response resources (DRRs) to contribute to the intraday markets improves both WPP's business and power system flexibility. In this context, providing an intraday demand response exchange (IDRX) market for trading demand response (DR) between DR providers and DR users (e.g., WPPs) is proposed. The problem uncertainties, such as wind power and market prices, are considered using a scenario-based approach. Moreover, an appropriate risk measurement, conditional value-at-risk (CVaR), is incorporated with the model. Numerical results illustrate that utilizing DR to compensate wind generation imbalances can increase WPP's profit and reduce the related risks.**

***Index Terms*—Demand response exchange (DRX), electricity market, risk management, wind power producer (WPP).**

NOMENCLATURE

A. Indices

d	Index of demand response (DR) providers (DRPs).
k	Index of bided blocks of DRPs.
s	Index of scenarios.
t	Index of hours.

B. Parameters

α	Confidence level.
ρ_s	Occurrence probability of scenario s.
β	Weighting factor to achieve tradeoff among profit and conditional value-at-risk (CVaR).
$\pi^D_{\mathrm{ts}}, \pi^I_{\mathrm{ts}}$	Day-ahead (DA) and intraday market prices.
π^B_{dt}	Bilateral contract price between DRP d and wind power producer (WPP).
r^+_t, r^-_t	Positive and negative imbalance ratios with DA market price.
$P^{\max}$	Installed wind power.
W_{st}	Wind power production.
c^k_{dt}	Bidding cost of block k of DRP d.
$\mathrm{DR}^{\max}_{\mathrm{dt}}$	Maximum bidding capacity of DRP d.

C. Variables

EP	Expected profits of WPP in scheduling horizon.
P^D_{ts}	Scheduled production of WPP in DA market.
$P^{\mathrm{I}}_{\mathrm{ts}}$, sell	Selling power of WPP in intraday market.
$P^{\mathrm{I}}_{\mathrm{ts}}$, buy	Buying power of WPP in intraday market.
q^k_{dt}	Scheduled power of block k of DRP d.
$\mathrm{DR}_{\mathrm{dts}}$	Traded power of DRP d in demand response exchange (DRX).
$\mathrm{CDRP}_{\mathrm{dts}}$	Cost of DR related to DRP d.
Δ_{ts}	Total deviation for wind production.
$\Delta^+_{\mathrm{ts}}, \Delta^-_{\mathrm{ts}}$	Positive and negative deviations.
ξ	Value-at-risk.
η_s	Auxiliary variable for computing CVaR.
B_s	Profit in scenario s.
$P^{\mathrm{Sch}}_{\mathrm{ts}}$	Total scheduled power of wind producer.
P^B_{dts}	Power quantity of bilateral contract between DRP d and WPP.

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I. INTRODUCTION

DUE TO the increase of energy consumption and environmental conservation concerns and decrease of fossil fuel resources, penetration of renewable resources has significantly grown throughout the world [1]. Among the renewable energies, wind power assigns a considerable share of the generation portfolio.

Government subsidies, tax exemption, and market-based and nonmarket-based support schemes are various solutions that have been designed and implemented to support wind power producers (WPPs) in different countries all over the world.

Nevertheless, it seems that providing an appropriate context for the participation of WPPs in a competitive electricity market to achieve profit through a market mechanism is the best way to encourage and support WPPs. Optimal wind site selection, creating efficient multitechnology portfolio (such as wind/storage or wind/hydro), achieving more accurate individual forecast, and system balance efficiency are the main positive effects of exposing WPPs to market signals [2]. However, enforcing WPPs to participate in electricity markets increases their risks and impose more transaction costs on them in comparison to the feed-in tariff system.

Because of limited predictability and associated uncertainty of wind power, WPPs are unable to compete with other market players unless a suitable condition is provided for them. Successful market integration of wind power will require efficient market designs. Despite undeniable advancements of wind power forecasting, the day-ahead (DA) forecasts can cause the uncertainty of electricity systems to increase. Changing the periods of wind forecast from DA to intraday can decrease forecast errors drastically. Allowing WPPs to react to the latest information gains (i.e., more accurate wind forecast) is the key for improving market design and facilitating WPPs' participation in electricity market.

Intraday markets have positive impacts on both producers and operation of power systems. Corrections needed after DA gate closure can lead to a reduction in volume and price of real-time balancing market and allows electricity markets to benefit from the integration of wind energy. Reducing the period of uncertainty around wind generation and allowing WPPs to adjust their offers more frequently are the main potential benefits of subhourly energy markets such as the intraday [3].

Several research works have been published to improve the performance of WPPs in electricity markets. The publications can be categorized into three major approaches:

1) improving market rules, regulations, and structures;
2) improving uncertainties' modeling accuracy;
3) utilizing other technologies and facilities beside WPPs.

A large amount of previous research has considered the structure of two conventional electricity markets: 1) DA and 2) balancing markets (e.g., [4], [5]). In these works, scenario-based stochastic programming approaches have been used from the WPP's viewpoint to maximize its profit. Uncertainties in wind availability and market prices are taken into account using scenario generation techniques. However, only a limited number of papers have considered an intraday market mechanism that allows WPPs to modify their offers before delivery time in order to reduce imbalance costs and increase expected profit [6]–[8]. In some previous works, improving the problem formulation has been accomplished by reducing the uncertainties of WPPs compared with other market players.

In [6], the uncertainty pertaining to wind power and market prices has been considered using ARIMA time series. In addition, risk on profit variability is considered in several papers using conditional value-at-risk (CVaR) (e.g., [5]–[7] and [9]). In [9], an improved problem formulation has been proposed to study the impacts of imbalance ratios on WPP's offering strategy in the DA market in order to deal with wind power variability. That paper considers the stochastic nature of wind power using the Kernel density estimation method. Furthermore, utility theory is applied alongside CVaR to consider the risk-aversion level of WPP.

Utilizing other technologies and facilities besides WPPs as supplemental resources has been addressed in recent studies. In [10] and [11], utilization of a storage device alongside wind farms has been suggested to reduce imbalance costs. Moreover, [12] deals with the review of various storage systems for wind power applications. The combined operation of wind farms and hydro power is another solution to decrease the wind power imbalance cost in electricity markets [13], [14]. Furthermore, gas turbines and compressed air energy storages (CAESs) have been compared in [15] for eventual supplemental generation besides wind farms. Two other papers have gone a step further by recommending demand response (DR) as a complementary resource [16], [17]. A flexible load following concept is proposed in [16] with the aim of satisfying a multiobjective problem. The load follows the wind farm output in order to satisfy objectives, such as available transmission capacity maximization while minimizing losses. Ref. [17] is one of the few studies that examines the impact of DR in WPP's profit. In [17], an offering optimization model for aggregated wind power and flexible loads in the DA market is suggested. Flexible load is considered as a storage unit that can cover wind fluctuations and reduce imbalance costs of WPP. The only uncertainty source of that paper is wind power generation, while WPP's risk is not considered.

In the 24th wind task of the International Energy Agency (IEA) that investigates issues, impacts, and economics of wind integration, DR was introduced as the most flexible and cost-effective option to facilitate the integration of wind [18]. DR technologies face low costs for providing intraday and balancing services, especially for positive balancing power such as load reduction. At present, strict rules prevent the large potential of demand response resources (DRRs) for engaging in intraday and balance markets. Also, only DA market provides a sufficient incentive for DR participants. However, using DRRs ensures the physical flexibility within the system. Moreover, formation of liquid markets close to delivery such as the intraday markets guarantees that this flexibility will be accessible for those who need it.

Hence, the current paper investigates the impacts of the full flexibility that DRRs can offer to limit cost growths due to wind uncertainty. Due to the considered mechanism for imbalance penalties, as explained below, the excess of wind power partially reduces WPP's revenues, while in cases where the shortage of wind power occurs a cost is imposed on WPPs.

Therefore, decreasing the amount of negative imbalances seems more crucial. In this situation, in intraday timescales, demands can adjust their consumption to compensate the deficit of wind power through load reduction at a given amount of payment. This problem has been modeled in terms of intraday demand response exchange (IDRX) market. It should be noted that, by considering the IDRX market, the first and third above previous approaches are taken into account together. The objective of WPPs while attending the market is the maximization of their profits considering the entire operation sequences, DA, intraday, and balancing markets, which are reflected in this paper using three-stage trading floors.

TABLE I
CLASSIFICATION OF DR STUDIES

No.	Name	Participants	Type of DR	Major issues
1	Retailer-based	Retailers vs. customers	Price-based and reward-based	Volatile spot price
2	TSO-based	TSOs vs. customers	Reward-based	System security
3	Distributor-based	Distributors vs. customers	Reward-based	System security
4	DRX market	Retailers, TSOs, distributors, etc.	Price-based and reward-based	Volatile spot price, system security, etc.

In short, the three main contributions of the present research are summarized as follows.

1) An efficient integration of short-time frame markets close to real time such as intraday, allowing WPPs to modify their offers due to the latest information gains.
2) A three-stage stochastic programming formulation is proposed to maximize WPP's profit and manage its risk to deal with wind power uncertainties.
3) Integrating DRR with intraday market in order to manage nondispatchable resource uncertainty, such as wind through designing the IDRX market in both pool-based and contract-based structure.

The paper continues as follows. Section II presents the problem description. Section III models the uncertainty characteristics related to wind power and market prices. Section IV describes the formulation of the proposed framework, which comprises DR modeling, risk modeling, and objective function representation. Section V implements the proposed framework on a case study. Section VI is the conclusion.

II. PROBLEM DESCRIPTION

Most of the energy is traded in DA market. Hence, WPP has to submit its offers for each hour of next day, several hours in advance. The offered energy has a degree of uncertainty due to the intermittent and volatile nature of wind power. The intraday market is a corrective market with a shorter time schedule that is closer to the operation hour. Consequently, WPPs can modify their offers suggested to DA market in intraday market when forecasts for the wind power generation become more accurate at shorter lead time. Due to the uncertainties related to consumers' participation in DR programs, it seems that DRRs have a large potential for enrolling in intraday market in comparison with DA market. This is because the intraday market is closer to real-time dispatch. Since the intraday market is closer to real time, the estimated DR is associated with a lower error and consumers can estimate the amount of their DRs more precisely. Hence, the consumers incur in less financial losses because of penalty payment prevention due to a more accurate DR estimation and they will be more and more encouraged to participate in DR programs.

The existing research on DR can be classified into four major categories: 1) the retailer-based, 2) the transmission system operator (TSO)-based, 3) the distributor-based, and 4) the demand

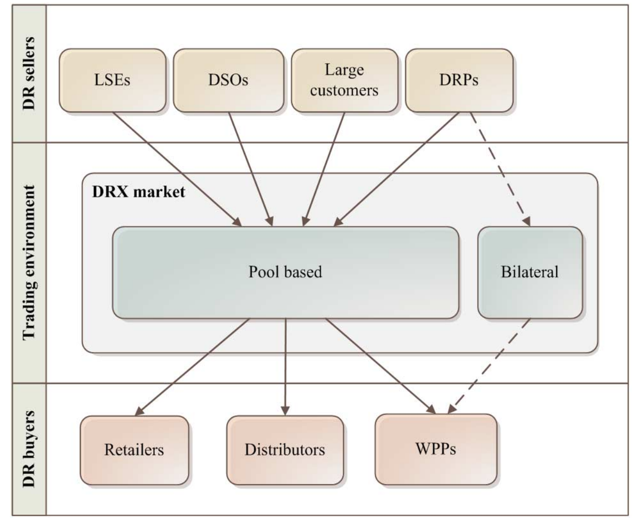

Fig. 1. Schematic of the proposed DRX model.

response exchange (DRX) market, as presented in Table I [19], [20]. As mentioned in [19] and [20], the first three DR research categories could be commonly called partial scheduling approaches because they focus on DR benefits for only a limited number of electricity market players. Consequently, partial solutions could be significantly suboptimal technically, financially, and socially as emphasized in [19]–[21].

The DRX concept was firstly proposed in [19]. Participants in the DRX market are categorized into two different groups: 1) DR sellers and 2) DR buyers.

Players in the first group are the ones who supply DR, including large consumers that can attend the DRX market by themselves or new market players such as distribution system operators (DSOs), load service entities (LSEs), and DRPs that are responsible for aggregating customers' responses. The schematic of the proposed intraday DRX model is shown in Fig. 1.

The second group includes retailers, distributors, and WPPs who purchase DR to improve their profitability and business. Nevertheless, DR is traded as a virtual commodity between the DR buyers and the DR sellers in two different ways: 1) pool-based and 2) contract-based.

As there are now multiple buyers and sellers in the IDRX market, there should be an intermediate role for settling the exchange of DR between them. This new entity is called demand response exchange operator (DRXO).

In order to ensure power system security, DRX must halt for the TSO to balance the whole power system using available generation reserves, usually in an hour-ahead time scale [19]. However, the mentioned issue is beyond the scope of this paper.

Although the DRX concept is not a contribution of this paper, consideration of a DRX market that is formed in intraday is a novel issue that has not been addressed in the literature. The most important motivations for the establishment of IDRX market, in addition to the conventional intraday market, are summarized as follows.

1) Since the DRX market can be a local market, its rules and regulations can depend on regions as well as they can be

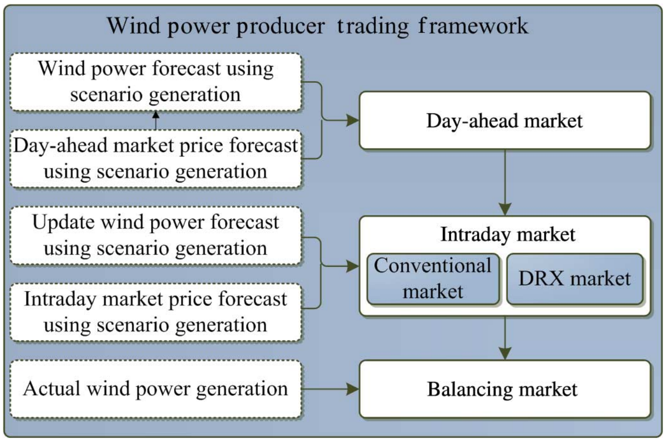

Fig. 2. Schematic of the proposed trading floors considering intraday DRX.

less strict than regular intraday market. For instance, the minimum required capacity for the market participants can be much less than the regular markets. On this basis, the number of participants in the DRX market can be increased; thus, competition between aggregators can be improved. This competitive situation will make the aggregators propose diverse incentive mechanisms and attractive programs for consumers in order to retain in competition with other participants. In addition, the consumers can sale their DR capacity with higher rates because they will be faced with more various DR buyers (i.e., aggregators). Therefore, the market performance and overall efficiency under DRX market will be increased.

2) As mentioned above, the DRX market can create an appropriate opportunity for small consumers to deal with multiple DR-involved players in a competitive way. This means that DRX market can attract the small consumers by making a competitive environment and consequently it can motivate them to participate in DR programs more actively. Moreover, it has been proven in [20] and [21] that trading DR in the DRX context has led to allocate payments among all the players fairly and with the aim of ensuring the maximum market efficiency.

The DRX market has additional advantages for DR users, DR providers (DRPs), and power grid. DR users buy DR to improve their business, whereas DRPs sell DR to improve their revenues. Particularly in the WPP problem, WPP can compensate its unexpected shortages in wind generation by participating in the local IDRX to decrease its imbalance penalties in balancing market. On the one hand, this can increase the profit of WPPs in the electricity market and consequently motivate private investors to invest in expansion of wind power in the power system. On the other hand, if WPPs can reduce their uncertainties locally, propagation of the uncertainties to upstream grid will be avoided.

Therefore, the need for reserve capacity in the power grid will be decreased. It means that the use of expensive fast response and high ramping generation units in the power grid with high penetration of wind power will be reduced. Hence, the total cost will be decreased and the overall efficiency will be improved.

Since the aim of WPP is to maximize the profit considering the entire operation cycle, a three-stage trading floor is proposed to cover DA, intraday and balancing markets. The proposed trading framework is illustrated in Fig. 2.

In the first stage of the proposed framework, wind generation and DA market price are forecasted for offering in DA market.

In the second stage, WPPs can get new information and hence update their DA scheduling between the closures of the DA and intraday market. Also, WPPs must predict intraday market clearing price in order to minimize the deviations between the latest existing forecast and the DA schedule, as well as minimize their financial risks. It is notable that market prices are supposed to be a stationary stochastic parameter. This means that the related market prices should be forecasted based on the trading floor just for once. On the other hand, the wind power generation is considered as a dynamic stochastic parameter that should be updated in each trading floor due to the latest obtained information in the decision making process.

The third stage of the proposed framework is appertained to balancing market. When wind generation is higher than the forecasted value in the second stage, the system requires downward regulation services that are provided by other generation units. In such situation, WPPs must resale the excess of their generations at a price lower than DA market's one.

On the contrary, in the case of wind power shortage, the system requires upward regulation services to compensate the deficit of generation. In this situation, WPPs must cover their shortages at a price higher than DA market's one, which seems rational. This mechanism is applied in the balancing market of Spain, as exerted in [6].

III. Uncertainty Characterization

In this paper, two major sets of uncertainty are considered: 1) uncertainty of market prices and 2) uncertainty of wind power generation. It is notable that load uncertainty can affect the problem. However, the load level and market price are closely dependent. This means that market price is low in off-peak periods and high in peak periods. On the other hand, load uncertainty does not have significance from the Generation Company (GenCo) viewpoint, such as WPP. Thus, market price uncertainty is modeled alongside wind power generation.

A. Wind Power Uncertainty Modeling

Wind power productions rely on wind speeds that vary randomly according to time. The distribution function of wind speed is usually considered using a Weibull distribution [22]. The probability density function (PDF) of wind speed may be formulated as

$$f_v(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^k\right] \tag{1}$$

where positive constants c and k denote the scale and shape factors, respectively. Also, V represents the parameter of distribution function (i.e., wind speed). The PDF is split into S_N

scenarios. The probability of each step prob_i $(i = 1, \ldots, S_N)$ can be obtained as follows:

$$\text{prob}_i = \int_{\text{WS}_i}^{\text{WS}_{i+1}} f_v(V)dV, \quad i = 1, 2, \ldots, S_N \tag{2}$$

where WS_i denotes the wind speed of ith scenario. The produced power $P_{\text{GW}(i)}$ corresponding to a specific wind speed WS_i can be obtained through

$$P_{\text{GW}} = \begin{cases} 0, & 0 \le \text{WS}_i \le V_c \text{ or } \text{WS}_i \ge V_{c0} \\ P_r\begin{pmatrix} A + B \times \text{WS}_i \\ +C \times \text{WS}_i^2 \end{pmatrix}, & V_c \le \text{WS}_i \le V_r \\ P_r, & V_r \le \text{WS}_i \le V_{co} \end{cases} \tag{3}$$

where A, B, and C are constants that can be computed in accordance with [22], while V_c, V_{c0}, and V_{cr} represent cut in, cut out, and rated speeds, respectively.

Different realizations of wind power production can be modeled using a scenario generation process based on Roulette wheel mechanism (RWM). First, the distribution function is separated into several class intervals. Afterward, each interval is related to a certain probability achieved by the PDF. Consequently, due to the various intervals and the mentioned probabilities, RWM is utilized to generate hourly scenarios, as in [23].

B. Market Prices Uncertainty Modeling

To successfully participate in the electricity market, WPPs have to forecast market prices. In this paper, two uncertain market prices are considered: DA and intraday. In order to develop an accurate model, market prices have been characterized by log-normal distribution in each hour [24].

Thus, the PDF of market prices is represented by

$$f_p(E^{\text{pr}}, \mu, \sigma) = \frac{1}{E^{\text{pr}}\sigma\sqrt{2\pi}} \exp\left[-\frac{(\ln E^{\text{pr}} - \mu)^2}{2\sigma^2}\right] \tag{4}$$

where μ and σ represent mean value and standard deviation, respectively, and E^{pr} is the distribution function parameter (i.e., electricity market price).

Because of considering a high level of precision, the distribution function should be divided into 20 segments in each hour and reflecting a probability for each segment.

Finally, in a similar way, RWM technique is applied for scenario generation in each hour. It is obvious that higher number of scenarios produce a more accurate model to consider the mentioned uncertainties. However, it yields an unmanageable optimization problem. Hence, a scenario reduction technique is considered, using KMEANS clustering technique [25], resulting in a scenario tree with 10 independent scenarios that are used in case studies. It should be noted that the correlations among market prices and wind generation are out of the scope of the present paper.

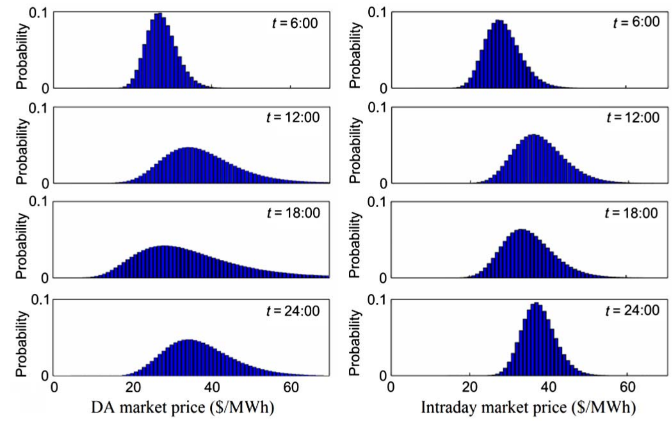

Fig. 3. Typical PDF of DA and intraday market prices for several hours.

Fig. 3 depicts a typical PDF of prices for DA and intraday markets obtained from historical data for 4 h, as a sample.

C. Stochastic Programming Approach

In order to consider the impact of the uncertainties mentioned above on the strategic behavior of WPP, they have been characterized as stochastic procedures and the problem has been solved using a three-stage stochastic programming approach. In the proposed approach, each stage denotes a market horizon. The classification of decision variables of each stage is presented as follows.

1) $S1$: The first stage (*here-and-now*) stochastic decision variables are related to DA market (P_{ts}^{D}).
2) $S2$: Stochastic variables (CDRP_{dts}, DR_{dts}, q_{dts}^{k}, P_{ts}^{I}, sell, P_{ts}^{I}, buy, and P_{dts}^{B}) are the second stage (*wait-and-see 1*) variables that denote the intraday horizon.
3) $S3$: The third stage (*wait-and-see 2*) stochastic decision variables are $P_{\text{ts}}^{\text{Sch}}$, Δ_{ts}^{+}, and Δ_{ts}^{-}.

IV. Mathematical Formulation

A. DR Modeling

DR refers to a tariff or program established to motivate changes in electricity consumption by end-use customers in response to changes in the price of electricity over time [26]. Several studies have described the advantages of DR in electricity markets [27], [28]. According to the benefits of DR programs for achieving reliable and efficient electricity markets, the programs have been legalized and implemented in several countries [29]. Ref. [30] has assessed DR benefits in seven categories: 1) economic; 2) environmental; 3) pricing; 4) market efficiency; 5) customer services; 6) lower cost electric system and services; 7) risk management and reliability.

Frequently, the customers express a lack of appetite for the perceived risk of DR involvement and exposure to a complex and unpredictable wholesale market. In order to improve DR

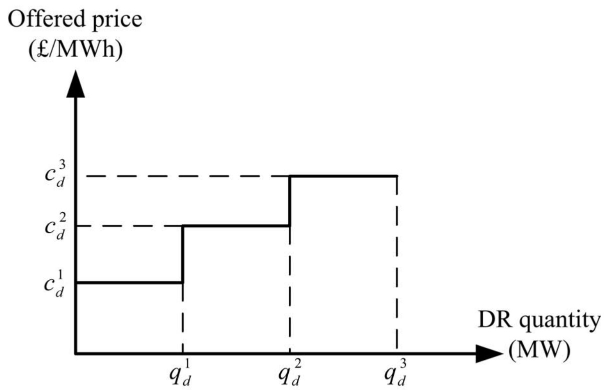

Fig. 4. Typical price-quantity offer of a DRP.

benefits, a player called DRP is proposed to take part in the electricity market. The most valuable role of DRPs is to aggregate and manage responses of small and other hard to reach customers. Nevertheless, DR is considered as a virtual commodity tradable between DR buyers and DR sellers, the so-called DRX market. In the present paper, both pool-based and bilateral DRX models have been considered in the intraday market.

The DRP offered price-quantity in the pool-based DRX market is illustrated in Fig. 4. The description of DRPs price-quantity is formulated as follows:

$$\mathrm{DR}_{\mathrm{dt}} = \sum_{k=1}^{\mathrm{NQ}_d} q_{\mathrm{dt}}^k \tag{5}$$

$$\mathrm{CDRP}_{\mathrm{dt}} = \sum_{k=1}^{\mathrm{NQ}_d} c_{\mathrm{dt}}^k . q_{\mathrm{dt}}^k \tag{6}$$

$$q_{\mathrm{dt}}^k \le q_{\mathrm{dt}}^{k,\max} \tag{7}$$

$$\mathrm{DR}_{\mathrm{dt}} \le \mathrm{DR}_{\mathrm{dt}}^{\max}. \tag{8}$$

Equation (7) limits the maximum achievable DR in each quantity block. The maximum amount of DR that DRP d can provide in each hour is given by (8).

Note that NQ_d represents the number of bidding blocks of DRRs.

B. Incorporating Risk Management

CVaR can be a suitable technique to incorporate risk management into the problem [31]. Value-at-Risk (VaR) has the additional difficulty for stochastic problems, because it requires the use of binary variables for its modeling. Instead, CVaR computation does not require the use of binary variables and it can be modeled by simple use of linear constraints.

The formulation of CVaR is indicated by

$$\mathrm{Max} \quad \xi - \frac{1}{1-\alpha} \sum_{s=1}^{S_N} \rho_s . \eta_s \tag{9}$$

subject to

$$-B_s + \xi - \eta_s \le 0 \tag{10}$$

$$\eta_s \ge 0. \tag{11}$$

The parameter α is usually assigned within the interval of 0.90–0.99, being in this work set to 0.95. If the profit of scenario s is higher than ξ, the value of η_s is set to 0. Otherwise, η_s is assigned to the difference between ξ and the related profit. The above formulated constraints are applied to unify the risk-metrics CVaR.

C. Objective Function

The objective of WPP is to maximize expected profit considering risk constraints. According to the proposed market model, the objective function can be expressed as shown in (12), at the bottom of the page. where E is a function that is applied to calculate the expected value by using the summation of the multiplied value obtained from each scenario and the occurrence probability of the related scenario.

The first line of the objective function in (12) denotes the expected profit obtained from the first stage of the stochastic programming approach ($S1$) and it is related to the incomes of selling energy in DA market.

The second line of (12) is associated to the expected profit resulting from the second stage of the stochastic programming approach ($S2$) when the first stage is completed. The second trading floor (i.e., intraday market) includes the incomes achieved from selling energy in intraday market and the costs of buying energy from conventional intraday market, as well as IDRX market in both pool- and bilateral-based.

The third line of the objective function represents the expected profit of the third stage of the stochastic programming approach ($S3$) when the first and second stages happen.

The expected profit is related to the incomes and costs in balance market caused by positive and negative imbalances, respectively. A rational mechanism is considered for imbalances so that producers must resale the excess of generation cheaper than the DA market's price and compensate the short on generation more expensive than DA market's price. Finally, risk is

$$\begin{aligned} \mathrm{Max}_{\rho_s} \quad \mathrm{EP} = \sum_t \Bigg\{ E_{S1} \Bigg[\pi_{\mathrm{ts}}^D \cdot P_{\mathrm{ts}}^D .. + E_{S2|S1} \Bigg[\pi_{\mathrm{ts}}^I \cdot P_{\mathrm{ts}}^{I,\mathrm{sell}} - \pi_{\mathrm{ts}}^I \cdot P_{\mathrm{ts},}^{\mathrm{I},\ \mathrm{buy}} - \sum_{d=1}^{\mathrm{ND}} \mathrm{CDRP}_{\mathrm{dts}} \\ - \sum_{d=1}^{\mathrm{ND}} \pi_{\mathrm{dt}}^B \cdot P_{\mathrm{dts}}^B + E_{S3|S2,S1} \left[\pi_{\mathrm{ts}}^D \cdot r_t^+ \cdot \Delta_{\mathrm{ts}}^+ - \pi_{\mathrm{ts}}^D \cdot r_t^- \cdot \Delta_{ts}^- \right] \Bigg] \Bigg] \Bigg\} \\ + \beta \left(\xi - \frac{1}{1-\alpha} \sum_{s=1}^{S_N} \rho_s \cdot \eta_s \right) \end{aligned} \tag{12}$$

incorporated to the objective function using CVaR in the last term. The objective function is maximized considering (5)–(8) and the constraints are described as follows:

$$0 \le P_{\text{ts}}^{D} \le P^{\max} \tag{13}$$

$$P_{\text{ts}}^{\text{Sch}} = P_{\text{ts}}^{D} + P_{\text{ts}}^{I,\text{sell}} - P_{\text{ts}}^{I,\text{buy}} - \sum_{d=1}^{\text{ND}} \text{DR}_{\text{dts}} - \sum_{d=1}^{\text{ND}} P_{\text{dts}}^{B} \tag{14}$$

$$0 \le P_{\text{ts}}^{\text{Sch}} \le P^{\max} \tag{15}$$

$$\Delta_{\text{ts}} = W_{\text{st}} - P_{\text{ts}}^{\text{Sch}} \tag{16}$$

$$\Delta_{\text{ts}} = \Delta_{\text{ts}}^{+} - \Delta_{\text{ts}}^{-} \tag{17}$$

$$-\sum_{t=1}^{T} \left[\begin{array}{l} \pi_{\text{ts}}^{D} \cdot P_{\text{ts}}^{D} + \pi_{\text{ts}}^{I} \cdot P_{\text{ts}}^{I,\text{sell}} - \pi_{\text{ts}}^{I} \cdot P_{\text{ts}}^{I,\text{buy}} + \pi_{\text{ts}}^{D} \cdot r_{\text{ts}}^{+} \cdot \Delta_{\text{ts}}^{+} \\ -\pi_{\text{ts}}^{D} \cdot r_{\text{ts}}^{-} \cdot \Delta_{\text{ts}}^{-} - \sum_{d=1}^{\text{ND}} \text{CDRP}_{\text{dts}} - \sum_{d=1}^{\text{ND}} \left(\pi_{\text{dt}}^{B} \cdot P_{\text{dts}}^{B} \right) \end{array} \right] + \xi - \eta_s \le 0 \tag{18}$$

$$\eta_s \ge 0. \tag{19}$$

Equation (13) imposes that the offer in the DA market should not be higher than the generation capacity of the units installed in the wind farm $P_{\max}$. The total scheduled energy of WPP in both DA and intraday markets is given in (14). Equation (15) limits the total scheduled energy in each scenario. Equations (16) and (17) are utilized to calculate the total energy deviation using the last scheduled energy (i.e., the sum of the transactions in the DA and intraday markets). Equations (18) and (19) are related to incorporating risk into the problem formulation.

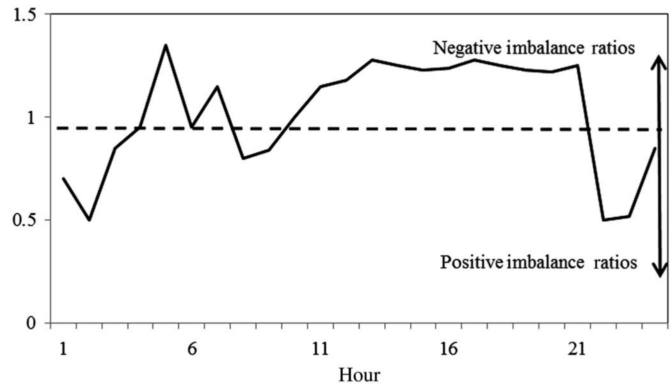

Fig. 5. Graphical representation of imbalance ratios.

TABLE II
PRICE-QUANTITY OFFER OF DRPS IN IDRX MARKET

k	1	2	3
q_{dt}^{k}	25% OF TOTAL RESPONSE	75% OF TOTAL RESPONSE	100% OF TOTAL RESPONSE
	Percentage of the mean intraday market price		
c_{1t}^{k}	40%	70%	100%
c_{2t}^{k}	50%	80%	110%
c_{3t}^{k}	60%	90%	120%

V. NUMERICAL STUDIES

In order to illustrate the accuracy of the model, some numerical studies are accomplished. For this purpose, a case study consisting of a 50-MW wind farm is considered. The case study is simulated for 4 days related to the four seasons of the year. Price and wind data used for the scenario generation process for DA, intraday and balance markets have been all obtained from hourly data of the Spanish electricity market in February, May, August, and November 2010 [32].

The imbalance ratios are calculated by taking the average of historical data and considered to be hourly variable throughout the day and fixed for all 4 days considered.

The graphical illustration of the amount of imbalance price ratios is shown in Fig. 5. Moreover, it is assumed that there are three DRPs that aggregate local customers and offer in IDRX market. The 24-h scheduled horizon is divided into three intervals: 1) valley period, 2) off-peak period, and 3) peak period. In order to achieve scalable DRP price-quantity offers, the DRPs price-quantity offer for each period is computed by multiplying mean intraday market price of the period in the elements of Table II.

The maximum capacity of DRX market is assumed to be 10 MW which is allocated to DRP1, DRP2, and DRP3 with the same shares. The proposed model was solved using the linear programming solver CPLEX in the general algebraic modeling system (GAMS).

In order to evaluate the effectiveness of the proposed approach, three different scenarios are considered. In the first scenario, WPP participates in intraday market without considering IDRX market. The second scenario is the same as the former with considering only pool-based IDRX market. In the third scenario, the impacts of both pool-based and bilateral IDRX market on WPP profit and risk are examined simultaneously.

Bilateral contract prices are dependent on mean intraday market prices in each month. Since the bilateral contract prices should be comparable to prices in conventional intraday market, the mean value in each $\text{month} \pm \%\text{error}$ is considered for bilateral prices in IDRX market.

As an example, the price of bilateral contracts for a typical day in November is considered to be 30, 35, and 40 €/MWh for DRP1, DRP2, and DRP3, respectively.

The hourly offered energy of a risk-neutral WPP in DA market is compared for each considered scenario in Fig. 6. The added amount of DA offering energy in scenarios 2 and 3 is represented as shown in Fig. 6. Moreover, in order to specify the significance of intraday market, DA offering quantities are compared in the presence of intraday and in the absence of intraday market mechanism.

Comparison of black dash lines in each month shows that WPP acts differently in the same hours in different months. Based on Fig. 6, it can be concluded that in the same hours but in different months due to wind speed diversity, WPP has varying generation potential that leads to act variously in different months. However, as no intraday market exists in this case, WPP tends to take no risk in DA market and as a result will not offer in some hours at all.

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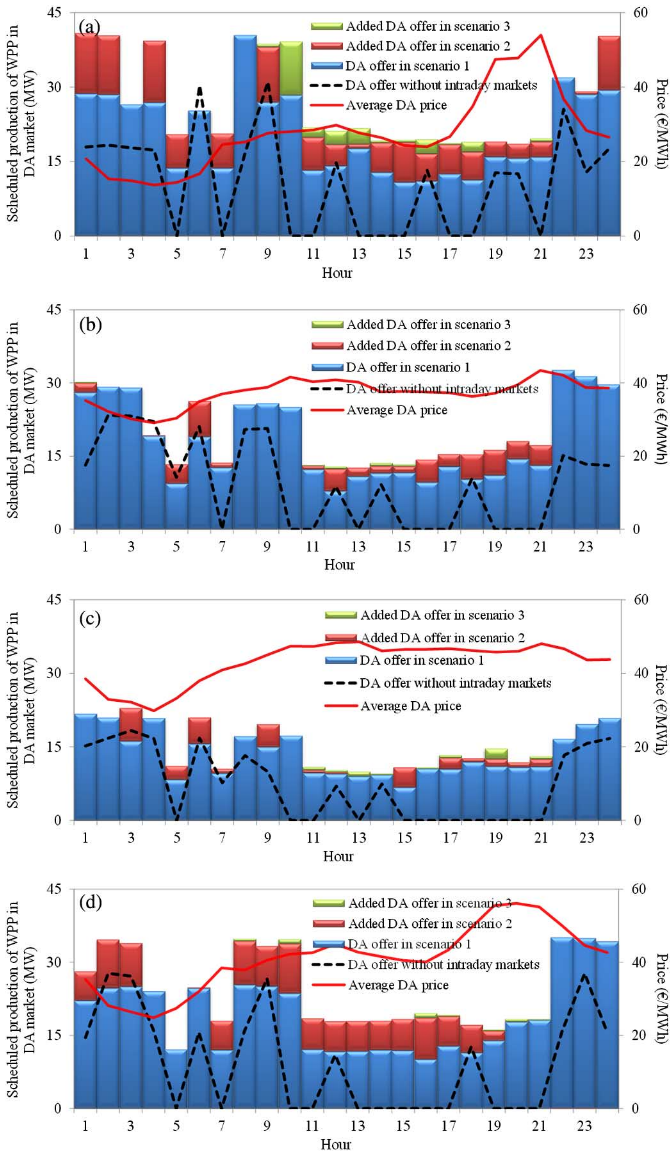

Fig. 6. Hourly WPP offering in DA market in different scenarios: (a) February; (b) May; (c) August; and (d) November.

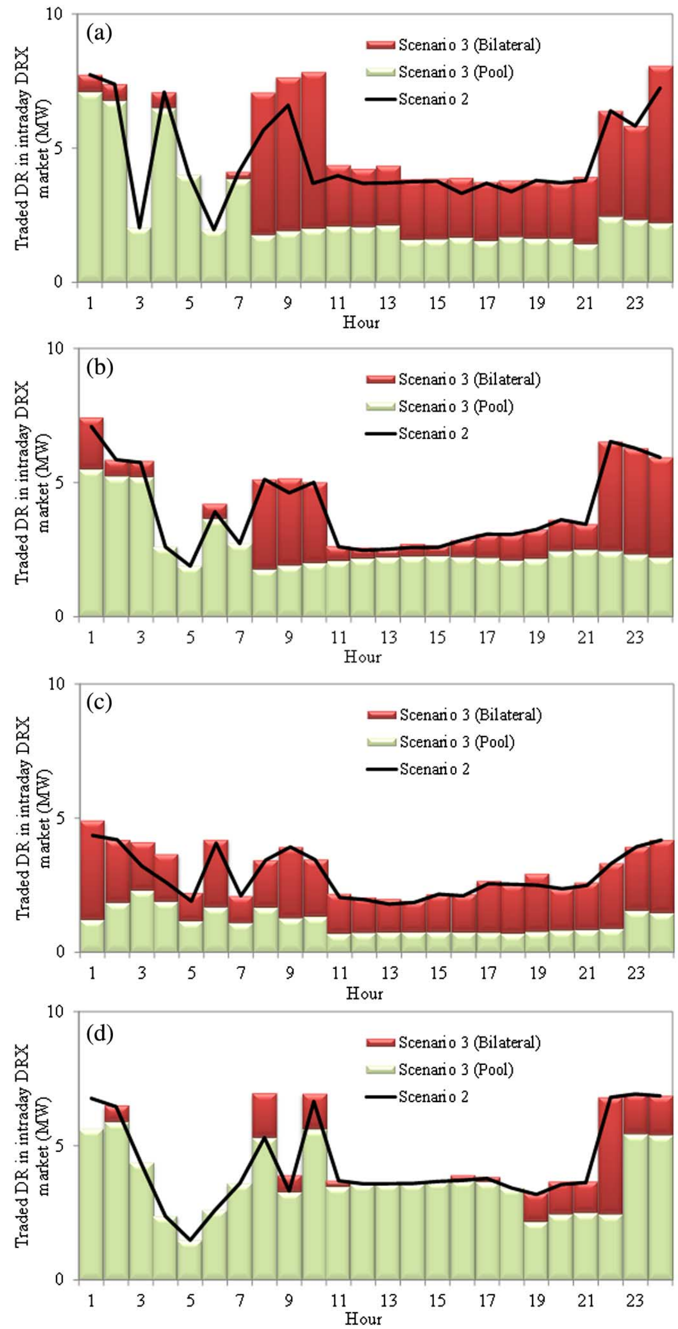

Fig. 7. Comparison of hourly traded DR in different scenarios: (a) February; (b) May; (c) August; and (d) November.

On the contrary, in scenario 1, it is observed that in the same hours it will take part in DA market. This is probably due to the presence of intraday markets that reduce the uncertainty of DA for WPP. It is obvious that the WPP generation potential highly affects its offers in market place. This is the main reason for different behaviors of WPP in different months of the year. As it can be seen, in February, where more wind is available, more market participation occurs. Another proof indicating that this conclusion to be correct is a more detailed analysis of WPP behavior during hours 9, 10, and 11.

In these hours in all four cases, it is observed that when no intraday market exists, WPP will not take a risk in hours 10 and 11 to offer in DA. Nevertheless, when an intraday market is introduced in scenario 1, higher quantity is offered in hours 9 and 10; yet, in hour 11, the amount of offer is reduced dramatically while in no intraday market case DA participation in this hour was equal to zero. This means that although the risk of uncertain power production influences the behavior of WPP, the presence of intraday can provide an environment for WPP to maintain this risk.

Scenarios 2 and 3 reveal other aspects of intraday market effectiveness. In Fig. 6, the blue diagram shows the DA participation of WPP in scenario 1. In Fig. 6, it is shown that when the DRX market is introduced in scenario 2, WPP will increase its DA offer quantity in most of the hours. Scenario 3 presents both pool-based and bilateral DRX. The green parts in Fig. 6 depict the extra offer took place in DA due to bilateral DRX. Although this amount is not very significant in most cases, it still shows, where it is possible the WPP will increase, its DA offer.

However, based on Fig. 7, it is observed that during all hours traded DR amount in DRX was considerable. This means that although in some hours WPP has not increased its DA offer, it still participated in the intraday market to maximize its benefit. Comparing the prices of DA and intraday in these four cases shows that in cases (b) and (c) (May and August) where intraday market prices are rather higher than DA, WPP prefers to take benefit of IDRX instead of increasing its offer in DA. On the other hand, in cases (a) and (d) (February and November), due to higher wind power production, potentiality WPP not only takes part in IDRX but also increases its DA offers.

As shown in Fig. 7, there is a slight difference in IDRX participation between scenarios 2 and 3. This means that IDRX participation mostly depends on available production possibility rather than IDRX market specifications. However, in scenario 3 where both pool and bilateral DRX is available, results that the tendency toward participating in bilateral IDRX are higher.

From another point of view, from Figs. 6 and 7, it can be concluded that where the environment is prepared for WPP to manage wind uncertainties, it will participate with its highest amount of generation possible (as it can maximize its benefit in this situation). This means that introducing IDRX has led to providing a more competitive environment for WPP while enabling it to manage its risks caused by its characteristics.

In Fig. 8, the expected profits of WPP are shown for various DRPs capacities. Parameter β is set to 0. As can be observed, increase in DRP participation level causes a linear increase in expected profit of WPP, up to about 20% of DRP participation level. After the knee point, the impact of DRX market capacity on WPP's profit is reduced, since the tendency of WPP for participating in DRX market is saturated. Moreover, it can be seen that bilateral contracts have a negligible effect on WPP's profit for higher participation levels of DRPs.

It is notable that the optimal amount of bilateral contracts in IDRX market should be carefully selected.

The deficit in the amount of bilateral contracts may expose WPP to intraday market price uncertainties and reduce its expected profit. Also, excessive use of bilateral contracts may lead to WPP's profit reduction. This fact is related to the nature of bilateral contracts. According to this kind of contracts, the agreed quantity must be supplied (consumed) by the seller (buyer). If the WPP contracts quantity to buy DR is more than enough to cover wind power uncertainties, the cost of bilateral contracts will be more than their revenue, and as a result the expected profit will be reduced.

In this regard, two different case studies are considered. In the first case, bilateral quantity variable is considered to be a fix quantity in all hours of the day (i.e., time invariant). However, in case 2, the bilateral quantity variable is assumed to be time variant. The optimal amount of bilateral contracts (between WPP and DRPs) for a risk-neutral WPP is illustrated in Fig. 9. The obtained results related to WPP's expected profit and CVaR index on February are given in Table III. As it can be seen, WPP participation in IDRX market increases its expected profit dramatically and manages its risk. Also, bilateral contracts between DRPs and WPP have a significant effect on profit maximization.

Until now, positive and negative imbalance ratios are considered to be a constant coefficient of DA market price. However, these ratios are not deterministic values and have uncertainties.

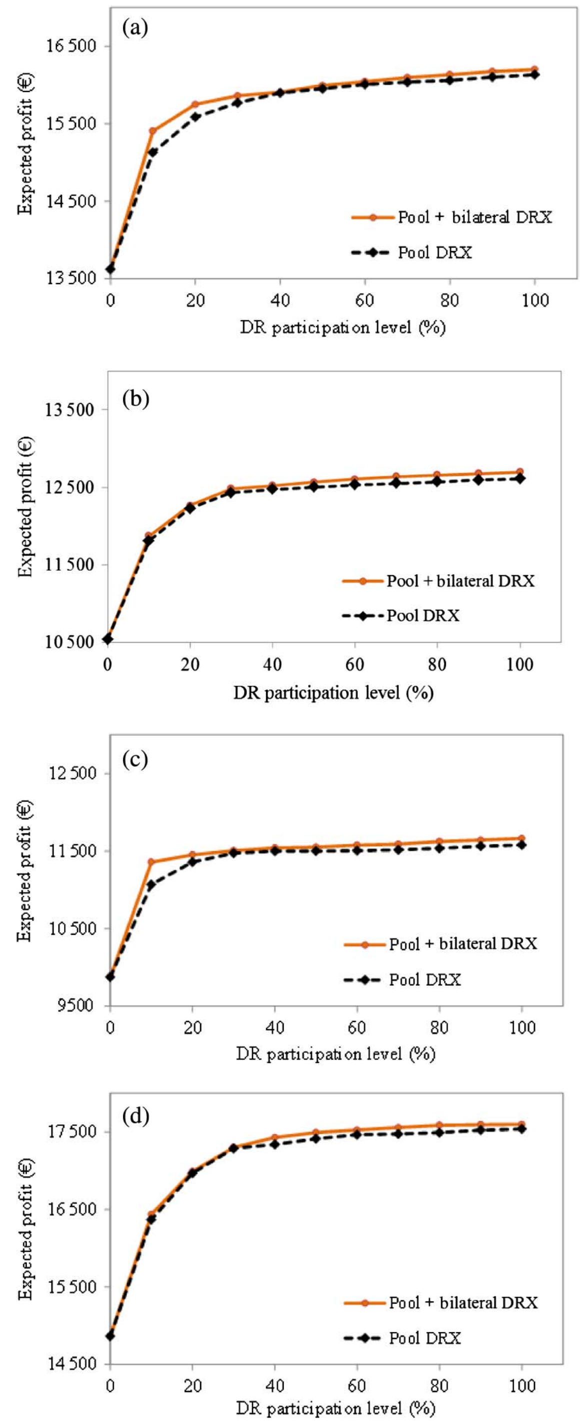

Fig. 8. Effect of DRP participation level on WPP's profit: (a) February; (b) May; (c) August; and (d) November.

Table IV investigates the impacts of uncertain imbalance ratios on expected profit of WPP in two different risk levels in February. For example, the term $\pm 10\%$ in Table IV indicates that positive and negative imbalance ratios are equal to be $0.9 \times r_t^+$ and $1.1 \times r_t^-$, respectively, which are the worst possible cases. As it can be seen, variations of the imbalance ratios and as a consequence balance market prices can cause a decrease on WPP's profit. Also, it can be concluded that WPP participation in

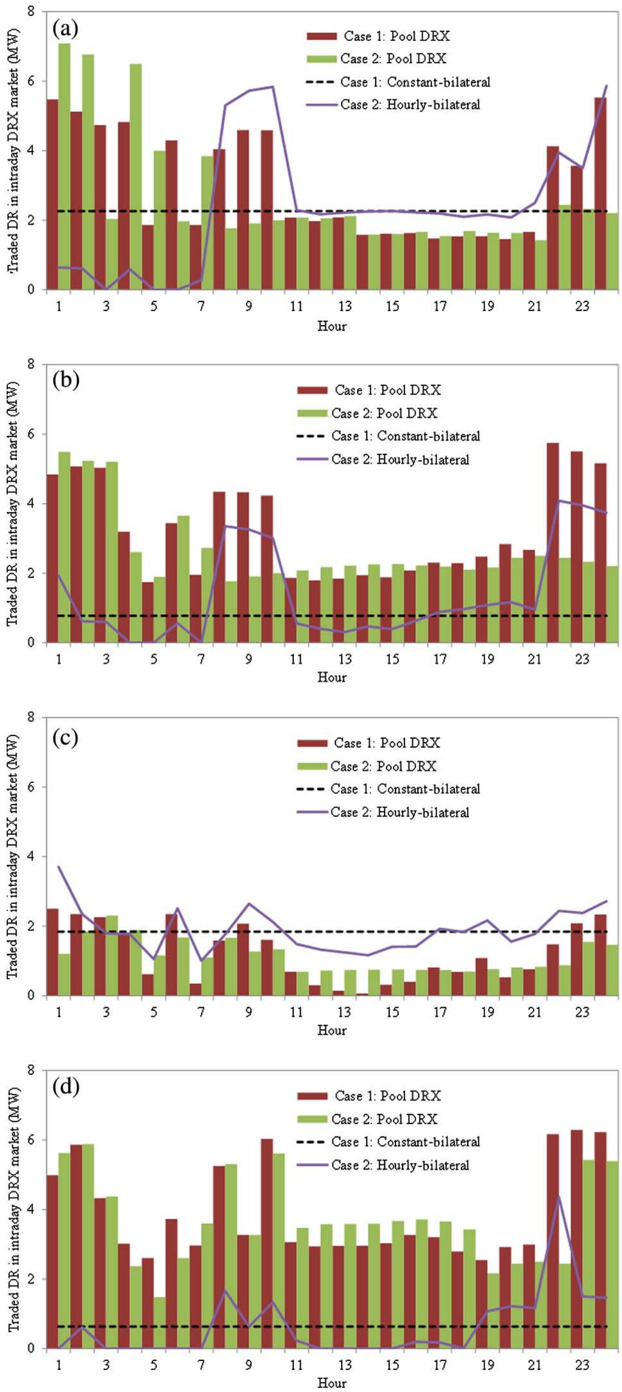

Fig. 9. Comparison of hourly and constant bilateral DRX: (a) February; (b) May; (c) August; and (d) November.

TABLE III
COMPARISON OF WPP'S PROFIT AND RISK IN VARIOUS SCENARIOS (FEBRUARY)

Risk level (β)	Scenario	Expected profit (€)	CVaR (€)
0	1	13 623.1	12 600.7
	2	15 128.5	13 933.0
	3	15 406.2	14 108.4
1	1	13 024.4	12 500.5
	2	14 068.6	13 995.9
	3	14 248.6	14 245.0

pool-based and bilateral IDRX market can increase WPP's profit dramatically as shown in Table IV.

TABLE IV
EFFECT OF IMBALANCE RATIO ON WPP'S EXPECTED PROFIT (FEBRUARY)

Risk level (β)	Scenario	Expected profit in 24 hour scheduling horizon(€)				
		Imbalance ratio forecast errors				
		±10%	±20%	±30%	±40%	±50%
0	1	13 259.0	13 214.8	13 197.3	13 188.4	13 182.7
	2	14 716.8	14 536.3	14 448.5	14 384.2	14 332.7
	3	14 946.5	14 738.2	14 646.2	14 570.6	14 504.6
1	1	12 853.9	12 523.5	12 512.8	12 363.2	12 237.5
	2	13 612.3	13 484.1	13 478.6	13 466.5	13 424.5
	3	13 870.3	13 828.3	13 667.5	13 638.1	13 617.8

TABLE V
EFFECT OF DRP PARTICIPATION LEVELS AND BILATERAL CONTRACT ON WPP'S COSTS AND REVENUES (FEBRUARY)

DRP participation levels (%)	0	10	10	20	20
Average bilateral contract over scheduled horizon (MW)	0	0	2.467*	0	1.668*
Revenue from DA market	18 253.5	21 585.4	22 409.5	22 646.3	22 792.2
Revenue from intraday market	–1357.3	269.9	261.4	285.8	285.0
Positive imbalance revenue	826.2	352.8	123.0	142.8	94.8
Negative imbalance cost	4099.3	5202.6	5550.7	5701.3	5783.0
Pool-based DRX cost	0	1877.1	862.3	1788.3	1033.9
Bilateral-based DRX cost	0	0	974.718	0	606.091
Expected profit (€)	13 623.1	15 128.5	15 406.2	15 585.3	15 749.1

TABLE VI
WPP'S EXPECTED PROFIT IN VARIOUS MONTHS (€)

DRP participation levels (%)	0	10	10	20	20
Bilateral contract	No	No	Yes	No	Yes
February	13 623.1	15 128.5	15 406.2	15 585.3	15 749.1
May	10 541.7	11 810.9	11 873.5	12 227.7	12 264.9
August	9876.3	11 070.7	11 357.9	11 359.674	11 451.8
November	14 864.9	16 366.3	16 434.0	16 901.1	16 910.2

In Table V, the effect of DRP participation levels and the optimal bilateral contract related to those levels on WPP's costs and revenues is investigated. The imbalance ratios are considered equal to the quantity in Fig. 5. The results are related to February. According to Table V, with the increase in participation levels of DRPs in IDRX market, WPP prefers to participate in intraday market and modify its offers by using DRRs. Thus, WPP uses DRRs to compensate its imbalance costs associated with the uncertain behavior of wind power. As shown in Table V, average optimal quantities of bilateral contracts are decreased by increasing DRP participation levels in IDRX market. This is due to the fact that using bilateral contracts is economical for only a few hours (especially peak hours) in which the price of pool IDRX market is high.

Table VI is given to represent the comprehensiveness of the model. The expected profit of WPP is obtained for each typical day in the four selected months, considering different DRP participation levels.

On this basis, if the IDRX market has an appropriate potential, WPPs are able to maximize their profits by participating in the mentioned market, instead of struggling with high uncertainties of prices in the intraday market.

Furthermore, using a well-selected bilateral contract besides participating in the pool-based IDRX market can increase WPP's profit. Hence, an appropriate IDRX market encourages WPPs to offer more quantities to the DA market, because they expect to compensate wind power uncertainties. Moreover, power systems may take the advantage of using DRRs to integrate more wind power.

VI. Conclusion

This paper studied the impacts of IDRX market on the optimal trading of WPPs in a market environment. WPP can participate in intraday market using DRRs through bilateral contracts or in a pool-based DRX market in order to maximize profits. Uncertain behavior of wind power, DA, and intraday market prices was modeled using a scenario-based method. Furthermore, CVaR was applied as a risk measure that the WPP can specify to attain a desirable weighting between expected profit and risk. Several numerical studies have been accomplished and various aspects of the problem were analyzed in detail. Due to the obtained results, an appropriate IDRX market can encourage WPPs to offer more quantities to the DA market. It was shown that the optimal amount of bilateral contracts (WPP and DRPs), besides pool-based IDRX market participation, may lead to an increased expected profit of WPP. Another important aspect was that the tendency of WPP for participating in IDRX market saturated after a specified amount of IDRX market capacity. The impacts of various imbalance ratios on WPP's profit were also evaluated. Moreover, a comprehensive economic analysis was carried out and the effect of DRP participation levels and the optimal bilateral contract related to those levels on WPP's costs and revenues was studied. The results showed that by establishing an intraday DRX market as an adjustment market may provide more opportunities for WPPs, as a new contribution to earlier studies. Indeed, DR represents an excellent opportunity for WPPs to increase expected profits and reduce risks.

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