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Risk-constrained demand response and wind energy systems integration to handle stochastic nature and wind power outage

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Abstract: Participation of wind generation in electricity markets is mainly restricted by the intermittent nature of wind and their possible outages. The great potential of flexible loads from demand response (DR) can be seen as a cost-effective option to handle such issues. In this regard, this study investigates the operation of a virtual power plant (VPP) that is constructed by a DR aggregator and wind power aggregator to handle the inherent volatility of wind generators as well as the possible wind power outage. A stochastic programming formulation in three stages is offered for the VPP that participates in the balancing, intraday and day-ahead markets. The model for DR is developed based on the elasticity concept, and the scenarios related to severe outages of the wind generators are considered. In order to manage the risk of the problem, conditional value-at-risk has also been employed in offering strategy. Case studies demonstrate that the VPP offering strategy can efficiently solve the balancing problem as well as outage risk of the wind generation while increasing the net profit in case of joint operation.

Nomenclature

Indices (subscripts)

s index of scenario
t index of time

Indices (superscripts)

DA index for day-ahead market
I index for intraday market
Sch index for scheduled power

Constants

N_s total number of scenarios
N_T scheduling time period
π_s occurrence probability of sth scenario
ρ price of energy in electricity market
$r_{t,s}^{+/-}$ positive/negative imbalance price ratios
β risk-aversion factor
α confidence level with $\alpha \in (0, 1)$
σ a factor for relating elasticity and price
W^{Max} maximum capacity of wind power producer
ϕ_1, ϕ_2 upper and lower bounds of demand response
γ a bounding index to limit intraday market offerings
μ maximum load percentage that is not necessary to be recovered
T^{Start} starting time step of wind power outage
T^{Stop} ending time step of wind power outage

Variables

P power produced by VPP
W power produced by wind power producer
D amount of the demand reduction to be offered to the market
$\delta V^{+/-}$ positive/negative deviation of the VPP generating from the scheduled value
δ total deviation of VPP power from the scheduled power
η supplementary variable to calculate CVaR
ζ_s continious non-negative variable to calculate CVaR
d_{0t} normal demand level in period t

1 Introduction

In the last decade, the incentives by government and technological advancement have resulted in a huge investment in wind farms and the utilisation of wind power generators around the world. The fundamental benefits of wind generation as a renewable resource of energy have been the primary motivations for such plans. However, the technical challenges of integrating renewables into the electricity grids and the economic participation of renewables in the electricity markets still need to be investigated carefully. Wind power generators are by nature stochastic and unstable. These issues along with their possible outages usually make it very difficult for them to participate in different markets of electricity aiming at competing with other traditional power-plants based producers. Hence, proposing new approaches for tackling these challenges is a vital task for wind producers [1–4].

Owing to the great changes in electricity networks such as the implementation of advanced metering infrastructures and smart meters [5], the huge increase in the number of electric vehicles [6, 7], and the advent of new technologies like smart appliances [8], the demand response (DR) potential of customer side has increased significantly. When such flexible loads are aggregated properly and operated collectively, they can improve the efficiency and reliability of electricity grids in different ways [9, 10]. One of these possible advantages is to facilitate the integration of renewable resources into power grids [11, 12]. In this regard, they can be utilised to improve the stability of electrical networks in the presence of intermittent producers or to assist such renewable generators to participate in electricity markets.

Joint operation of DR resources and wind power aggregators (WPAs) can be defined based on the broader concept of virtual power plant (VPP). A VPP can be realised by the aggregation of various heterogeneous distributed energy resources (DERs) to function as a single entity [13, 14]. A VPP may include one or some of these components: non-dispatchable and dispatchable power plants including renewable and non-renewable ones, storage units such as batteries and pump storage, and flexible loads like DR resources. VPPs are usually categorised based on their fundamental functions into two main groups: commercial VPPs and technical VPPs [15]. A commercial VPP, which is the concern of this paper, mainly considers the optimisation and scheduling of production of DERs and DR aggregators (DRAs). This hybrid operation of these resources can bring economic benefits to both

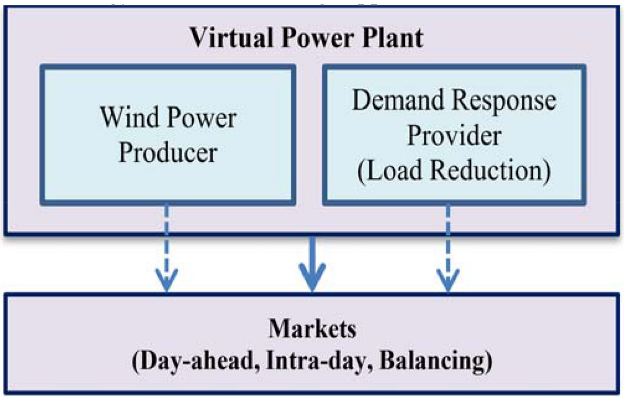

Fig. 1 *Structure of VPP*

parties. To this end, this paper investigates the joint operation of wind power plants with DR resources and reports outcomes. The structure of such an operation is presented in Fig. 1 which demonstrates individual offerings of wind generator owners and DRAs to the markets and also, the VPP offerings on behalf of both of them. This is achieved by formulating the problem as a stochastic programming problem which properly considers the effects of bidding in three electricity markets. The concern here is to compare the individual operation of DRAs and wind generators with their joint operation. In this regard, the comparisons are made from the perspective of the optimal offerings to the markets, the profits they earn and the risk considerations.

The rest of this research is structured as follows: the corresponding literature and contributions of the paper are reviewed in Section 2. In Section 3, the proposed methodology for the offering approach of the VPP is explained. Section 4 discusses the results of applying VPP strategy. In conclusion, Section 5 draws some conclusions based on the obtained results of the study.

2 Literature review and contributions

2.1 Literature survey

A large number of researches present offering strategies for the participation of a WPA in different power markets [16–18]. For instance, in [19] an offering scheme is proposed for a WPA in which different electricity markets are considered. Besides, the uncertainties of price in markets as well as the stochastic nature of wind are modelled. Baringo and Conejo [20] considers the same uncertainties while it suggests that the WPA can act as a price-maker aggregator in the day-ahead (DA) power market. Zugno *et al*. [21] presents a WPA offering strategy by considering this unit as a price-maker of the balancing market while a price-taker in the DA market. Beside energy markets, participation in ancillary service markets has also been investigated in some studies. In [22] two distinct strategies are proposed for offering the task of a WPA in both primary reserve and energy markets.

The offering strategies of WPAs joined with other producers have been investigated in some publications [23–25]. Optimal bidding strategy of a WPA combined with energy storage in multi-stage electricity markets is investigated in [26]. Authors in [27] study a cooperative operation between a pumped-storage unit and a WPA considering the uncertainties of market prices and wind generation. Coordination of a WPA, pumped-storage energy system, and combined heat and power aggregator are considered in [28] to participate in different electricity markets. The effect of wind chaos on the amount of energy stored in the pumped-hydro system of future UK is assessed in [29]. De la Nieta *et al*. [30] proposes some bidding schemes for a hydro unit and a WPA aiming at participating in a DA market and employs the conditional value-at-risk (CVaR) factor to tackle the financial risk. On the other hand, Greenblatt *et al*. [31] explores two competing structures using a cost-optimisation model which compares the joint operation of a WPA combined with a gas turbine, and a WPA combined with a compressed air energy storage.

As stated in the previous section, the recent changes that have happened in the electricity networks increased the potential volume of DR that can be provided from industrial, commercial or residential customers. For example, various studies consider the aggregation of DR resources [10, 32, 33], provision of DR from thermostatically controlled loads [34, 35] and electric vehicles [7, 36] for ancillary service provision [37], benefiting renewable energy resources [11, 38] and making VPPs [12]. In this regard, different publications appeared in recent years which propose the utilisation of DR resources to cope with the volatile characteristics of wind-based generation [12, 39]. Zhao and Wu [40] determines the optimum value of the DR unit to enhance the control of congestion as well as the use of wind-based generation. An offering policy for the combination of a flexible load and a WPA with the capability of covering the wind power imbalances is proposed in [41]. This join operation is formulated to participate in a DA electricity market. Total operating costs of a join aggregator comprising fines corresponding to wind energy over/under-commitment are minimised in [42] by proposing optimal scheduling based on critical peak pricing. This has been accomplished by utilising a DR unit which employs wind power to suitably trade in the DA market. Heydarian-Forushani *et al*. [43] presents a novel offering plan for a WPA to participate in balancing, intraday, and DA electricity markets with the assist of a DR resource that is permitted to participate in the intraday market. Furthermore, a new technique is developed in [44] that models the uncertainties of the load and wind power for a corrective control of voltage to manage the challenging situations in which the power system experiences voltage instability as the result of severe contingencies.

2.2 Paper contributions and approach

This research offers a methodology for the joint operation of a WPA and a DRA as a commercial VPP in which the WPA utilises the DRA as a storage unit. This VPP then offers the bids to the balancing, intraday, and DA markets. The uncertainties associated with wind power generation, its outages, and price of energy in three markets are modelled through a set of scenarios which results in a stochastic programming problem. The relationship between the electricity price and load consumption is modelled by the elasticity concept, and the outage times of wind generator are modelled by a probability distribution function. CVaR as a well-known risk measure in the power market literature is also added to the final problem to control the cost deviations.

The contributions of the paper are given as follows:

- The development of an optimal offering strategy model for the joint operation of a WPA and a DRA as a VPP to maximise their expected profit and also to mitigate uncertainties related to stochastic nature and wind power outage.
- The implementation and analysis of the proposed framework on three different electricity markets in a realistic case study.
- Offering a risk constrained VPP model to overcome financial risks of electricity markets.
- To attain optimal offering curves for the VPP to be submitted to the DA and intraday market.

3 Proposed methodology

The offering outline of VPP is explained in this section. Three energy markets are considered in the market settlements which run in different time frames. For the DA market, the suppliers (customers) offer their bids to the market one day ahead of the actual delivery. Therefore, the closure of this market happens many hours before the real-time operation. On the other hand, the intraday market provides this opportunity for market participants to correct their offers that they previously made in the case that they cannot meet the pledged power supplies (demands). Finally, the balancing market runs near the real-time operation to cover the imbalances that may happen in the system. The intraday and balancing markets are suitable setups for WPAs to modify the offered bids as they cannot precisely predict the amount of produced power.

The presented model of VPP including three aforementioned electricity markets is formulated as a profit (revenue of VPP minus its total cost) maximisation problem. Then, mathematic expression of the objective function can be formulated as

(see (1))

The first part of this equation shows the offering strategies of VPP in the three markets. The revenues are composed of two parts: wind power generation offerings in the markets and DR revenue which is achieved through load shifting. Based on the scenarios, the VPP could incur some costs from the balancing market which are shown as a negative term in the objective function (1). The terms $\rho_{t,s}^{\rm DA}\cdot P_{t,s}^{\rm DA}$ and $\rho_{t,s}^{I}\cdot P_{t,s}^{I}$ are the revenue from DA market and revenue (cost) from the intraday market, respectively; while the terms $\rho_{t,s}^{\rm DA}\cdot r_{t,s}^{+}\cdot \delta V_{t,s}^{+}$ and $\rho_{t,s}^{\rm DA}\cdot r_{t,s}^{-}\cdot \delta V_{t,s}^{-}$ indicate the revenue/cost from the positive/negative energy deviations in the balancing market. The load model is derived based on the elasticity concept which illustrates the exponential relationship between the price ρ_t and demand D_t [12]:

$$D_t = k\cdot e^{\sigma\cdot\rho_t} \quad (2)$$

where σ is a negative number and k is a constant. The last term in (1) is related to the modelling of CVaR measure. The parameter β is for managing the risk. To attain a proper trade-off between the risk and profit, the parameter β of CVaR is considered to be changed from zero to one in which 'zero' corresponds to the risk-neutral problem. It is noteworthy that as shown in Fig. 2, $(1-\alpha)$ regulates the area of profit distribution function covering the least profitable scenarios.

Operating and aggregators' constraints associated with modelling of DRA, WPA are detailed in this section. The offer limitation of the VPP to the DA market can be written as follows:

$$0\le P_{t,s}^{\rm DA}\le W^{\rm Max}+\phi_1\cdot d_{0t}\quad \forall t,\forall s \quad (3)$$

where $\phi_1\cdot d_{0t}$ is the capacity of DRA. The minimum value for constraint (3) is zero because VPP is regarded as a generation company in this study. Equation (4) formulates scheduling power of VPP including DA and intraday offers

$$P_{t,s}^{\rm Sch}=P_{t,s}^{\rm DA}+P_{t,s}^{I}\quad \forall t,\forall s \quad (4)$$

The scheduled power of VPP is limited by

$$0\le P_{t,s}^{\rm Sch}\le W^{\rm Max}+\phi_1\cdot d_{0t}\quad \forall t,\forall s \quad (5)$$

The VPP imbalances (i.e. total, negative, and positive) based power production of WPA and DRA can be written as follows:

$$\delta_{t,s}=W_{t,s}+D_{t,s}-P_{t,s}^{\rm Sch}\quad \forall t,\forall s \quad (6)$$

$$\delta_{t,s}=\delta V_{t,s}^{+}-\delta V_{t,s}^{-}\quad \forall t,\forall s \quad (7)$$

$$0\le \delta V_{t,s}^{+}\le W_{t,s}+D_{t,s}\quad \forall t,\forall s \quad (8)$$

$$0\le \delta V_{t,s}^{-}\le W^{\rm Max}+\phi_1\cdot d_{0t}\quad \forall t,\forall s \quad (9)$$

where $W_{t,s}$ and $D_{t,s}$ are delivered power production of WPA and DRA, respectively. It is an assumption in this paper that the scheduled value of DRA and its active power are equal, which means no uncertainty has been considered for DRA production. The limit of intraday offer about the DA offer can be expressed as follows:

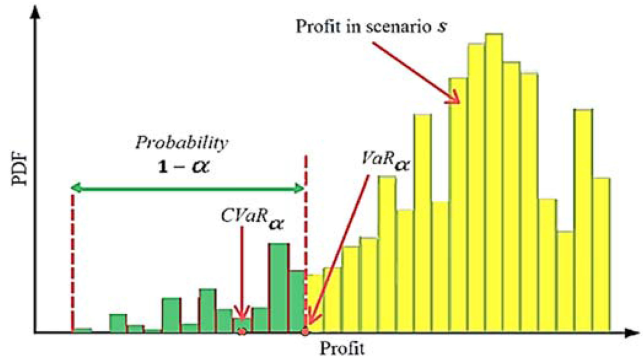

Fig. 2 *CVaR calculation*

$$-\gamma\cdot P_{t,s}^{\rm DA}\le P_{t,s}^{I}\le \gamma\cdot P_{t,s}^{\rm DA}\quad \forall t,\forall s \quad (10)$$

Following constraints are employed to calculate the risk factor:

$$-\sum_{t=1}^{N_T}\Big[\rho_{t,s}^{\rm DA}\cdot P_{t,s}^{\rm DA}+\rho_{t,s}^{I}P_{t,s}^{I}+\frac{1}{2}\cdot\frac{1}{\sigma\cdot d_{0t}}\cdot\left(D_{t,s}^{\rm Sch}\right)^2 +\rho_{t,s}^{\rm DA}\cdot r_{t,s}^{+}\cdot\delta V_{t,s}^{+}-\rho_{t,s}^{\rm DA}\cdot r_{t,s}^{-}\cdot\delta V_{t,s}^{-}\Big]+\eta-\zeta_s\le 0\quad \forall s \quad (11)$$

$$\zeta_s\ge 0\quad \forall s \quad (12)$$

The constraints related to the modelling of flexible load are mathematically expressed by

$$D_{t,s}^{\rm Sch}=D_{t,s}^{\rm DA}+D_{t,s}^{I}\quad \forall t,\forall s \quad (13)$$

$$\phi_2\cdot d_{0t}\le D_{t,s}^{\rm DA}\le \phi_1\cdot d_{0t}\quad \forall t,\forall s \quad (14)$$

$$\phi_2\cdot d_{0t}\le D_{t,s}^{\rm Sch}\le \phi_1\cdot d_{0t}\quad \forall t,\forall s \quad (15)$$

$$\sum_{t=1}^{N_T}D_{t,s}^{\rm Sch}\le \mu\cdot\sum_{t=1}^{N_T}d_{0t}\quad \forall s \quad (16)$$

$$D_{t,s}^{\rm Sch}=D_{t,s'}^{\rm Sch}\quad \forall t,\forall s,\forall s'\quad \text{if}\quad \upsilon_{t,s}^{\rm DA}=\upsilon_{t,s'}^{\rm DA} \quad (17)$$

$$D_{t,s}^{I}=D_{t,s'}^{I}\quad \forall t,\forall s,\forall s'\quad \text{if}\quad \upsilon_{t,s}^{\rm DA}=\upsilon_{t,s'}^{\rm DA} \quad (18)$$

Low bands of constraints (14) and (15) is changed from zero to $\phi_2\cdot d_{0t}$ ($\phi_2<0$) because the DR unit can exploit wind power and escalates its load in the joint operation. Equations (17) and (18) define the non-anticipativity of decisions in the market of intraday.

The VPP optimisation problem (1)–(18) is formulated to achieve the optimal quantities instead of optimal offering curves for every hour of the DA. However, it is more appropriate to attain optimal offering curves for a VPP to be submitted to the DA market. To do so, variables $P_t^{\rm DA}$ must be extended to all scenarios as $P_{t,s}^{\rm DA}$ and the constraints (19) and (20) must be added to the stochastic programming model (1)–(18)

$$\left(P_{t,s}^{\rm DA}-P_{t,s'}^{\rm DA}\right)\cdot\left(\rho_{t,s}^{\rm DA}-\rho_{t,s'}^{\rm DA}\right)\ge 0\quad \forall t,\forall s,\forall s' \quad (19)$$

$$\sum_{t=1}^{N_T}\sum_{s=1}^{N_s}\pi_s\Big[\rho_{t,s}^{\rm DA}\cdot P_{t,s}^{\rm DA}+\rho_{t,s}^{I}\cdot P_{t,s}^{I}+\frac{1}{2}\cdot\frac{1}{\sigma . d_{0t}}\cdot\left(D_{t,s}^{\rm Sch}\right)^2+\rho_{t,s}^{\rm DA}\cdot r_{t,s}^{+}\cdot\delta V_{t,s}^{+}-\rho_{t,s}^{\rm DA}\cdot r_{t,s}^{-}\cdot\delta V_{t,s}^{-}\Big] +\beta\left(\eta-\frac{1}{(1-\alpha)}\sum_{s=1}^{N_s}\pi_s\zeta_s\right). \quad (1)$$

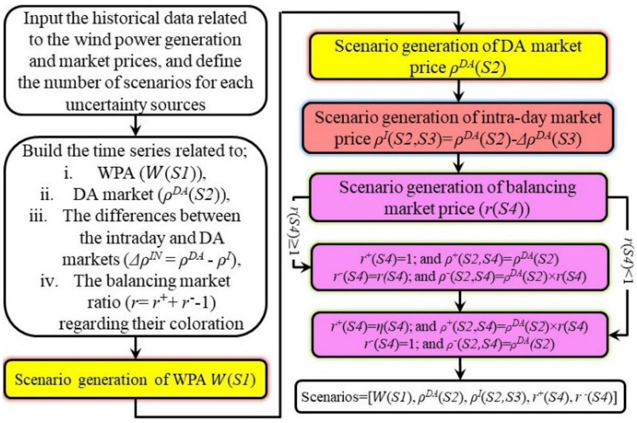

Fig. 3 *Flowchart of stochastic variable modelling process*

Table 1 Distribution of outage time probability for WPA

Parameter	Probability distribution characteristics			
	St. Dev.	Mean	Max.	Min.
T^{Start}	1	13.5	16	11
T^{Stop}	1	20	23	17

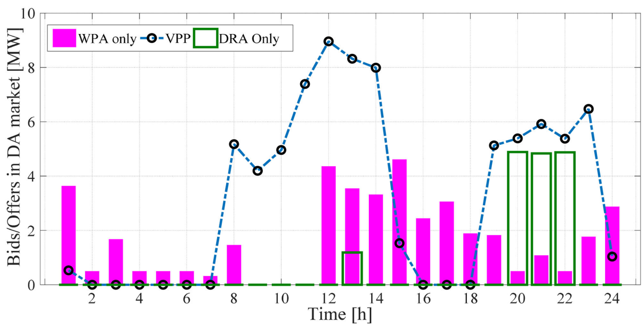

Fig. 4 *Optimal hourly power bids for the DA market*

$$P_{t,s}^{\text{DA}} = P_{t,s'}^{\text{DA}} \quad \forall t, \forall s, \forall s' \quad \text{if} \quad \rho_{t,s}^{\text{DA}} = \rho_{t,s'}^{\text{DA}} \tag{20}$$

Constraint (19) is intended to make offering curves to be non-decreasing, which is an obligation in almost all electricity markets. Constraint (20) is also used for a non-anticipativity formulation as only one offering curve can be submitted to the DA market for each hour. It is important to mention that the new model with constraint (20) has less constraints due to the removal of too many constraints by non-anticipativity formulation.

4 Case study and results

4.1 Assumptions and data

The aim of the proposed approach is to coordinate a WPA and a DRA while tackling the uncertainties associated with the production of WPA, electricity price in markets, and outage of wind power. To this end, three different structures based on that depicted in Fig. 1 is simulated including DRA only, WPA only, and VPP. Uncertainties of markets' price and wind power are generated and modelled with some scenarios utilising a joint block of improved particle swarm optimisation and adapted virtual neural network. A statistical analysis has been used to generate scenarios regarding severe outages of the wind units.

The proposed technique is applied on a real wind farm in the Sotavento of Spain with the capacity of 17.56 MW [45]. The chaotic feature of wind power is generated by the procedure proposed in [12]. Historical data of the year 2010 is utilised to train the artificial neural network. Based on the procedure presented in [46], a three-step formulation has been employed in this study for modelling market prices. The historical data from market prices and demand are based on the electricity market of the Iberian Peninsula [47]. A scenario-tree based approach has been applied for uncertainty modelling of the problem which contains 3000 scenarios ($6 \times 10 \times 5 \times 10$) with six, ten, five and, ten scenarios for wind generation ($S1$), and prices in DA market ($S2$), intraday market ($S3$), and balancing market ($S4$), respectively.

The flowchart of the stochastic modelling process is shown in Fig. 3. This figure demonstrates how all scenarios related to the optimisation problems, i.e. how $W(S1)$, $\rho^{\text{DA}}(S2)$, $\rho^{I}(S3)$, $r^{+}(S4)$, $\rho^{-}(S4)$ are generated. Note that the yellow highlighted section indicates the first category of uncertainty source which is the wind power generation and DA market price scenarios, the red highlighted section designates the second category of uncertainty source which is the intraday market price scenarios, and finally the pink section describes the third category of uncertainty source which is the balancing market price scenarios. As it can be seen from highlighted pink colour part of Fig. 3, after scenario generation of balancing market prices $r(S4)$, there are two ways of calculating the balancing market prices ($r^{+}(S4)$, $r^{-}(S4)$) based on the values of $r(S4)$.

Randomly generated values are used for outage time of the wind power. Table 1 details the probability distribution for the outage time of wind power.

The outage times shown in this table are added to the previously generated stochastic profile of wind generation as a zero power replacement. The data for 12 March 2010 has been used for obtaining simulation results. It is assumed that 0.067% of the total electricity loads of the Spanish grid are united to take part as a DRA in the market.

The scenario generation/reduction procedure of the proposed method is primarily executed in MATLAB software and are then imported into the GAMS software by means of a GAMS/MATLAB interface to solve the given optimisation problem. Note that the CPLEX is used as the solver of the GAMS software. The execution time of simulations is 120.756 s on a 2.3 GHz Intel® CORE$^{\text{TM}}$ i5 laptop with 8 GB of RAM.

4.2 Numerical studies

In this paper, four studies are done to evaluate the applicability and effectiveness of the proposed approach as follows:

4.2.1 Comparison of power bids: In this section, the effect of the joint operation of DR and wind producer on their power offerings will be discussed. Hourly power bids to the DA market for scenario number 5 are depicted in Fig. 4 regarding different configurations: WPA only, VPP operation, and DRA only while generation system experiences no wind outage condition. As it can be seen, DRA with the assist of WPA can store more energy in the joint operation during the hours of off-peak, while this stored energy is released to the market during the peak hours. Note that under both normal operations and wind outage conditions, WPA's wind productions in the clock 9–11 are always equal to zero because of the weather condition that there is not enough wind during that period.

Optimal power bids of independent VPP and WPA are shown in Figs. 5 and 6 for scenario number 5 under two conditions of normal operation and wind outage. Obviously, independent WPA provides no offering during the periods of wind power outage including 9–12 and 14–23 h.

However, the VPP offers slightly less power to the DA market when the occurrence of the wind outage comparing to the normal condition. The optimal bids of DRA in DA market under both conditions of independent and joint operation are shown in Fig. 7. As it can be illustrated, near the full capacity of the DRA can be utilised in some hours when it cooperates with the WPA.

4.2.2 Comparison of profits: Fig. 8 shows the hourly comparison of expected net profit for three given configurations while considering wind outage. Based on this figure, especially around 7 a.m.–3 p.m., the hourly profits are increased significantly. However, for about 3 hours (3–6 p.m.), VPP incurs some losses due to the offering policies that it takes for maximising the profit. On the other hand, the behaviour of VPP and DRA during peak

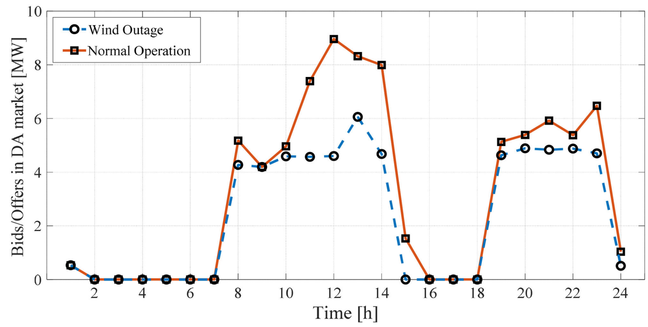

Fig. 5 *VPP optimal power bids in the DA market under normal operation and wind outage*

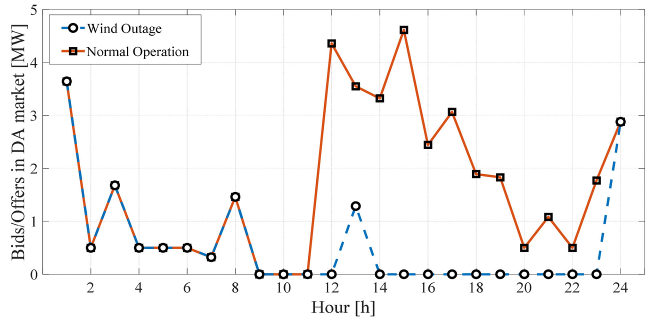

Fig. 6 *Optimal power bids of independent WPA in the DA market under normal operation and wind outage*

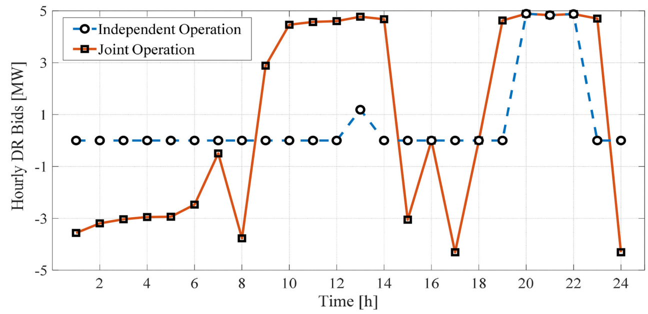

Fig. 7 *Optimal power bids of DRA in the DA market under independent operation and joint operation*

hours is quite interesting. As it is anticipated, the DR offers most of the load shifting in this period as usually, the highest electricity price happens in this time frame and the highest profit can be earned. Consequently, VPP also earns great profit in this period as it possesses the DR.

Furthermore, Figs. 9 and 10 show hourly expected profit of the independent WPA and VPP under two conditions of normal operation as well as wind outage. Comparison of these figures also demonstrates the benefits of joint operation as the wind outage has less effect on the expected profits of VPP than individual utilisation of wind generator. Here the expected profit which is the result of all probable scenarios is considered, and this expected profit of wind producer in the outage period is not zero. With the help of DRA, VPP can store extra energy during the off-peak hours, and sell the stored energy to the market during the peak hours when the price is higher. This joint strategy obtains €96.171 extra profits compared to two other independent operation strategies under the wind outage condition.

4.2.3 Effect of the risk: As mentioned earlier, risk consideration is a key matter that affects the final decision of all participants in electricity markets. Maximisation of the expected value of profit does not essentially mean that scenarios with low profits or even negative ones will not occur. Those scenarios can have a non-negligible probability of occurrence. To limit the effect of those undesired scenarios, a risk measure is usually added to the final

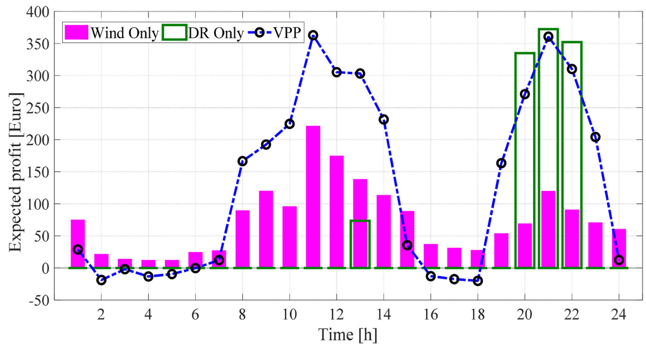

Fig. 8 *Hourly comparison of expected net profit under three configurations: DRA only, WPA only, and VPP*

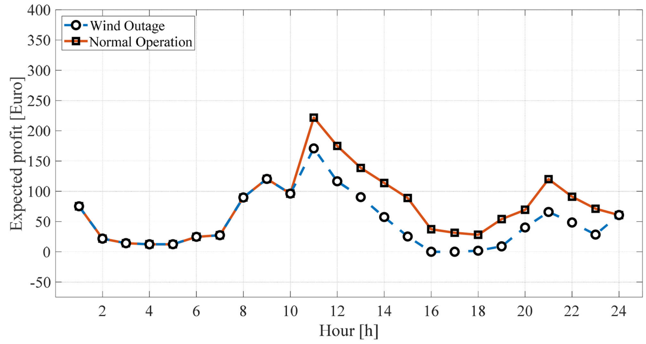

Fig. 9 *Hourly expected net profit of independent WPA under two different conditions of normal operation and wind outage*

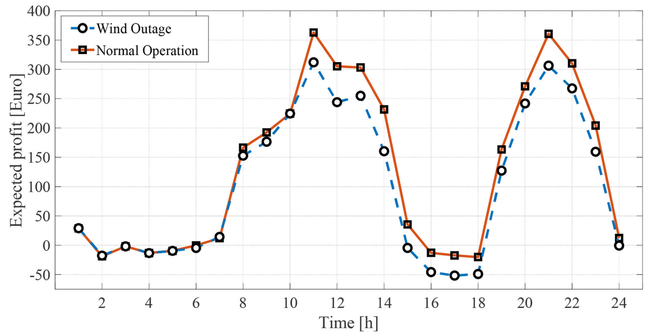

Fig. 10 *Expected net profit of VPP under two different conditions of normal operation and wind outage*

formulation. In the CVaR measure, the weight of the risk on the final problem is determined by the risk factor β.

Fig. 11 shows the extra profits of VPP under two conditions of wind outage and normal operation for different values of the risk factor β. As it has been illustrated from this figure, the extra profits of VPP are declined.

It should be mentioned that an increase in risk factor β causes the extra profit to be decreased along with the increase of β under both normal operation and wind outage conditions.

As it can be seen, maximum obtained extra profit (i.e. € 124.056) is attained under the normal condition at risk factor $\beta = 0.1$, while its minimum value (i.e. € 74.986) is reached at $\beta = 1$ under the condition of wind outage.

4.2.4 Case study over a one-year period: This case study analyses the VPP for contributing in the three markets over the course of one year. Wind power and electricity prices scenarios are produced based on the historical data of wind speed and Iberian Peninsula electricity market for the year 2016. Fig. 12 compares the profit and cumulative profit (C-Profit) for the three configurations including DRA only, WPA only, and VPP for a duration of one year. As shown in Fig. 12, the daily profit of VPP is higher than the individual operation of WPA and DRA.

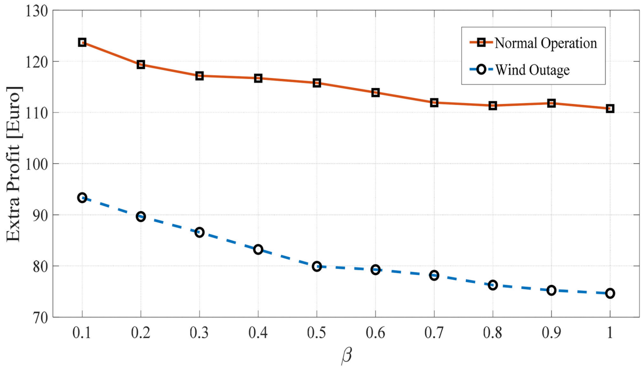

Fig. 11 *Extra profit comparison of VPP for a set of β values under two conditions of wind outage and normal operation*

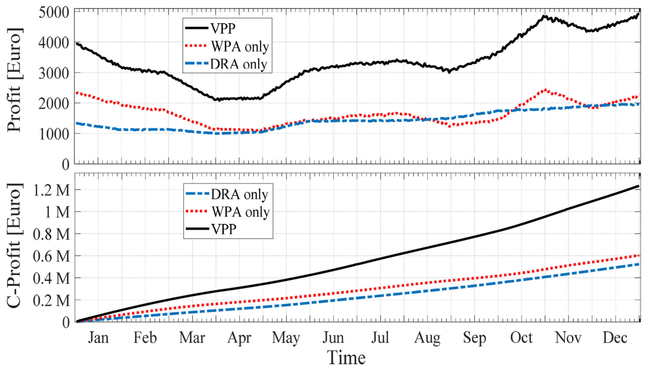

Fig. 12 *Profit and cumulative profit (C-Profit) comparison for DRA only, WPA only and VPP for one year*

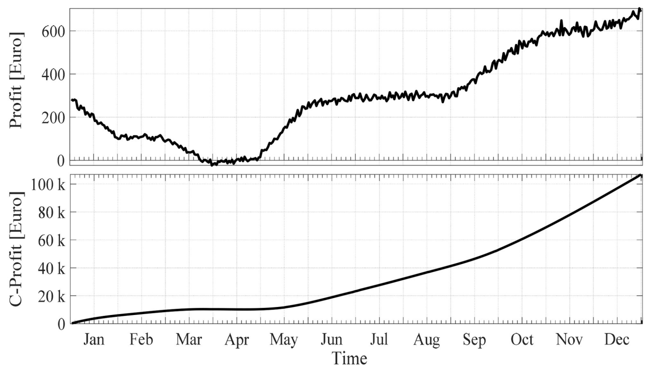

Fig. 13 *Profit and cumulative profit (C-Profit) for extra profit of VPP over the course of one year*

Moreover, the cumulative profit of VPP is superior to the ones with independent configurations.

Fig. 13 also investigates the profit and C-Profit for the extra profit of VPP over the course of one year. As you can see in this figure, the maximum amount of extra profit happens at the end of the year when the price of electricity is too high. The total amount of extra profit of VPP for this year is € 106,850.

5 Conclusion

This research coordinates a WPA and a DRA to form a VPP which participates in different types of electricity markets comprising DA, intraday and balancing markets. Price of energy in electricity markets, wind production, and its outage are considered as uncertain parameters. In this regard, a random procedure has been utilised to generate uncertainty of wind outage which is added to the normal operation of wind producer. Considering the given market structure, three-stage stochastic programming has been formulated to clear the DA market in this first stage, while the intraday market and balancing market are cleared afterward in the next two stages. CVaR technique has been applied to the formulation of problems to tackle the financial risk of the market operation. Results demonstrated superiorities of joint operation as a VPP comparing to the independent participation of wind and DR producers in the markets.

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