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An Approach to Divide Wind Power Capacity Between Day-Ahead Energy and Intraday Reserve Power Markets

Mehdi Tavakkoli, Student Member, IEEE, Sajjad Fattaheian-Dehkordi, Student Member, IEEE, Mahdi Pourakbari-Kasmaei, Senior Member, IEEE, Matti Liski, and Matti Lehtonen

***Abstract*— Wind power producers have recently gained a significant penetration in the electric power network, which might cause some challenges for the system operation due to the uncertainties in the generated power. In this way, wind power owners may offer different services, such as providing reserve capacity besides their conventional role of delivering just energy. Currently, conventional generators are the main responsible for providing some reserve in case of uncertainty in renewable generation and demand changes. Therefore, this paper introduces a novel approach that allows wind power producers to participate in both energy and reserve markets alongside conventional generators. A two-stage stochastic programming model is deployed for this purpose and the proposed approach is examined on the IEEE RTS 24-Bus. The simulation results demonstrate that for ensuring a higher level of reliability by the suggested scheme, both conventional generators and wind power producers will receive more revenue in both markets, although the demands should pay more.**

***Index Terms*—Wind power producers, energy market, reserve market, optimization programming.**

NOMENCLATURE

A. Indices and Sets

T	Set of the time period
N	Set of buses
S	Set of scenarios
G	Set of generation units
W	Set of wind power units
D	Set of demands
K	Set of lines
Ψ_n^G	Set of generation units located at bus n
Ψ_n^W	Set of wind power units located at bus n
Ψ_n^D	Set of demands located at bus n
Υ_b^G	Set of the blocks of the g_{th} generation unit
Υ_l^W	Set of the blocks of the w_{th} wind power unit
Υ_j^D	Set of the blocks of the d_{th} demand
$r(k)$	Receiving-end bus of line k
$s(k)$	Sending-end bus of line k

B. Parameters

$P_{w,l,t}^{forecast}$	Hourly expected wind power (W)
π_s	Probability occurrence of scenario s
C_{gb}	Marginal cost of unit g, block b
$C_{g,b}^{RU}$	Upward reserve capacity cost for unit g, block b
$C_{g,b}^{RD}$	Downward reserve capacity cost for unit g, block b
$C_{g,b}^{U}$	Cost of increasing generation of unit g, block b at the balancing stage
$C_{g,b}^{D}$	Cost of decreasing generation of power unit g, block b at the balancing stage
$C_{w,l}$	Marginal cost of wind power unit w, block l
$C_{w,l}^{RU}$	Upward reserve capacity cost for wind power unit w, block l
$C_{w,l}^{RD}$	Downward reserve capacity cost for wind power unit w, block l
$C_{w,l}^{U}$	Cost of increasing generation of wind power unit w, block l at the balancing stage
$C_{w,l}^{D}$	Cost of decreasing generation of wind power unit w, block l at the balancing stage
$C_{w,l}^{Penalty}$	Cost of penalty for wind power unit w, block l
$C_{w,l}^{curtail}$	Cost of curtail for wind power unit w, block l
$a_{w,l}^{Res,Up}$	Constant values which specify max upward reserve offer based on the forecasted power
$a_{w,l}^{Res,Down}$	Constant values which specify max Downward reserve offer based on the forecasted power

C. Variables

$P_{g,b,t}$	Power cleared to be produced by the b_{th}block of the g_{th} generation unit
$P_{w,l,t}$	Power cleared to be produced by the l_{th}block of the w_{th} wind power unit
$P_{d,j,t}$	Power cleared to be consumed by the j_{th}block of the d_{th} generation unit
$R_{g,b,t}^{U}$	Upward reserve capacity of unit g, block b at time t
$R_{g,b,t}^{D}$	Downward reserve capacity of unit g, block b at time t
$R_{w,l,t}^{U}$	Upward reserve capacity of wind power unit w, block l at time t
$R_{w,l,t}^{D}$	Downward reserve capacity of wind power unit w, block l at time t
$P_{g,b,t,s}^{U}$	Upward balancing energy of unit g, block b, deploying from $R_{g,b,t}^{U}$ at time t and scenario s
$P_{g,b,t,s}^{D}$	Downward balancing energy of unit g, block b, deploying from $R_{g,b,t}^{D}$ at time t and scenario s

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$P^{U}_{w,l,t,s}$	Upward balancing energy of wind power unit w, block l, deploying from $R^{U}_{w,l,t}$ at time t and scenario s
$P^{d}_{w,l,t,s}$	Downward balancing energy of wind power unit w, block l, deploying from $R^{U}_{w,l,t}$ at time t and scenario s
$P^{Penalty}_{w,l,t,s}$	Power bought by wind power unit from market when real power is less than scheduled power
$P^{Curtail}_{w,l,t,s}$	Curtailed power of wind power unit w, block l, at time t and scenario s
$\delta^{0}_{n,t}$	Voltage angle in the day-ahead stage at bus n, time t
$\delta_{n,t,s}$	Voltage angle in the balancing stage at bus n, time t, and scenario s
$f^{0}_{k,t}$	Power flow through line k in the day-ahead stage at bus n, time t
$f_{k,t,s}$	Power flow through line k in the balancing stage at bus n, time t, and scenario s

I. Introduction

WIND Wind power farms, as the most common type of renewable energy resources (RERs), are environmentally and economically viable options that have attracted significant interest during the last years because of being emission-free and low-cost resources [1], [2]. However, due to the unpredictable nature of these resources, which cause some inevitable errors in predicting the real wind-generated power, the increasing integration of wind in the grid results in some challenges such as uncertainty for the operation of the power system [3]. On the other hand, the demand side also might change its consumption level in real-time compared to the cleared demand in the day-ahead (DA) market that causes additional uncertainty on the power system.

In order to deal with this issue, it is required to provide more flexibility for the network, which generally leads to procuring extra operational reserve capacity to guarantee a reliable function of the power system [4]. Current practices are mostly dependent on the conventional generators for providing such a reserve for the system. Some studies have been working towards specifying the amount of reserve for the power grid where there is a large integration of renewable energy in the system. While some of them were focusing on the deterministic approaches [5], the others were working on the stochastic methods [6], [7]. The authors in [8] proposed a dynamic reserve policy based on forecasted wind power to determine the required reserved capacity on an hourly basis instead of a fixed reserve for longer periods. For addressing the uncertainty via robust optimization techniques, an adjustable robust approach for the procurement of reserve was developed in [9], while in [10], a two-stage data-driven distributionally robust reserve and energy scheduling model was presented. A probabilistic approach for predicting the amount of required reserve was proposed in [11] by suggesting an approach to distinguish between fast-response reserves and slow-response reserves based on the imbalance power of wind generation. The authors in [12] adopted a heuristic approach called the Imperialistic Competition Algorithm to find the optimal solution for generation scheduling problems in the presence of high integration of wind farms.

Some research works have recently been investigating the impact of energy storage systems (ESSs) as a new source of flexibility to provide a higher level of reserve capacity for the power system. In order to increase the profit, authors in [13] proposed using on-site ESS to handle wind power fluctuations and provide spinning reserve and frequency response under different levels of uncertainty in the electricity price and wind power prediction. In [14], the authors proposed to use the low-price retired EV batteries in order to combine it with the wind power plant to obtain more profitability. The suggested methodology was examined economically in both the DA market and frequency containment normal operation reserve (FCR-N) market via a two-stage optimization model. In [15], three different types of reserve services comprising spinning reserve, downward and upward regulation reserves were provided by deploying ESSs in the presence of large penetration of wind power. The size and location of ESSs were determined by considering a combination of unit commitment and AC optimal power flow to find the optimal planning and operation of ESS in radial networks. In [16], a hybrid ESS, including flywheel ESS and adiabatic compressed air ESS, was deployed to alleviate the fluctuations of the wind-generated power.

Some literature has also been studying the optimal offering strategy of wind generation in the electricity market to limit the effect of uncertainty of the wind power by taking the balancing stage into account. An offering strategy for a wind power producer that takes part in both the DA and balancing market was presented through a multi-stage risk-constrained stochastic complementarity model in [17]. The conditional-value-at-risk (CVaR) metric was adopted to consider the profit risk related to the offering decisions. In [18], the participation of a power plant comprising wind power and a battery ESS was investigated in both the energy market and ancillary-services market. The data-processing method and model predictive control strategy were used to analyze the probabilistic distribution of uncertainty factors in both markets and manage the battery ESS in real-time operation, respectively. Two different imbalance pricing policies based on the supply curve were considered in [19], including one price estimation strategy (SCOPES) for the one price system and multivariate interdependence minimizing imbalance cost strategy (MIMICS) for the two price system. Then, a stochastic model was built to analyze the impacts of the suggested pricing policies on the electricity market.

In contrary to the abovementioned literature, little consideration has been placed on providing joint energy and reserve by the wind power producers. With the ever-increasing penetration of wind energy in the power system, it would be beneficial to have wind power generators to provide flexibility and ancillary services in the same way as traditional generators. In this way, wind power producers are capable of offering reserve power and take part in the balancing stage as well as participating in the energy market. Recently, there have been some regulatory impulses in order to have such a function by RERs [20]. As an instance, the federal energy regulatory commission (FERC) has suggested eradicating the exclusion of wind power plants for proving reactive power [21].

This paper presents a novel approach that enables wind power producers to operate like conventional generators and participate in both energy and reserve markets. Based on the proposed method, wind power producers can hold a portion of their potential generation for participating in the reserve market instead of offering the whole predicted energy in the day-ahead market. In case of failing to provide the cleared energy, the wind power producers are penalized for such a violation. The main difference between this work and studies like [13], [14], and [18] is that they used battery energy storage in their model, which impose investment and maintenance cost to the system. In [17], wind power units are considered price-makers for participating in both the day-ahead and balancing markets, while in our work, the wind power units are modeled as price takers.Therefore, the contributions of this work are as follows.

1) Deriving and presenting a stochastic optimization model for optimal joint energy and reserve market, which incorporate reserve capacity for the wind power producers along with conventional generators.

2) Implementing the presented model on the IEEE RTS 24-Bus system and providing detailed discussion on the results and comparisons with the benchmark model [22], which did not include reserve capacity for the wind power producers. This shows the applicability of the suggested method.

The remainder of this paper is organized as follows. Section II presents the stochastic optimization model for the joint energy and reserve markets. Section III provide and discuss the simulation results, and Section IV presents the conclusion

II. Problem formulation for market clearing

With the aim of guaranteeing a reliable operation of the power system in the real-time, system operator assigns sufficient reserve capacity for the balancing stage in advance. Generally, there are two ways of trading reserve in the electricity market. One way is to procure reserve power after scheduling energy in the DA market, and the other way is to optimize the energy and reserve simultaneously. In this paper, we adopt the latter way of procuring joint energy and reserve in the electricity market. Because simultaneous dispatch of energy and reserve considers the coupling between these two commodities which will decrease the total cost or increase the social welfare. This is possible by using a two-stage stochastic model that takes the interaction between DA and the balancing stage into account. In this way, there exists adequate reserve capacity to handle the uncertainties of the generation and consumption in real-time. In order to build the formulation, we need to make a set of assumptions:

1) A DC power flow has been considered for the transmission network.

2) We assume the demand to be inelastic. Hence, the social welfare maximization for the objective function will boil down to the cost minimization.

3) The market clearing process is affected by the uncertainties from wind power producers and demand consumptions, which are modeled through a different set of scenarios.

4) conventional generation units are supposed fully dispatchable, which can produce power from zero to their maximum power capacity.

According to the abovementioned assumptions, the proposed two-stage stochastic optimization programming is formulated as equations (1)-(34).

$$\begin{aligned}\min \sum_{t=1}^{T}\sum_{g\in G}\sum_{b\in \Upsilon_b^G}&(C_{g,b}P_{g,b,t}+C_{g,b}^{RU}R_{g,b,t}^{U}+C_{g,b}^{RD}R_{g,b,t}^{D})\\ +\sum_{t=1}^{T}\sum_{w\in W}\sum_{l\in \Upsilon_l^W}&(C_{w,l}P_{w,l,t}+C_{w,l}^{RU}R_{w,l,t}^{U}+C_{w,l}^{RD}R_{w,l,t}^{D})\\ +\sum_{t=1}^{T}\sum_{s\in S}\pi_s&\left[\sum_{g\in G}\sum_{b\in\Upsilon_b^G}(C_{g,b}^{U}P_{g,b,t,s}^{U}-C_{g,b}^{D}P_{g,b,t,s}^{D})\right.\\ &\left.+\sum_{w\in W}\sum_{l\in\Upsilon_l^W}\begin{matrix}(C_{w,l}^{U}P_{w,l,t,s}^{U}-C_{w}^{D}P_{w,l,t,s}^{D})\\ -C_{w,l}^{Penalty}P_{w,l,t,s}^{Penalty}\end{matrix}\right]\end{aligned} \tag{1}$$

s.t.

$$\begin{aligned}&\sum_{g\in\Psi_n^G}\sum_{b\in\Upsilon_g^G}P_{g,b,t}+\sum_{w\in\Psi_n^W}\sum_{l\in\Upsilon_w^W}P_{w,l,t}-\sum_{k\in \mathrm{K}|s(k)=n}f_{k,t}^{0}\\ &+\sum_{k\in \mathrm{K}|r(k)=n}f_{k,t}^{0}=\sum_{d\in\Psi_n^D}\sum_{j\in\Upsilon_d^D}P_{d,j,t}\ :\lambda_{n,t}^{DA},\forall n,\forall t\end{aligned} \tag{2}$$

$$\begin{aligned}&\sum_{g\in\Psi_n^G}\sum_{b\in\Upsilon_g^G}(P_{g,b,t,s}^{U}-P_{g,b,t,s}^{D})+\sum_{w\in\Psi_n^W}\sum_{l\in\Upsilon_l^W}\Big(P_{w,l,t,s}^{U}-P_{w,l,t,s}^{D}\\ &-P_{w,l,t,s}^{Penalty}\Big)+\sum_{k\in \mathrm{K}|s(k)=n}(f_{k,t}^{0}-f_{k,t,s})-\sum_{k\in \mathrm{K}|r(k)=n}(f_{k,t}^{0}-f_{k,t,s})\\ &=\sum_{d\in\Psi_n^D}\sum_{j\in\Upsilon_d^D}P_{d,j,t,s}^{Real}-P_{d,j,t}:\gamma_{n,t,s}^{Bal},\forall n,\forall t,\forall s\end{aligned} \tag{3}$$

$$f_{k,t}^{0}=B_k(\delta_{s(k),t}^{0}-\delta_{r(k),t}^{0}),\forall k,\forall t \tag{4}$$

$$f_{k,t,s}=B_k(\delta_{s(k),t,s}-\delta_{r(k),t,s}),\forall k,\forall t,\forall s \tag{5}$$

$$-f_k^{\max}\le f_{k,t}^{0}\le f_k^{\max},\forall k,\forall t \tag{6}$$

$$-f_k^{\max}\le f_{k,t,s}\le f_k^{\max},\forall k,\forall t,\forall s \tag{7}$$

$$-\pi\le\delta_{n,t}\le\pi,\forall n\setminus n:ref,\forall t \tag{8}$$

$$\delta_{n,t}=0,n:ref,\forall t \tag{9}$$

$$-\pi\le\delta_{n,t,s}\le\pi,\forall n\setminus n:ref,\forall t,\forall s \tag{10}$$

$$\delta_{n,t,s}=0,n:ref,\forall t,\forall s \tag{11}$$

$$P_{g,b,t},R_{g,b,t}^{U},R_{g,b,t}^{D}\ge 0,\forall g,\forall b,\forall t \tag{12}$$

$$P_{g,b,t,s}^{U},P_{g,b,t,s}^{D}\ge 0,\forall g,\forall b,\forall t,\forall s \tag{13}$$

$$P_{g,b,t}+R_{g,b,t}^{U}\le P_{g,b}^{\max},\forall g,\forall b,\forall t \tag{14}$$

$$P_{g,b,t}-R_{g,b,t}^{D}\ge P_{g,b}^{\min},\forall g,\forall b,\forall t \tag{15}$$

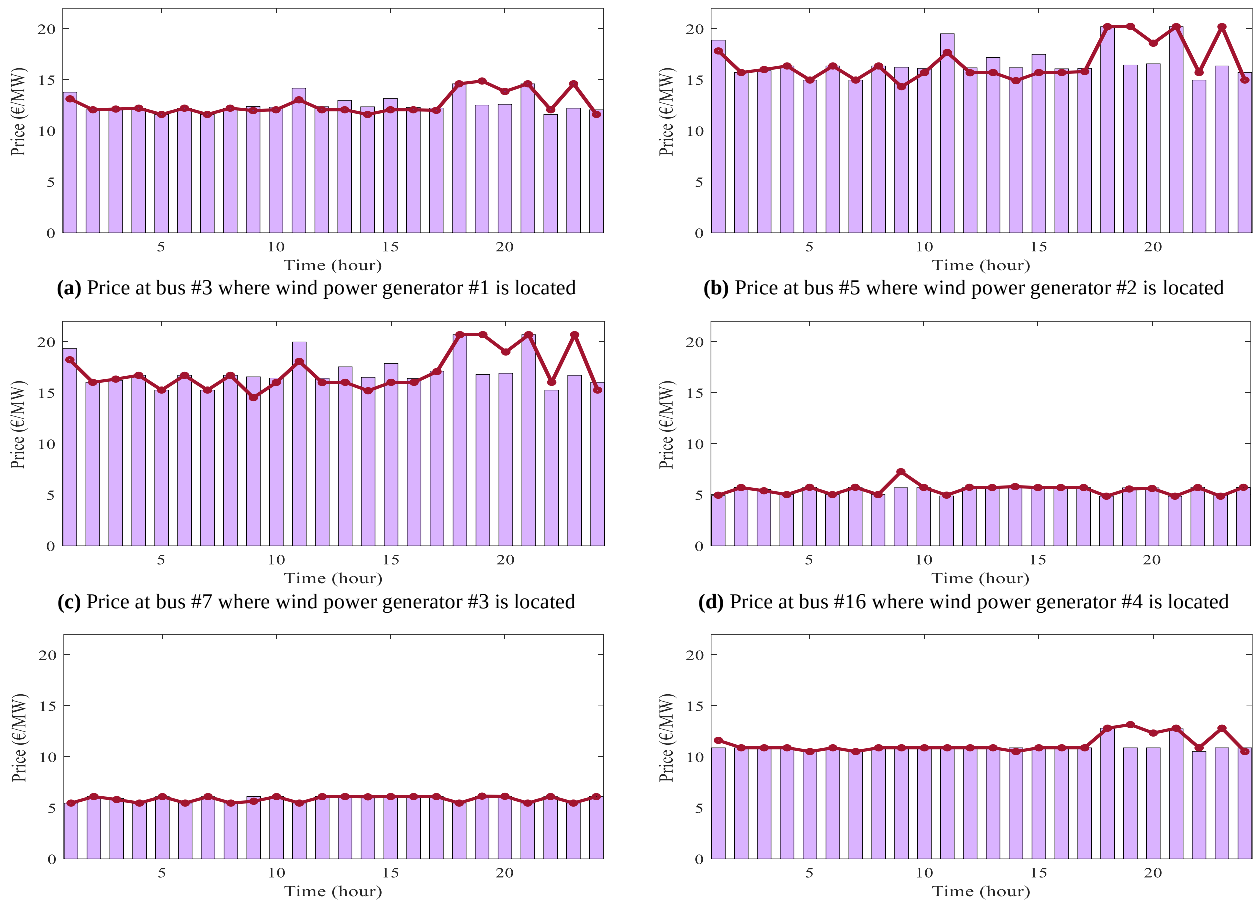
$$R_{g,b,t}^{U}\le R_{g,b}^{U,\max},\forall g,\forall b,\forall t \tag{16}$$

$$R_{g,b,t}^{D}\le R_{g,b}^{D,\max},\forall g,\forall b,\forall t \tag{17}$$

$$P_{g,b,t,s}^{U}\le R_{g,b,t}^{U},\forall g,\forall b,\forall t,\forall s \tag{18}$$

$$P_{g,b,t,s}^{D}\le R_{g,b,t}^{D},\forall g,\forall b,\forall t,\forall s \tag{19}$$

$$P_{w,l,t},R_{w,l,t}^{U},R_{w,l,t}^{D}\ge 0,\forall w,\forall l,\forall t \tag{20}$$



(a) Price at bus #3 where wind power generator #1 is located

(b) Price at bus #5 where wind power generator #2 is located

(c) Price at bus #7 where wind power generator #3 is located

(d) Price at bus #16 where wind power generator #4 is located

(e) Price at bus #21 where wind power generator #5 is located

(f) Price at bus #23 where wind power generator #6 is located

Fig. 1. Day-ahead price for Scenario A, purple bars: cleared price in case 1, solid red lines: cleared price in case 2

$$P^{U}_{w,l,t,s}, P^{D}_{w,l,t,s}, P^{Curtail}_{w,l,t,s} \geq 0, \forall w, \forall l, \forall t, \forall s \tag{21}$$

$$P_{w,l,t} + R^{U}_{w,l,t} \leq P^{forecasted}_{w,l}, \forall w, \forall l, \forall t \tag{22}$$

$$P_{w,l,t} - R^{D}_{w,l,t} \geq 0, \forall w, \forall l, \forall t \tag{23}$$

$$R^{U}_{w,l,t} \leq \alpha^{ResUp\_Max}_{w,l} P^{forecast}_{w,l}, \forall w, \forall l, \forall t \tag{24}$$

$$R^{D}_{w,l,t} \leq \alpha^{ResDown\_Max}_{w,l} P^{forecast}_{w,l}, \forall w, \forall l, \forall t \tag{25}$$

$$P^{U}_{w,l,t,s} \leq R^{U}_{w,l,t}, \forall w, \forall l, \forall t, \forall s \tag{26}$$

$$P^{D}_{w,l,t,s} \leq R^{D}_{w,l,t}, \forall w, \forall l, \forall t, \forall s \tag{27}$$

$$P^{U}_{w,l,t,s} \leq \max(0, P^{Real}_{w,l,t,s} - P_{w,l,t}), \forall w, \forall l, \forall t, \forall s \tag{28}$$

$$P^{D}_{w,l,t,s} \leq P^{Real}_{w,l,t,s}, \forall w, \forall l, \forall t, \forall s \tag{29}$$

$$P^{D}_{w,l,t,s} \leq P_{w,l,t}, \forall w, \forall l, \forall t, \forall s \tag{30}$$

$$P^{Curtail}_{w,l,t,s} \leq P^{Real}_{w,l,t,s}, \forall w, \forall l, \forall t, \forall s \tag{31}$$

$$P^{Penalty}_{w,l,t,s} = \max(0, P_{w,l,t} - P^{Real}_{w,l,t,s}) \tag{32}$$

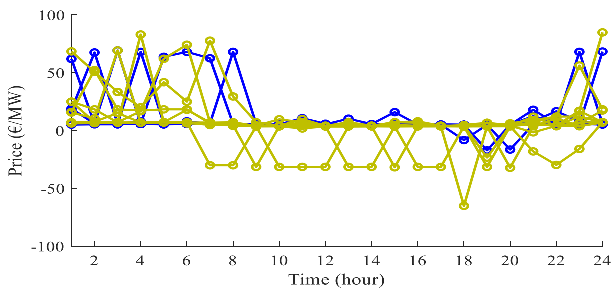
$$P^{a}_{w,l,t,s} = \max(0, P^{Real}_{w,l,t,s} - P_{w,l,t}) \tag{33}$$

$$P^{Curtail}_{w,l,t,s} = P^{a}_{w,l,t,s} - P^{U}_{w,l,t,s} + P^{D}_{w,l,t,s}, \forall w, \forall l, \forall t, \forall s \tag{34}$$

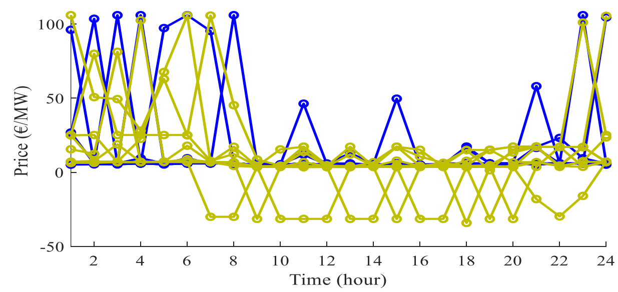
The objective function in (1) seeks to minimize the total expected operational cost consisting of expected energy and reserve cost in the day-ahead plus anticipated balancing cost in real-time operation of the power system. The first line of the objective function, which contains three terms, shows the day-ahead energy cost, upward reserve capacity cost, and downward reserve capacity cost, respectively for the conventional generators. The second line of the objective function shows similar costs for the wind generating units. The third line of the objective function indicates balancing costs for conventional generators. Finally, the fourth line demonstrates the balancing cost for the wind power units, which is comprised of energy cost for upward and downward balancing plus penalty cost when the wind power units are violating their scheduled power. Constraints (2) and (3) are the power balance equations for the day-ahead energy dispatch and real-time energy redispatch, respectively. Moreover, $\lambda^{DA}_{n,t}$ and $\gamma^{Bal}_{n,t,s} / \pi_s$ show the day-ahead energy price and prediction of the balancing market price for scenario s, respectively. Equations (4) and (5) indicate the

Table I Costs of the Wind Power Generating Units

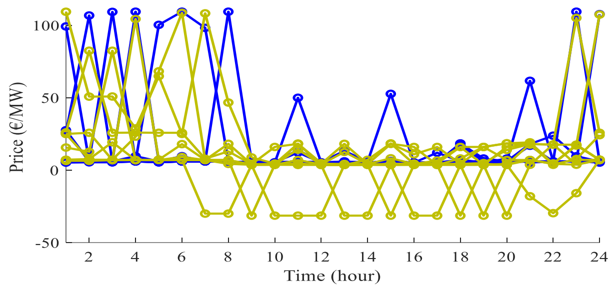
unit	$C_{w,l}$	$C^{RU}_{w,l}$	$C^{RD}_{w,l}$	$C^{U}_{w,l}$	$C^{D}_{w,l}$	$C^{Penalty}_{w,l}$
1	5	4	3.8	6.2	4.2	7
2	6	4.8	4.2	6.4	4.1	8
3	5.2	3.9	3.5	7	3.6	7.2
4	5.4	5	4	6.8	3.8	7.4
5	6.1	4.4	3.6	7.2	3.7	8.1
6	5.1	3.8	3.4	6.9	4	7.1



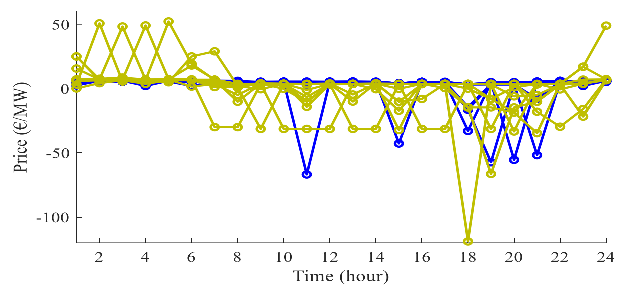
(a) Price at bus #3 where wind power generator #1 is located



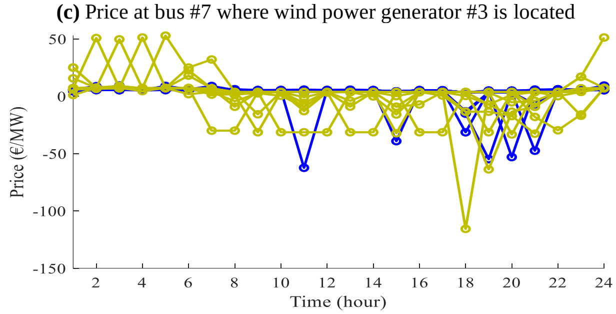
(b) Price at bus #5 where wind power generator #2 is located



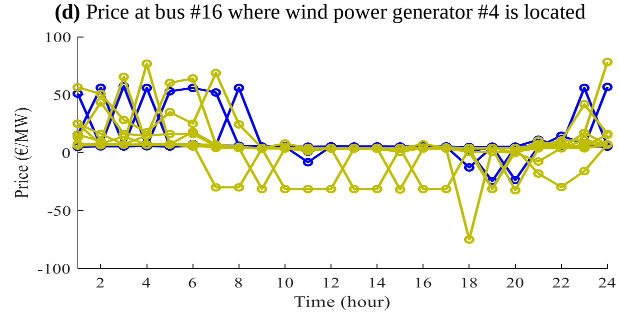
(c) Price at bus #7 where wind power generator #3 is located



(d) Price at bus #16 where wind power generator #4 is located



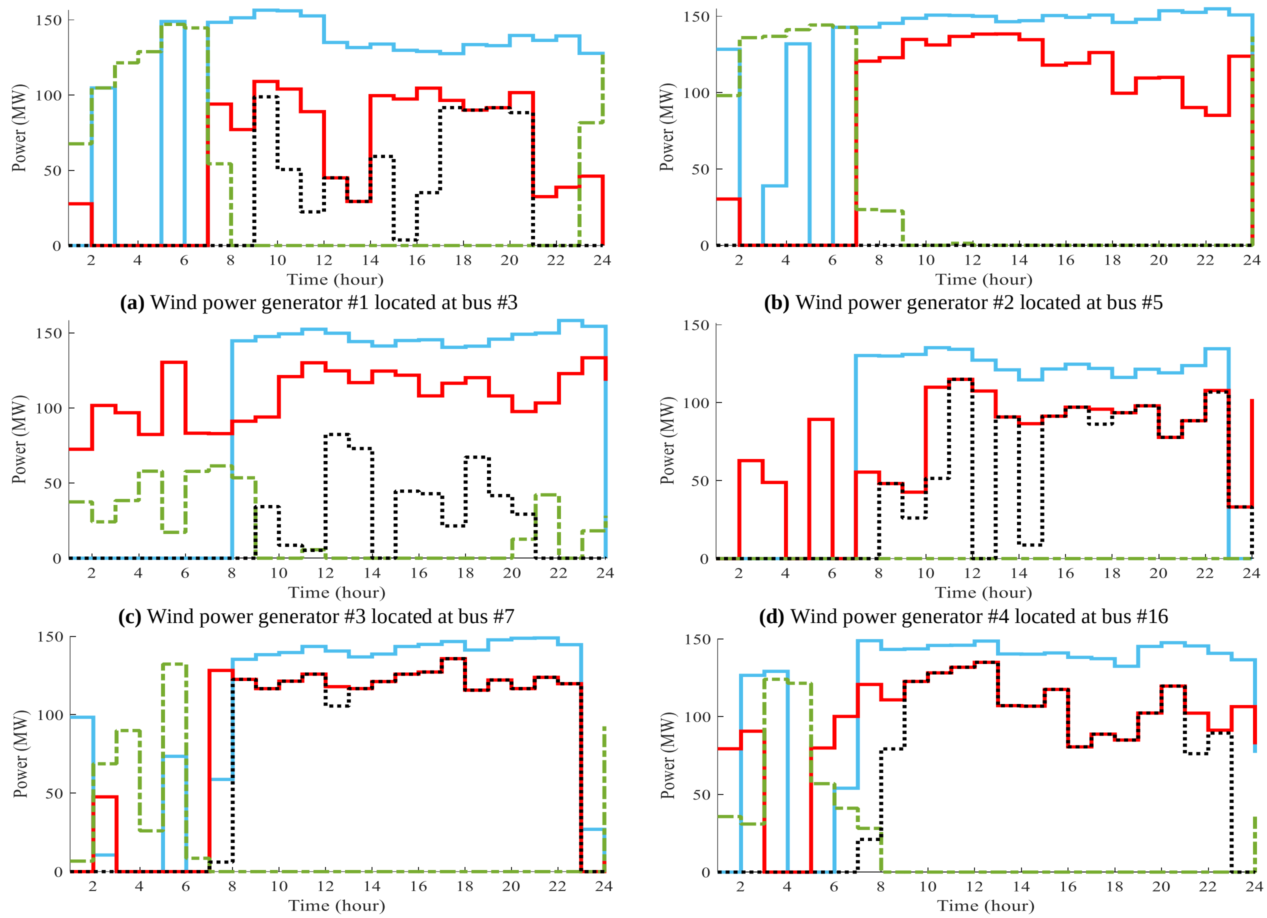
(e) Price at bus #21 where wind power generator #5 is located



(f) Price at bus #23 where wind power generator #6 is located

Fig. 2. Balancing price for Scenario A, Blue lines: balancing price in case 1, yellow lines: balancing price in case 2

transferred power for each line, and (6) and (7) enforce the capacity limits for each line in the day-ahead and balancing stages, respectively. Constraints (8) and (10) bound the voltage angles of each bus where (9) and (11) set the voltage angle of the reference bus to zero in the day-ahead and balancing stages, sequentially. Constraints (12), (13), (20), and (21) declares non-negativity for the variables. The relation between energy and reserve with regards to the maximum and minimum power of of the conventional producers is declared by (14) and (15). Moreover, (16) and (17) impose restrictions on the quantity of the upward and downward reserve capacity of each conventional generator to be less than or equal to their reserve offer. The amount of increased or decreased energy by the conventional generators in the balancing stage, which are obtained from their upward and downward reserve capacity, are restricted by (18) and (19), respectively. Constraints (22) and (23) limit the energy and reserve for the wind power producers with regards to the forecasted power. Constraints (24) and (25) declare the maximum upward and downward reserve capacity offered by the wind power producers, sequentially. In addition, (24) and (25) impose limits for increasing or decreasing the energy by the wind power producers in the balancing stage for each scenario. Constraints (28) enforce that the upward power provided by the wind power generators to be smaller than or equal to residual power left from real power after delivering the day-ahead power. Furthermore, (29)-(31) bound the maximum amount for downward and curtailment power of wind power producers. Finally, (32) declares that wind power producers are obliged to buy some power from the utility in case their day-ahead cleared power to be delivered is larger than their real generated power. Equation (33) also introduces auxiliary variables to calculate the curtailment amount of wind power producers in equation (34). simulation, namely Case 1 and Case 2. Case 1 is related to the situation where there is no reserve capacity provided by the wind power producers, while Case 2 introduces the circumstances where reserve capacity offered by the wind farms is incorporated into the model, see (1)-(34). The formulation for Case 1 is based on [22]. In order to study the performance of the presented approach, it has been applied to the IEEE RTS 24-Bus System [23]. Six wind farms have been added in different locations of the grid, including 3, 5, 7, 16, 21, and 23 buses. In order to study the impact of wind power generation factor in the proposed model, two penetration level is assumed for wind power where 1) each wind power unit has 200 MW power capacity, and 2) each wind power unit has 300 MW power capacity. Considering the maximum load demand in the network (2544.48 MW), the penetration level 1 and penetration level 2 is around 47% and 71%, respectively.



(a) Wind power generator #1 located at bus #3

(b) Wind power generator #2 located at bus #5

(c) Wind power generator #3 located at bus #7

(d) Wind power generator #4 located at bus #16

(e) Wind power generator #5 located at bus #21

(f) Wind power generator #6 located at bus #23

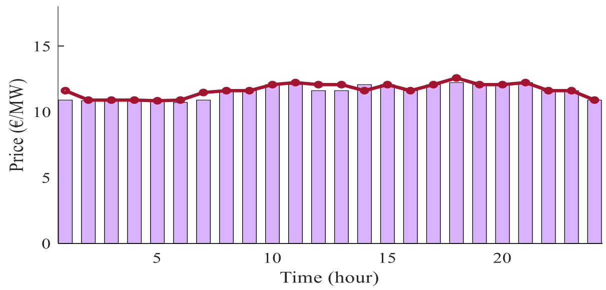
Fig. 3. Cleared day-ahead power and reserve capacity for wind power generators in Scenario A,
solid blue lines: cleared power of wind generators in case 1
solid red lines: cleared power of wind generators in case 2
dotted dashed green lines: up reserve of wind generators in case 2
dotted black lines: down reserve of wind generators in case 2

III. Simulation Results

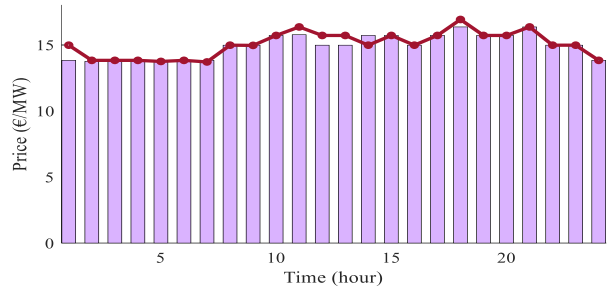
In this section, we consider two different cases for the The cost data of the wind power producers are presented in Table I. Twenty four hours of one day, spanning from 1 A.M. to 24 P.M. has been considered for implementing the simulation. Ten scenarios are provided for wind power by [24]. In addition, two different scenarios, including Scenario A and Scenario B, have been considered for the real-time demand consumption where each of them contains ten scenarios. To this end, load and wind duration curves are used to generate the scenarios for modeling the uncertainties while taking into account the correlation between the wind power and load demand [25]. Scenario A represents scenarios in which the demand is consuming approximately around the forecasted load, while Scenario B represents the scenarios where the demand is consuming less than the forecasted load. The real-time and forecasted data of demand consumption and wind power generation are available in [26]. The proposed model has been implemented on an HP Z240 Tower Workstation with eight Intel Xeon E3-1230 v5 processors at 3.4 GHz and 16 GB of RAM using CPLEX 12.8 [27] under GAMS 25.1.2 [28].

A. *Wind Penetration Level 1*

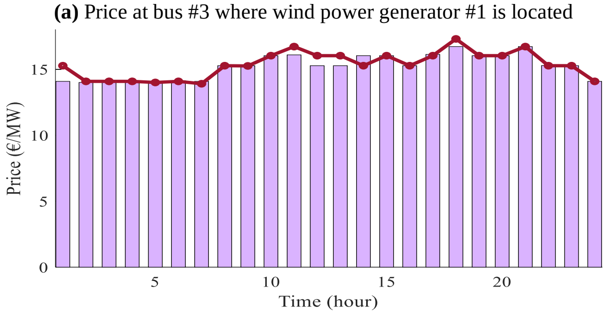
The simulation has been conducted where each wind turbine capacity is 200 MW. Fig. 1 and Fig. 4 show the day-ahead electricity prices for the case studies A, and B, respectively. These prices are for buses 3, 5, 7, 16, 21, and 23, where the wind power producers are located. According to these figures, between case 1 and case 2 under both case studies A and B. This implies that the day-ahead prices are cleared mostly regardless of considering the reserve capacity potential for the wind power producers. However, the balancing prices demonstrate significant changes while wind power generators are the day-ahead prices do not indicate significant changes participating in providing reserve capacity and taking part in the balancing market. Regarding Fig. 2 and Fig. 5, which show the balancing prices in case studies A, and B, respectively, and for the buses where wind power generators are placed, it can be seen that the balancing prices in Case 2 are mainly lower than Case 1. This happens because wind power producers are offering cheaper reserve capacity and balancing services in comparison to the conventional generators. Nevertheless, it does not necessarily mean that consumers should always pay less if they are not following their scheduled power in the day-ahead market.



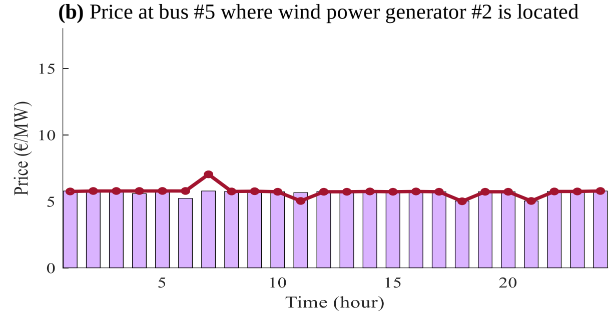
(a) Price at bus #3 where wind power generator #1 is located



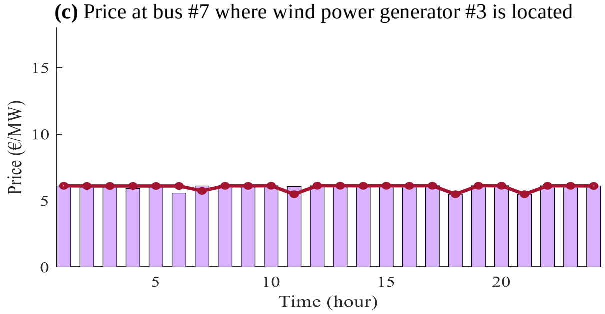
(b) Price at bus #5 where wind power generator #2 is located



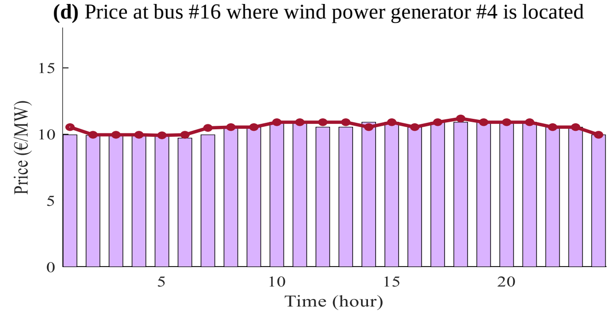
(c) Price at bus #7 where wind power generator #3 is located



(d) Price at bus #16 where wind power generator #4 is located



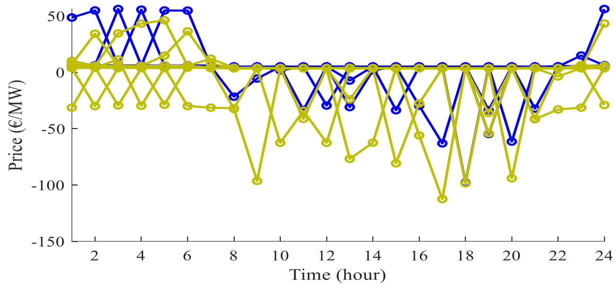
(e) Price at bus #21 where wind power generator #5 is located



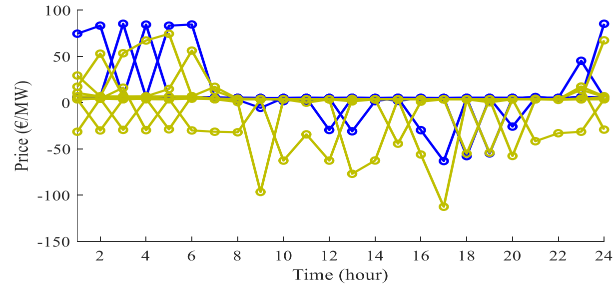
(f) Price at bus #23 where wind power generator #6 is located

Fig. 4. Day-ahead price for Scenario B, purple bars: cleared price in case 1, solid red lines: cleared price in case 2

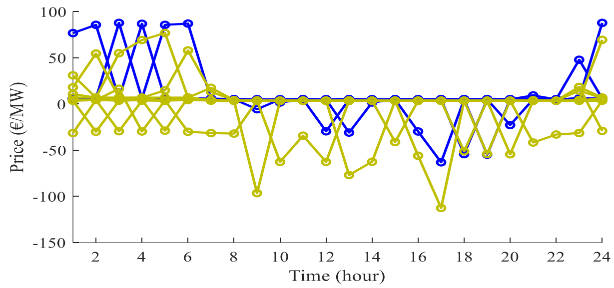
Because the wind power producers require to be paid for providing reserve capacity besides the balancing stage cost and revenue. In addition, for hours in which the balancing prices are negative (see Fig. 2 and Fig. 5), these prices in Case 2 are lower than Case 1. In this situation, if the real-time demand of the consumers is less than what was cleared in the day-ahead market, they have to pay more in Case 2 compared to Case 1. This is obvious, especially in Scenario B, where the real-time demand consumption scenarios are mostly less than their scheduled power in the day-ahead market. This occasion occurs when the system balance is positive, which means that the produced power is more than power consumption. This can also be deduced from Fig. 7 (c) and Fig. 8 (c), which show the total cost for the demands. According to these figures, the payments for the day-ahead stage for both Cases 1 and 2 do not show a large difference. However, the balancing stage is costlier for the consumers in Case 2 rather than Case 1, particularly in Scenario B where the balancing prices are highly negative. The cleared day-ahead power in Case 1 and cleared day-ahead power, up reserve, and down reserve capacities in Case 2 for the wind power producers are depicted in Fig. 3 and Fig. 6, for Scenario A and B, respectively. These figures show that wind power producers in Case 2 are dedicating some portion of their power as a reserve capacity to provide services for the balancing stage. The amount of day-ahead power, up reserve, and down reserve capacities for the wind power generators are dependent on the day-ahead prices, the balancing prices, and the demand forecast. For example, considering Fig. 1, which shows the day-ahead electricity prices in Scenario A, all buses except bus#16 have lower prices at the early hours of the day. Moreover, the balancing market prices are predominantly positive in the early hours (mostly before 8 A.M.), where it is negative after 8 A.M. Furthermore, the total load consumption at the beginning of the day is less than the rest of the day. Consequently, the wind power producers assign some portion of their power at the early hours (mostly before 8 A.M.) as up reserve capacity. On the other hand, when the total demands start to increase after 8 A.M., wind power producers are contributing more in the day-ahead power market and also considering some portion of their power as the down reserve capacity. This situation is even more noticeable in Scenario B, where all the wind power producers are allocating their full cleared power in the day-ahead market as a down reserve capacity (see Fig. 6). Because in this scenario, the real-time demand consumption is vastly lower than the scheduled power, and the balancing prices are also greatly negative for the most part. In this situation, the wind power producers consider a large share of their forecasted power as a down reserve capacity aiming at curtailing their output power when the system balance is positive. Fig. 7 (a) and Fig. 8 (a) show the total revenue and cost for all the conventional



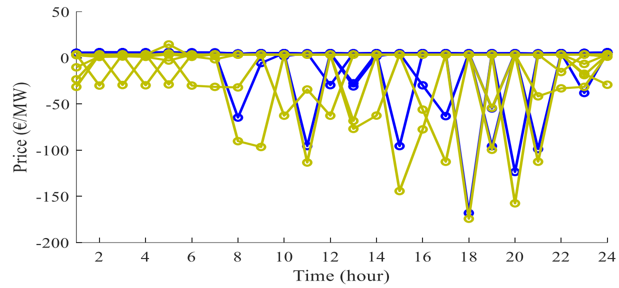
(a) Price at bus #3 where wind power generator #1 is located



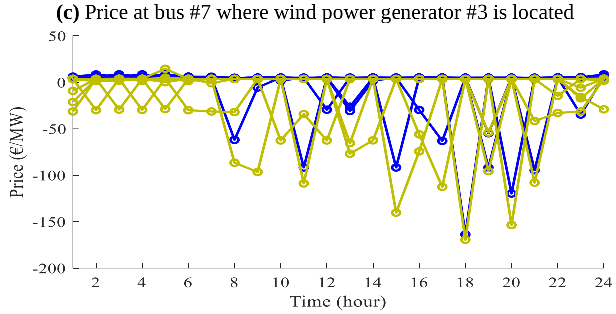
(b) Price at bus #5 where wind power generator #2 is located



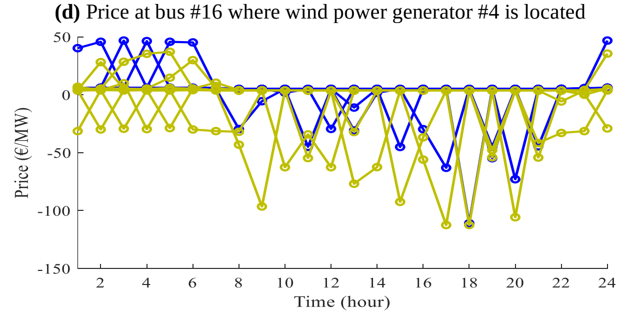
(c) Price at bus #7 where wind power generator #3 is located



(d) Price at bus #16 where wind power generator #4 is located



(e) Price at bus #21 where wind power generator #5 is located



(f) Price at bus #23 where wind power generator #6 is located

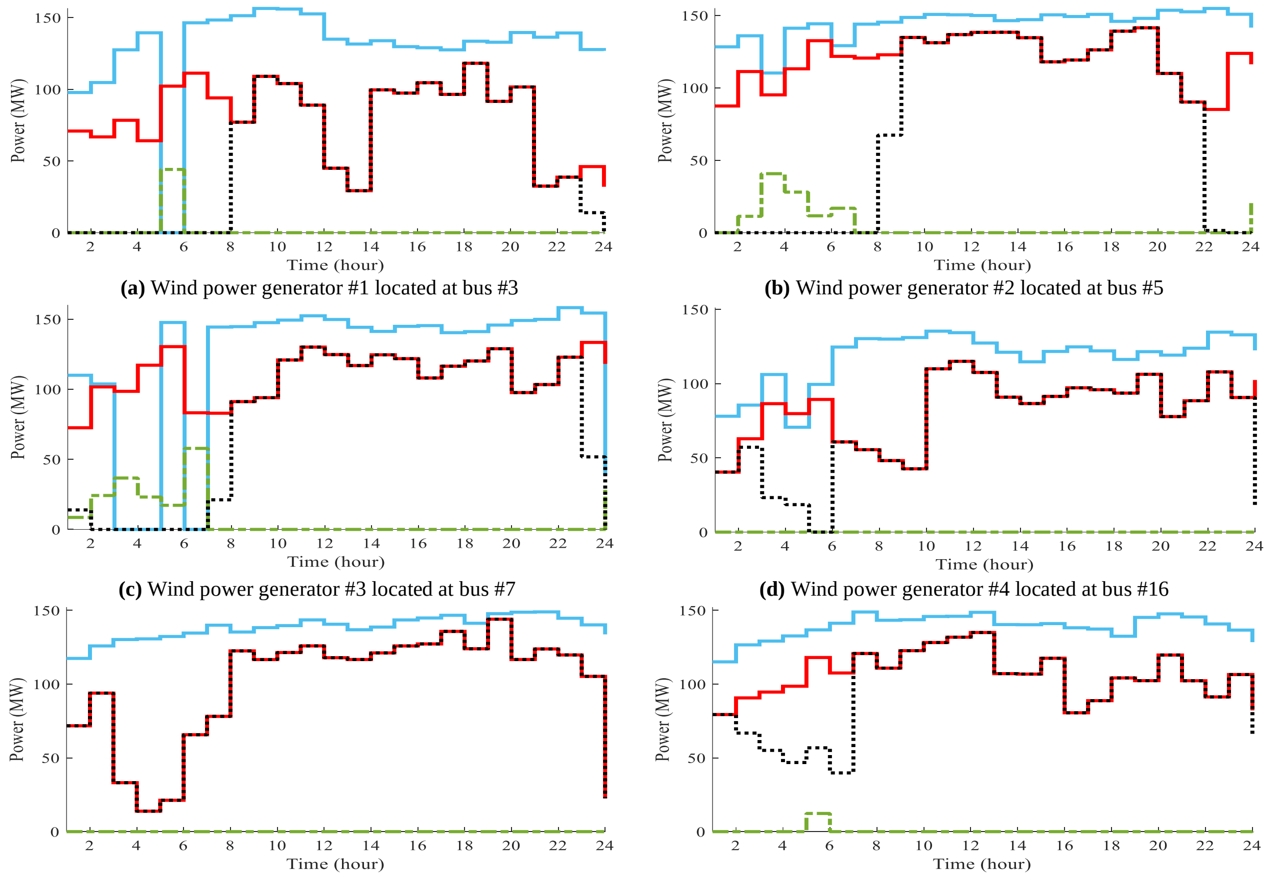
Fig. 5. Balancing price for Scenario B, Blue lines: balancing price in case 1, yellow lines: balancing price in case 2

generators in Scenario A and Scenario B, respectively. Firstly, we can see that the day-ahead revenue for the conventional generators in Case 2 has been increased compared to Case 1. This is due to the producing more power in the day-ahead market by conventional generators to compensate for the power reduction by the wind power producers, which has been dedicated to the reserve capacity. Secondly, the revenue coming from reserve capacity for conventional generators has increased as well. This is more noticeable in Scenario B where higher down reserve capacity is offered by the conventional generators to cover the decrease in the real-time demand consumption. Thirdly, the revenue for the balancing stage, which was slightly negative in Case1, shows an increase in case 2 because of covering the uncertainty of wind power generation. Finally, it can be seen that the operational cost between Case 1 and Case 2 does not indicate a large difference. Consequently, the total returns for conventional generators, which is the summation of revenue from day-ahead, balancing, and reserve market minus the operational cost indicate an increase in Case 2 compared with Case 1 where there is no reserve capacity for wind power producers.

Fig. 7 (b) and Fig. 8 (b) illustrate the overall revenue and operational cost for the wind power producers in Scenario A and Scenario B, respectively. As some portion of the forecasted power is dedicated to reserve capacity for both Scenarios A and B, the wind power producers are receiving less revenue in the day-ahead market in Case 2 rather than in Case 1. However, they are profited from the reserve market in Case 2 where they were not supposed to receive any benefit in Case 1. In addition, from these figures it can be seen that where the balancing revenue for Case 1 is relatively small in Scenario A, and slightly negative in Scenario B, it becomes significantly higher for Case 2 in both Scenario A and B. Regarding the operational cost, due to the producing slightly less power in Case 2 compared with Case 1, the wind power producers are incurring lower cost in both Scenarios A, and B. Finally, the total profit for the wind power producers which is the summation of revenue from day-ahead, balancing, and reserve market minus the operational cost, is noticeably higher in the case 2 instead of the case 1.

From the consumers' side, although their payment for the day-ahead market is not changing largely, they are paying more for the balancing stage. Therefore, the total cost for demand consumption shows an increase based on Fig. 7 (c) and Fig. 8 (c) for Scenario A and Scenario B, respectively.

Finally, Fig. 9 illustrates the total up reserve and down reserve capacity provided by both conventional generators and the wind power producers. As can clearly be observed from both Scenarios A, and B, the total reserve capacity is showing a substantial increase in Case 2 with comparison to Case 1, which results in improving the power system reliability to a



(a) Wind power generator #1 located at bus #3

(b) Wind power generator #2 located at bus #5

(c) Wind power generator #3 located at bus #7

(d) Wind power generator #4 located at bus #16

(e) Wind power generator #5 located at bus #21

(f) Wind power generator #6 located at bus #23

Fig. 6. Cleared day-ahead power and reserve capacity for wind power generators in Scenario B
solid blue lines: cleared power of wind generators in case 1
solid red lines: cleared power of wind generators in case 2
dotted dashed green lines: up reserve of wind generators in case 2
dotted black lines: down reserve of wind generators in case 2

great extent. While for Scenario A, the wind power producers are providing both up reserve and down reserve capacity for the system, they are providing mainly down reserve capacity for Scenario B. this is due to the considerable reduction of real-time load consumption rather than scheduled demand in that case.

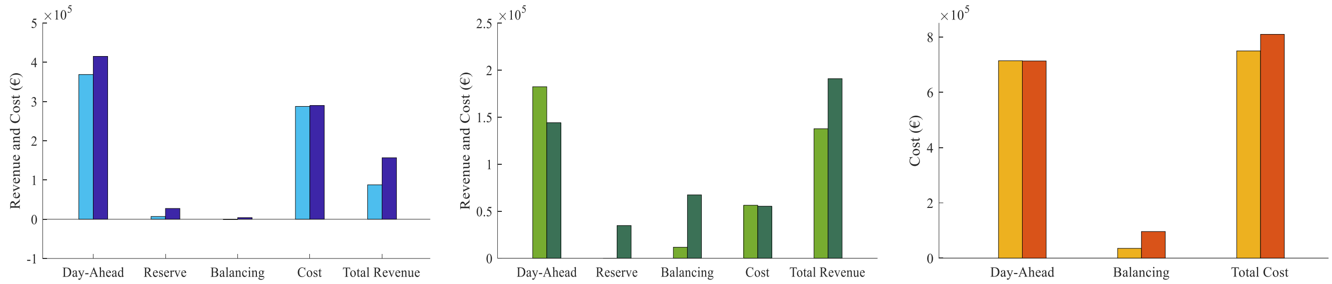
B. Wind Penetration Level 2

The simulation has been conducted where each wind turbine capacity is 300 MW. Fig. 11 shows the day-ahead electricity prices for the case study A. These prices are for buses 3, 5, 7, 16, 21, and 23, where the wind power producers are located. According to these figures, day-ahead prices do not indicate significant changes between case 1 and case 2. However, as wind power penetration increases, the day-ahead prices fall in all buses that wind power units are connected except buses 4 and 5. The electricity prices in buses 4 and 5 do not show big differences. Comparing penetration level 2 with level 1, conventional generators are being paid less in both the energy and reserve markets (see Fig. 10 (c) with Fig. 7(c)). This is due to increasing the penetration of wind power and decreasing the electricity price. On the other hand, as it can be perceived by comparing Fig. 10 (b) and Fig. 7 (b) in both Cases 1 and 2, wind power units are receiving more profit because of providing more energy and reserve capacities. This happens due to increasing the wind power factor in the network.

From the consumers' side, as the wind power factor increases in the network, they need to pay less. This can be seen from Fig. 10 (c) and comparing it with Fig. 7 (c). In both Cases 1 and 2, when the penetration level increases, the total payment by the consumers decreases. However, it should be mentioned that consumers are required to pay more in Case 2 compared to Case 1 in both wind power penetration 1eveles. That is, the total reserve capacity provided by both conventional generators and wind power units has increased significantly in Case 2 compared with case 1. The increased total reserve capacity improves the power network reliability in facing the load demand and wind generation units' uncertainty.

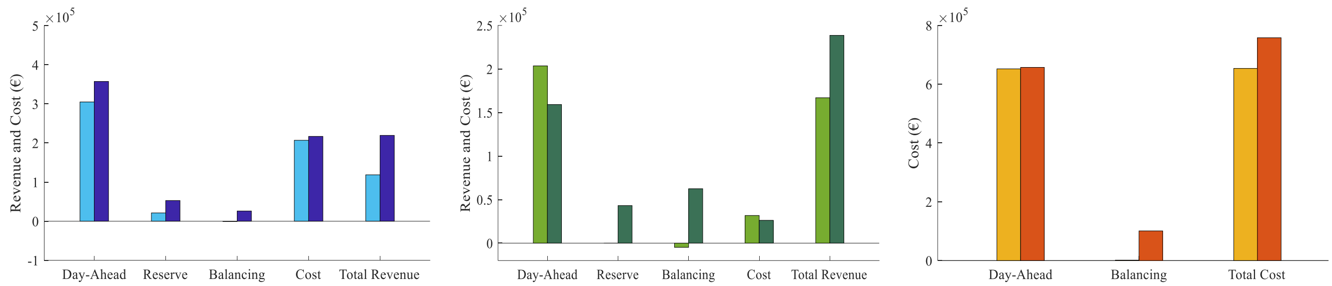
IV. Conclusion

This paper presented an optimal way to divide wind power capacity between energy and reserve markets. The IEEE RTS 24-Bus system has been considered for demonstrating the proposed model. Two wind power factors with 47% and 71% are adopted to further investigate the impact of wind power generation on the electricity price and revenue for all participants. The simulation results showed that when the wind power producers are able to participate in the reserve and balancing markets, they will receive more profit. In addition,



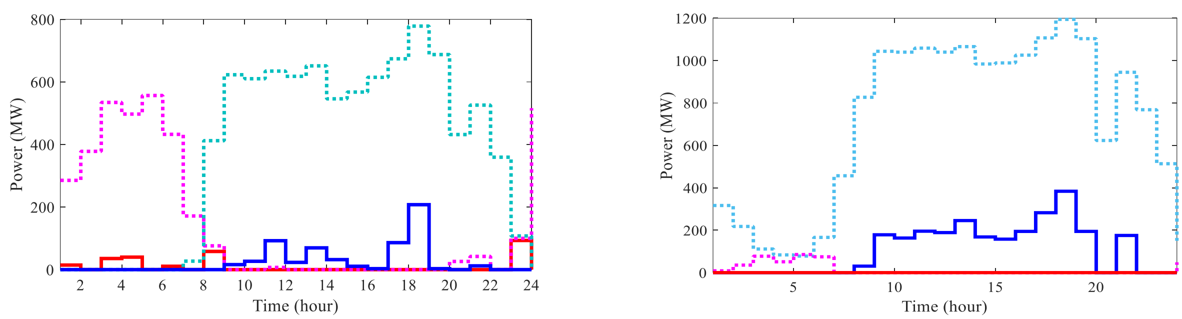
(a) Revenue and cost for conventional generators **(b)** Revenue and cost for wind power producers **(c)** Cost for demand

Fig. 7. Total revenue and cost in Scenario A for conventional generators, wind power producers and demands



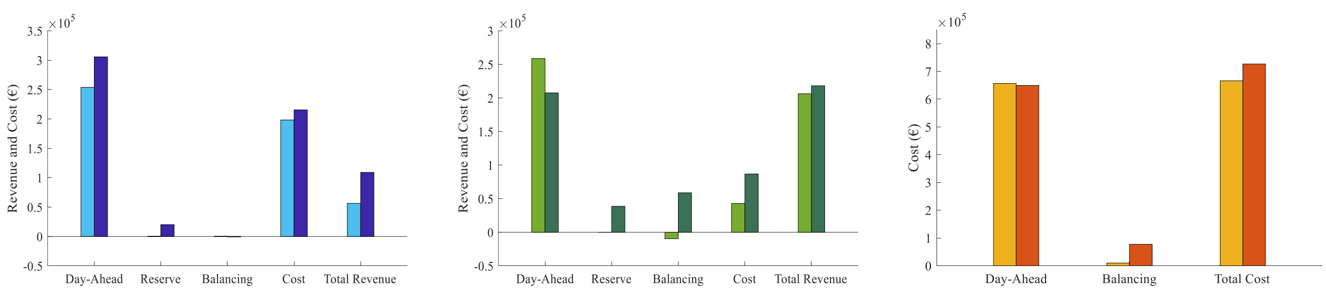
(a) Revenue and cost for conventional generators **(b)** Revenue and cost for wind power producers **(c)** Cost for demand

Fig. 8. Total revenue and cost in Scenario B for conventional generators, wind power producers and demands



(a) Scenario A **(b)** Scenario B

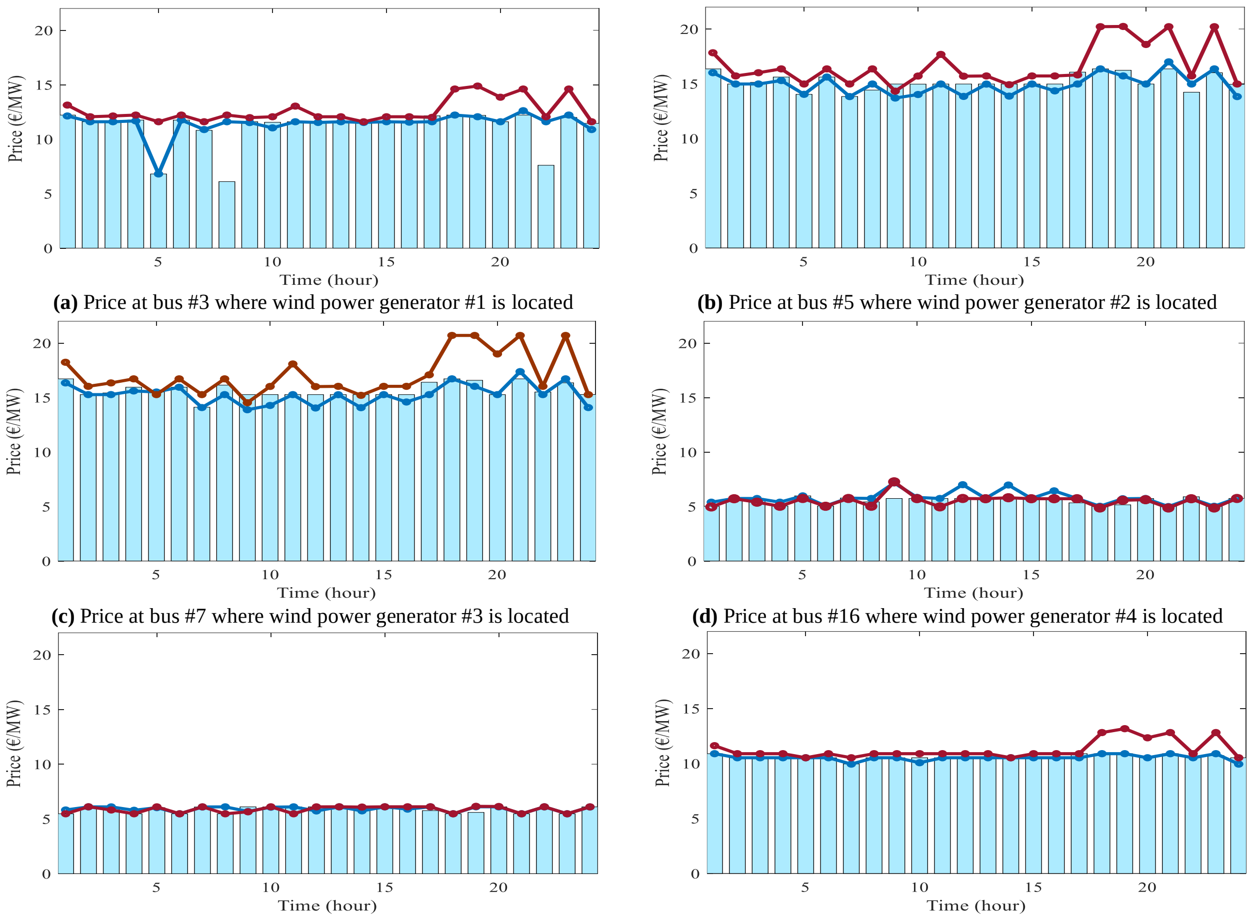
Fig. 9. Total up and down reserve capacity provided by the conventional generators and wind power producers
solid dark blue lines: down reserve provided in case 1
solid dark red lines: up reserve provided in case 1
dotted light blue lines: down reserve provided in case 2
dotted light pink lines: up reserve provided in case 2



(a) Revenue and cost for conventional generators **(b)** Revenue and cost for wind power producers **(c)** Cost for demand

Fig. 10. Total revenue and cost in Scenario B for conventional generators, wind power producers and demands

the conventional generators are also getting more revenue due to providing a higher amount of power for the day-ahead and reserve market. However, consumers should pay an extra cost in this case. For example, comparing Case 2 with Case 1 in Scenario A shows that the total revenue of the conventional generators and wind power producers has been increased by 78.7% and risen about 8%. These figures for the Scenario B showed 85% and 42.9% growth for the conventional generators and the wind power producers, respectively, where the additional payment for the demand was around 16%. Moreover, the simulation results showed that when the penetration level of wind power increases in the network, it would be beneficial for both wind power units and the demands because of receiving more profits in energy and reserve markets, and paying less for their consumption, respectively. On the other hand, the conventional generation indicated that their revenue decreases due to less contribution in both energy and reserve markets. The other important feature of considering reserve capacity for the



(a) Price at bus #3 where wind power generator #1 is located
(b) Price at bus #5 where wind power generator #2 is located
(c) Price at bus #7 where wind power generator #3 is located
(d) Price at bus #16 where wind power generator #4 is located
(e) Price at bus #21 where wind power generator #5 is located
(f) Price at bus #23 where wind power generator #6 is located

Fig. 11. Cleared day-ahead price for the Scenario A
blue bars: cleared price in case 1 with 71% wind power penetration
solid blue lines: cleared price in case 2 with 71% wind power penetration
solid red lines: cleared price in case 2 with 47% wind power penetration

wind power producers is that it leads to a considerable increase in the total up reserve and down reserve capacity of the power system. This will result in enhancing the power system reliability for covering the uncertainties from the wind power production and the demand consumption as well.

Finally, it should be noted that the results are dependent on the offering prices of the wind power producers in the day-ahead market, reserve market, and balancing market (see Table I) if the offering prices by the conventional generators are assumed to be fixed.

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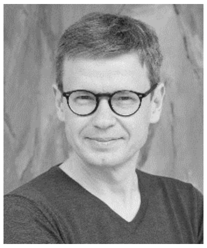

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