Participation of a Combined Wind and Storage Unit in the Day-ahead and Local Balancing Markets

Mana Farrokhseresht, Nikolaos G. Paterakis, Madeleine Gibescu, J. G. Slootweg
Electrical Energy Systems, Eindhoven University of Technology
Eindhoven, the Netherlands
{m.farrokhseresht, n.paterakis, m.gibescu, j.g.slootweg}@tue.nl

***Abstract*—In this paper, the market participation of an independent energy producer owning a combined wind generator-energy storage system (WG-ESS) connected to the distribution network is considered. A mathematical model for the profit maximization of the WG-ESS participating strategically in wholesale day-ahead and local balancing markets (LBMs) is proposed. We assume that in a future dominated by uncertainty and variability from distributed renewable energy sources, such a LBM, to be operated by a new entity called distribution market operator (DMO) will evolve. A stochastic bi-level optimization algorithm is adopted, where the WG-ESS maximizes its profit in the day-ahead market and the DMO-operated LBM. The results show that the strategic decisions of the WG-ESS in multiple markets significantly change compared to a single DA energy-only market.**

***Index Terms*—Bi-level stochastic optimization, Day-ahead market, Energy storage systems, Local balancing market, Wind power.**

TABLE I: Sets and Indices

$e(E)$	Index(set) of energy storage systems.
$i(N_D)$	Index(set) of sending nodes.
$j(J)$	Index(set) of receiving nodes.
$l(L)(L_D)$	Index(set) of distribution line.
$s(S)$	Index(set) of scenarios.
$t(T)$	Index(set) of time steps.
$w(W)$	Index(set) of wind generator.

I. Introduction

The integration of Renewable Energy Sources (RES) increases uncertainty on the supply side and can jeopardize the security of the power system if planning and operational philosophies are not adapted to deal with increasing RES penetration. However, technologies such as energy storage systems (ESS) have the potential to provide balancing services to both the transmission system operator (TSO) and the distribution system operator (DSO). Coupling RES with ESS can smoothen their output and offer the advantage of controlability. This in turn allows the combined unit to participate in the balancing market not only in such a way that reduces the deviation penalty costs to be paid by the RES owner, but also by actively contributing to restoring the balance of the system [1].

Nowadays, resources connected to the distribution network have started participating in the system-level balancing market which is typically being operated in a centralized fashion by the TSO [2]. When the TSO uses these resources, this service is decided without any involvement of the DSO and considerations of its network constraints, which could potentially lead to problems such as voltage violation or congestionin the

TABLE II: Parameters

B_i	Nodal susceptance (p.u.).
C_t^{DN}/C_t^{UP}	Downward/upward regulation offering price (€/MWh).
E_e^{ini}	Initial energy value for the ESS (MWh).
E_e^{max}/E_e^{min}	Maximum/minimum ESS state-of-charge (MWh).
G_i	Distribution nodal admittance (p.u.).
M	A large positive number
$P_e^{ch,max}$	Maximum charging power of ESS (MW).
$P_e^{dis,max}$	Maximum discharging power of ESS (MW).
$P_e^{ch,min}$	Minimum charging power of ESS (MW).
$P_e^{dis,min}$	Minimum discharging power of ESS (MW).
$P_{i,t}^{load}/Q_{i,t}^{load}$	Active/reactive power load demand (MW/MVAr).
P_i^{gmax}/P_i^{gmin}	Maximum/minimum power output (MW).
$P_{w,t,s}^{act}$	Actual wind farm power production (MW).
P_w^{max}	Installed wind farm power (MW).
Q_i^{gmax}/Q_i^{gmin}	Maximum/minimum reactive power (MVAr).
$r_i^{DN,max}/r_i^{UP,max}$	Maximum downward/upward regulation (MW).
R_l	Resistance of a distribution line.
$S_{i,t}$	Rated apparent power of generator i (MVA).
$S_{l,t}$	Rated apparent power of line (MVA).
V_i^{max}/V_i^{min}	Maximum/minimum bus voltage (p.u.).
X_l	Reactance of a distribution line.
π_s	Scenario probability.
η^{ch}/η^{dis}	Charging/discharging efficiency of the ESS (p.u).
$\lambda_{t,s}^{DA}$	Day-ahead market price (€/MWh).
$\lambda_{t,s}^{+}/\lambda_{t,s}^{-}$	Negative/positive imbalance price (€/MWh).

TABLE III: Decision Variables

$E_{e,t,s}$	Energy stored in the ESS (MWh).
$I_{l,t,s}$	Square of line current (A).
$P_{l,t,s}/Q_{l,t,s}$	Active/reactive power flow (MW/MVAr).
$P_{i,t,s}^{g}/Q_{i,t,s}^{g}$	Active/reactive power output from generator after scenario realization (MW/MVAr).
$P_{e,t,s}^{ch}$	Charging rate of ESS (MW).
$P_{e,t,s}^{dis}$	Discharging rate of ESS (MW).
$P_{w,t}^{DA}$	Scheduled wind power (MW).
$P_{w,t,s}^{WBL}$	Wind power in balancing market (MW).
$P_{l,t,s}^{loss}/Q_{l,t,s}^{loss}$	Active/reactive power losses of line (MW/MVAr).
$r_{i,t,s}^{DN}/r_{i,t,s}^{UP}$	Deployed downward/upward active power regulation from generator (MW).
$V_{i,t,s}/V_{j,t,s}$	Square of bus voltage (p.u.).
$\lambda_{t,s}^{BL}$	Balancing market price (€/MWh).

distribution network. Smart grid developments make it feasible to introduce similar balancing market mechanisms operated by the DSO in the distribution network [3].

In this paper, we propose a decision-making tool based on stochastic bi-level modeling to determine the strategy of a combined wind and storage system (WG-ESS) in day-ahead market (DA) and balancing market, while considering the uncertainty in wind power and DA prices. The WG-ESS is a price-taker in the DA and a price-maker in the newly-introduced Local Balancing Market (LBM), which is cleared by a so-called Distribution Market Operator (DMO). The interaction between energy and balancing markets provides an opportunity for the WG-ESS system to raise its expected profit. The main contributions of this work are summarized in the following:

- From the conceptual point of view, a new problem formulation is presented where a combined wind and storage unit acts as a price-taker in the DA energy market and as a price-maker in the LBM cleared by the DMO.
- From the methodological point of view, a bi-level stochastic optimization problem is derived. This allows for extensive simulations to be performed in order to demonstrate the impact of participating in a LBM on the WG-ESS operation and the storage benefits that arise from optimal scheduling.

The rest of this paper is organized as follows. The mathematical formulation of the proposed model is provided in section II. The results are presented and discussed in section III. Finally, the paper is concluded in section IV. The main nomenclature used in this paper is listed in Tables I-III.

II. PROBLEM FORMULATION

The proposed model is a stochastic bi-level programming problem, which is a type of Stackelberg game with one leader in the upper-level problem and one or more followers in the lower-level problem [4]. In this paper, the WG-ESS is the leader, whereas the follower is the clearing problem in the LBM. This hierarchical structure is illustrated in Fig. 1. The WG-ESS as the leader makes its offer decisions in the upper-level while anticipating the market-clearing problem in the lower level. For a given WG-ESSs decision, the follower maximizes social welfare through the market clearing process. The lower-level problems represent the DA and the LBM. It is assumed that the WG-ESS is only a passive contributor to the system-level imbalance market. In this hierarchical optimization algorithm, the lower-level problem is a constraint for the upper-level problem. The offer decisions of other market players (conventional generators) are considered as parameters, as this problem is solved from the WG-ESS point of view. The upper and lower level problems of this bi-level optimization are formulated in sections III-A and III-B respectively.

A. *Upper-level Problem: Profit Maximization of WG-ESS*

The total expected profit maximisation of WG-ESS consists of three parts: the expected revenue gained in the DA, the expected cost or revenue (opportunity loss) due to the deviation between the actual generated wind power at interval t and the bidding amount in the DA, and finally the expected revenue in the DMO's LBM. As there are uncertainties in the wind power output, when the actual generated wind power at interval t is higher than the bidding value in the DA, it is called positive imbalance and the reverse situation is the negative imbalance. The DA bidding and the balancing operating strategy of the WG-ESS are explained below.

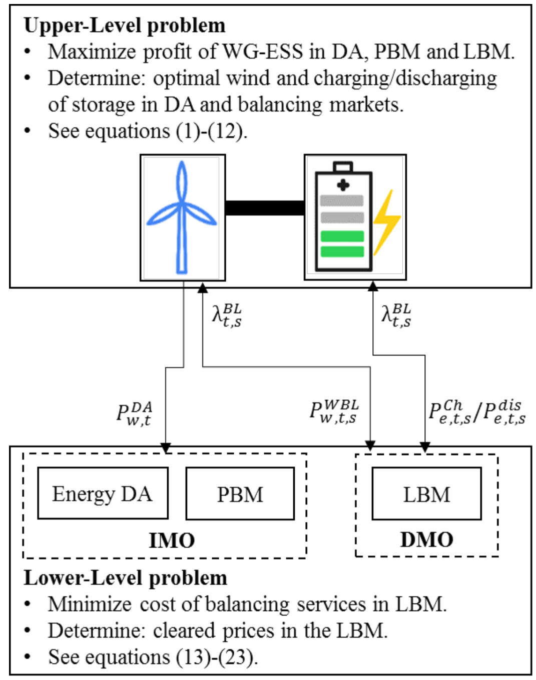

Fig. 1: The proposed bi-level stochastic optimization model

1) WG-ESS's bidding strategy in day-ahead market and the passive system balancing contribution: The DA bidding strategy of the WG-ESS works assuming the wind generator is working alone. The generator participates as a price-taker in the DA which is cleared by an Independent Market Operator (IMO). Depending on the positive or negative imbalance, the wind generator receives or makes a payment through a Passive Balancing Market (PBM) mechanism. When the positive imbalance happens, the wind generator is paid with a price less than the DA price. On the contrary, the wind generator has to pay with a price higher than the DA price when a negative imbalance happens. This classic model of pool trading is explained in [5]. The positive and negative imbalance prices can be expressed as ratios of the DA prices. In this paper, the uncertainty comes from actual wind power output, DA and system imbalance market prices. These uncertainties are modelled with a set of scenarios. The market clearing then determines the optimal bidding of the wind generator in the DA for the various time intervals in a 24 time horizon.

2) WG-ESS's strategic bidding in the local balancing market: As mentioned above, for obtaining the real added value of combined operation of WG and ESS, participation of the wind generator and the storage in the LBM is considered. Unlike the DA, the WG-ESS acts as a price maker trying to strategically make profit in the LBM. Therefore, in the LBM, the prices are variables which are actually Lagrangian multipliers of the power balance equation of the distribution grid in the lower level. The LBM is cleared by the DMO as is explained in section II-B.

3) Formulation of bidding and operating strategy of WG-ESS: Based on the operating strategy of WG-ESS in DA and balancing markets which are explained above, the strategic optimization problem of the WG-ESS is presented below.

$$\begin{aligned} Maximize \sum_{t\in T}\sum_{s\in S}\sum_{e\in E}\sum_{w\in W} \pi_s \cdot \{\lambda^{DA}_{t,s}\cdot P^{DA}_{w,t} \\ + \lambda^{+}_{t,s}.(1-b_{w,s,t})\cdot[(P^{act}_{w,t,s} \\ + P^{dis}_{e,t,s} - P^{ch}_{e,t,s}) - P^{DA}_{w,t}] \\ + \lambda^{-}_{t,s}.b_{w,s,t}\cdot[P^{DA}_{w,t} - (P^{act}_{w,t,s} \\ + P^{dis}_{e,t,s} - P^{ch}_{e,t,s})] - \lambda^{BL}_{t,s}\cdot P^{ch}_{e,t,s} \\ + \lambda^{BL}_{t,s}\cdot(P^{dis}_{e,t,s} + P^{WBL}_{w,t,s})\} \end{aligned} \tag{1}$$

The total expected profit of WG-ESS at each interval can be expressed in the form of (1). The first term is the expected DA bidding revenue of the wind generator. The second and third terms are the imbalance cost or revenues in the PBM. the binary variable $b_{w,s,t}$ is used to enforce either positive or negative happens at time t. The forth and fifth terms are the profit of purchasing/selling down/up regulation of wind generator and storage in the LBM. $\lambda^{BL}_{t,s}$, is the balancing price and the Lagrangian multiplier of the power balance equation in the lower-level problem. Following constraints have to be enforced:

$$\begin{aligned} (P^{WBL}_{w,t,s} + P^{dis}_{e,t,s} - P^{ch}_{e,t,s}) - P^{DA}_{w,t} \le M.b_{s,t}, \\ \forall w,e,t,s \end{aligned} \tag{2}$$

$$\begin{aligned} P^{DA}_{w,t} - (P^{WBL}_{w,t,s} + P^{dis}_{e,t,s} - P^{ch}_{e,t,s}) \le M.(1-b_{s,t}), \\ \forall w,e,t,s \end{aligned} \tag{3}$$

$$P^{ch,min}_{e} \le P^{DA}_{w,t} \le P^{max}_{w}, \forall w,e,t,s \tag{4}$$

$$0 \le P^{WBL}_{w,t,s} \le P^{act}_{w,t,s}, \forall w,t,s \tag{5}$$

$$0 \le P^{ch}_{e,t,s} \le u_{e,t,s}\cdot P^{ch,max}_{e}, \forall e,t,s \tag{6}$$

$$0 \le P^{dis}_{e,t,s} \le (1-u_{e,t,s})\cdot P^{dis,max}_{e}, \forall e,t,s \tag{7}$$

$$E^{min}_{e} \le E_{e,t} \le E^{max}_{e}, \forall e,t \tag{8}$$

$$E_{e,1} = E^{ini}_{e}, \forall e \tag{9}$$

$$E_{e,t,s} = E_{e,t-1,s} + P^{ch}_{e,t,s}\cdot\eta^{ch} - \frac{P^{dis}_{e,t,s}}{\eta^{dis}}, \forall e, t>1, s \tag{10}$$

Equations (2) and (3) ensure that at each time interval either positive or negative imbalances is happened. Equations (4) and (5) limit the wind generator's bidding values in the DA and balancing market respectively. Equations (6) and (7) enforce the charging and discharging modes of the storage in the operation limits. $u_{e,t,s}$ are the binary variables indicating the operating mode of the storage. Equation (8) corresponds to the state of charge of the storage system.

B. Lower-Level Problem: Local balancing market clearing

In this section, the LBM clearing process is explained. At this stage, the DA prices and the system imbalance prices are known parameters for the wind generator. Therefore there is no need to model the IMO market clearing problem in the lower-level. On the contrary, WG-ESS acts strategically in the LBM where the prices are variables defined as the Lagrangian multipliers of the power balance equation in the distribution network. Therefore it is necessary to model the market clearing problem of the DMO in the lower-level. This balancing market is called the DMO-operated LBM. The objective of this market clearing is to minimize the cost of procuring balancing services and it is formed as:

$$\begin{aligned} Minimize \sum_{t\in T}\sum_{s\in S}\sum_{i\in N_D}\sum_{e\in E}\sum_{w\in W} \pi_s.[C^{DN}_{s,t}.(P^{ch}_{e,t,s} \\ + r^{DN}_{i,t,s}) - C^{UP}_{s,t}.(P^{dis}_{e,t,s} + P^{WBL}_{w,t,s} + r^{UP}_{i,t,s})] \end{aligned} \tag{11}$$

In (11), the first term stands for downward regulation costs and the second term represents upward regulation costs of the WG-ESS and other conventional generators connected to the distribution grid. The distribution network is represented through a Second Order Conic Program (SOCP) relaxation, which is tight for radial distribution networks [6]. Given a distribution node $i \in N_D$, j refers to its unique ancestor. Equations (16)-(27) are distribution network constraints which have to be enforced during the LBM clearing, as explained below.

$$\begin{aligned} V_{i,t,s} = V_{j,t,s} + 2(R_l.P_{l,t,s} + X_l.Q_{l,t,s}) \\ - I_{l,t,s}.(R_l^2 + X_l^2), \forall i \in N_D, l \in L_D, t, s \end{aligned} \tag{12}$$

$$\begin{aligned} \sum_{l=(i,j)} P_{l,t,s} - \sum_{l=(j,i)} (P_{l,t,s} - I_{l,t,s}.R_l) - P^{g}_{i,t,s} \\ + \sum_{e\in i}(P^{ch}_{e,t,s} - P^{dis}_{e,t,s}) - \sum_{w\in i} P^{WBL}_{w,t,s} - r^{UP}_{i,t,s} \\ + r^{DN}_{i,t,s} + P^{load}_{i,t} + G_i.V_{i,t,s} = 0, \forall i \in N_D, t, s \end{aligned} \tag{13}$$

$$\begin{aligned} \sum_{l=(i,j)} Q_{l,t,s} - \sum_{l=(j,i)} (Q_{l,t,s} - I_{l,t,s}.X_l) - Q^{g}_{i,t,s} \\ + Q^{load}_{i,t} - B_i.V_{i,t,s} = 0, \forall i \in N_D, t, s \end{aligned} \tag{14}$$

$$\begin{aligned} (P_{l,t,s})^2 + (Q_{l,t,s})^2 \le V_{i,t,s}.I_{l,t,s}, \\ \forall i \in N_D, l = (i,j) \in L_D, t, s \end{aligned} \tag{15}$$

$$(P_{i,t,s})^2 + (Q_{i,t,s})^2 \le S^2_{i,t,s}, \forall i \in N_D, t, s \tag{16}$$

$$V^{min}_{i} \le V_{i,t,s} \le V^{max}_{i}, \forall i \in N_D, t, s \tag{17}$$

$$Q^{gmin}_{i} \le Q^{g}_{i,t,s} \le Q^{gmax}_{i}, \forall i \in N_D, t, s \tag{18}$$

$$P^{gmin}_{i} \le P^{g}_{i,t,s} \le P^{gmax}_{i}, \forall i \in N_D, t, s \tag{19}$$

$$0 \le P^{ch/dis}_{e,t,s} \le P^{ch/dis,max}_{e}, \forall e, t, s \tag{20}$$

$$0 \leq r_{i,t,s}^{DN/UP} \leq r_i^{DN/UP,max}, \forall e, t, s \tag{21}$$

Equations (13) and (14) are active and reactive power balance equations of the distribution system. Note that the Lagrangian multiplier of (13) is equal to $\lambda_{t,s}^{BL}$. Equation (15) shows the relation between voltage and current and active and reactive power flow over a line. At the same time, (15) is the conic equation of the distribution grid as explained in [6]. Equation (16) is related to the generation capability curves and is linearised by the method explained in [7]. Equations (17)-(21) impose limits for their corresponding variables.

C. *Formulating the bi-level optimization problem*

The solution technique of the bi-level optimization problem is explained as follows: we first replace the lower-level problem of the DMO – which corresponds to (11)-(21) – by its Karush-Kuhn-Tucker (KKT) conditions [8]. These KKT conditions provide the necessary optimality conditions for any type of continuous problems and since the lower-level problem is convex, they are both necessary and sufficient. The KKT equations of the lower level problem will be added to the upper-level problem which correspond to (1)-(10). The resulting single-level optimization model is a mathematical program with equilibrium constraints. This model, however, is non-linear. There are two sources of non-linearity that can be linearized as described below:

1) The first source of non-linearity are the complementarity conditions which are within the KKT conditions. Each complementarity condition can be linearized using a Big-M approach [9].
2) The second source of non-linearity comes from the bilinear terms in the objective function (1). By using the method in [10], those bilinear terms are linearized.

III. Case Study and Results

The proposed model is tested using the radial 6-bus test system used in [11] with one ESS and one wind generator, both located at bus 1 (at the end of the feeder). The case study parameters are shown in Table IV. The DA and imbalance market prices are obtained from the Belgian TSO Elia [12]. The load profiles are based on the data from [13]. The load of each bus is the summation of the domestic and non-domestic loads related to selected week days in autumn scaled to the nominal load of the buses. A scenario generation/reduction technique based on autoregressive integrated moving average (ARIMA) time series modelling and the k-means clustering algorithm is used in order to obtain a set of 75 scenarios of wind power generation, DA and imbalance market prices [14]. The optimization problem is formulated in the General Algebraic Modelling System (GAMS) and solved with MOSEK.

A. *WG-ESS in different market pools*

In order to study the role of the storage system and the impact of participating in the LBM on expected profit of WG-ESS, four different combinations of wind generator and storage system in different market pools are compared. These four cases are explained below in more details.

TABLE IV: Component parameters

Component	**Parameters**
Load	*power factor* $= 0.9$
Wind farm	$P_w^{max} = 3$MW
ESS	$P_e^{ch,max} = P_e^{dis,max} = 1$MWh $E_e^{ini} = 1$MWh $E_e^{max} = 5$MWh $\eta^{ch} = \eta^{dis} = 0.8$

- *Case (1):* An energy-only DA is considered where wind generator participates without any storage system. The only profit source of the wind generator is the wind energy traded in the DA. The deviation between $P_{w,t}^{DA}$ and $P_{w,t,s}^{act}$ leads to the revenue or cost for the wind generator which should be received or paid in the PBM.
- *Case (2):* An energy-only DA is considered where wind generator participates. But in this case there is also a storage system which is applied in order to reduce the penalty costs paid for the deviation between $P_{w,t}^{DA}$ and $P_{w,t,s}^{act}$ in the PBM.
- *Case (3):* Both DA and balancing markets are considered where wind generator participates without the storage system. Therefore, the wind generator makes profit in both DA and balancing market. The deviation cost/revenue has to be paid/received in the PBM.
- *Case (4):* Both DA and balancing markets are considered. Wind generator participates in the DA and its storage system participates in the LBM. Therefore, the WG-ESS makes profit from energy traded by its wind generator in DA and also energy traded from storage system in the balancing market. Again, the penalty cost or opportunity loss has to be paid or received in the PBM.

The results of total expected profit, the revenue in DA and balancing markets and the deviation cost/revenue in the PBM (see last column, with positive and negative values indicating the revenue and cost respectively) for Case 1-4 are provided in Table V. The expected profit in Case 4, where the storage system participates in the balancing market is the highest among all cases. Th second most profitable case is Case 3 where the wind generator participates in the balancing market. Therefore, participating in the balancing market either with or without the storage system makes more profit for the wind generator rather than bidding in the DA alone. Comparing Case 2 with Case 4 shows that although the total expected profit is lower, the wind generator earns more expected revenue in DA. Generally, Case 2 where wind generator has a storage system to compensate its imbalance in the PBM, has the highest bidding value in DA among other cases. However, Case 1 where the wind generator has no compensating tools e.g. storage system and/or balancing market participation, shows the lowest willingness to participate in the DA and earns the highest expected revenue related to the opportunity loss in the PBM.

TABLE V: Expected market results (€) of cases 1-4

	Total profit	DA revenue	BL market revenue	Deviation cost/revenue
Case 1	3204.48	2718.21	-	486.26
Case 2	3366.35	2959.79	-	406.56
Case 3	3770.73	2921.93	566.95	281.84
Case 4	3965.57	2922.98	761.12	281.46

TABLE VI: Expected market results (€) for S.C. = 5 MW

	Total profit	DA revenue	BL market revenue	Deviation cost/revenue
Case 2	3803.79	3361.14	-	442.56
Case 4	7191.28	2922.10	3986.86	282.31

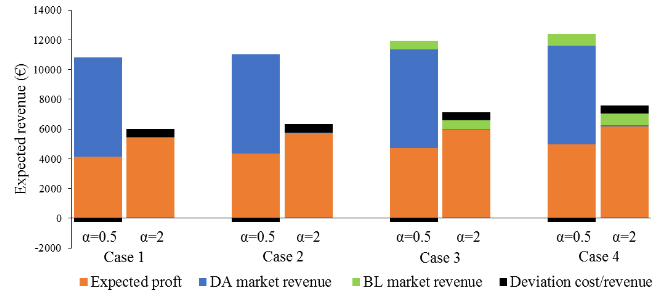

Fig. 2: Market results for different values of α

B. Sensitivity Analysis

1) Storage capacity: In this paragraph, the effect of increasing or decreasing the charging and discharging capacity of the storage system on the WG-ESS offering strategy and associated profits is investigated. Considering $P_e^{ch,max}$ and $P_e^{dis,max}$ equal to 1MW as reference values, Table VI shows that by increasing the capacity of the storage from 1MW to 5MW, the expected profit of Case 2 becomes about 10% higher than Case 3 (while it is the opposite of reference values). It is evident that increasing the storage capacity can compensate the income from the balancing market. In Case 4 where the storage system participates in the balancing market, increasing of the storage capacity leads to a significant increase in the expected profit of WG-ESS. Therefore by increasing the capacity of the storage system, WG-ESS can earn more profit in case where the storage participates in the LBM rather than only applying it to compensate the deviation of the wind generator between DA and real-time.

2) Imbalance prices: The effect of the selection of system imbalance prices, $\lambda_{t,s}^{+}, \lambda_{t,s}^{-}$, on the WG-ESS offering strategy and associated profits is investigated here. Considering $\alpha = 1$ as the reference value for the imbalance prices (results shown in Table V), where α is the ratio multiplied to the reference imbalance prices. Fig. 2 shows changes in the market results when using different values of α. The expected profits has increased in all 4 cases with $\alpha = 0.5$. The highest increase happens in the DA. In addition, with $\alpha = 0.5$, the column related to the deviation penalty has negative values for all cases, indicating the cost has to be paid by the wind generator in the PBM. When $\alpha = 2$, although the expected profit has raised notably, the expected revenue in the DA has dropped significantly. However, the changes in system imbalance prices do not have any significant effect on the expected revenue of Case 3 and Case 4 in the LBM.

IV. Conclusion

In this paper, a novel problem formulation was introduced, which allows a combined wind and storage system (WG-ESS) to maximize its profit in the day-ahead market (DA) and strategically participate in a DSO-operated local balancing market (LBM). The combined strategy of this WG-ESS system as a price-taker in the DA and as a price-maker in the LBM is proposed and formulated. The uncertainty in the wind power output, DA and system imbalance prices is reflected through a set of scenarios. Four different combinations of wind generator and storage systems together with different DA and balancing market bidding strategies are discussed in the DA energy-only market and the DA and balancing markets. The results show that the strategic decisions of the WG-ESS in multiple markets significantly change compared to a single DA energy-only market. Finally, results of two sensitivity analyses, namely the effect of increasing the storage capacity and the effect of different imbalance prices on the market results, are discussed.

References

[1] "Governance of data and information management in smart distribution grids: Increase efficiency by balancing coordination and competition," *Utilities Policy*, vol. 44, pp. 63–72, 2017.

[2] "Study on the effective integration of demand energy recourses for providing flexibility to the electricity system," Sweco, Ecofys, Tractbel Engineering and PWC, Final report to The European Commission, 2015.

[3] F. Hvelplund, "Renewable energy and the need for local energy markets," *Energy*, vol. 31, no. 13, pp. 2293–2302, 2006.

[4] R. Sioshansi, P. Denholm, T. Jenkin, and J. Weiss, "Estimating the value of electricity storage in PJM: Arbitrage and some welfare effects," *Energy Economics*, vol. 31, pp. 1269–277, 2009.

[5] A. J. Conejo, M. Carrin, and J. M. Morales, *Decision Making Under Uncertainty in Electricity Markets*. Spring Street, New York, USA: Springer Science and Business Media, 2010.

[6] M. Farivar and S. H. Low, "Branch flow model: Relaxations and convexification-part I," *IEEE Tran. on Power Syst.*, pp. 2554–2564, 2013.

[7] M. Farrokhseresht, N. G. Paterakis, and M. Gibescu, "Joint day-ahead clearing of energy, active and reactive power reserves for systems with significant RES-related uncertainty," *European Energy Market (EEM) Conference*, 2016.

[8] A. Papavasiliou, "Analysis of Distribution Locational Marginal Prices," *IEEE Trans. on Smart Grid*, 2017.

[9] A. Baillo, M. Ventosa, M. Rivier, and A. Ramos, "Optimal offering strategies for generation companies operating in electricity spot market," *IEEE Trans. Power Syst*, vol. 19, no. 2, pp. 745–753, May 2004.

[10] A. C. Medina, J. F. Franco, M. J. Rider, A. P. Feltrin, and R. Romero, "A mixed-integer linear programming approach for optimal type, size and allocation of distributed generation in radial distribution systems," *ELSEVIER Electric Power Systems Research*, vol. 97, pp. 133–143, 2013.

[11] E. R. Ramos, J. R. Santos, and J. Reyes, "A simpler and exact mathematical model for the computation of the minimal power losses tree," *ELSEVIER Electric Power Systems Research*, vol. 31, Jan. 2010.

[12] B. T. Elia. (2017). [Online]. Available: http://www.elia.be

[13] Ukerc energy data centre. [Online]. Available: http://ukerc.rl.ac.uk

[14] N. G. Paterakis, A. A. S. de la Nieta, J. P. S. Catalao, A. G. Bakirtzis, A. Ntomaris, and J. Contreras, "Evaluation of load-following reserves for power systems with significant res penetration considering risk managemen," in *IEEE International Conference on Smart Energy Grid Engineering*, Oshawa, Canada, Aug. 2015.