Optimal Coordinated Wind and Generic Storage System Bidding in Electricity Markets

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***Abstract*—The volatility of the wind generation reduces the profits of wind generators as a consequence of the differences between the real wind generation and the wind power offered in the electricity markets. This paper presents two models: i) wind and generic storage system offering without a physical connection and ii) wind and generic storage system offering with a physical connection to mitigate the wind positive imbalances (excess of the wind generation with respect to the wind power offered). The objective of the models is to maximize the expected profit of selling the energy in the day-ahead market, where the energy can come from the wind power and the storage system. Moreover, the wind power imbalance is penalized in the balancing market reducing the profits. The problems are modeled using stochastic mixed integer linear programming. A case study of a week (168 hours) is simulated to evaluate the models. After the simulations, the results are discussed and a summary of the main conclusions are presented.**

***Index Terms*—Day-ahead market, generic storage system, stochastic mixed integer linear programming, wind power.**

NOMENCLATURE

Indexes

t	Index referring to a period [hour].
w	Index referring to a scenario.

Parameters

BID^{MAX}	Upper limit of the purchase bid [MW].
BID^{MIN}	Lower limit of the purchase bid [MW].
c^{STG}	Marginal cost of the energy stored [€/MWh].
c^{W}	Wind marginal cost [€/MWh].
e^{MAX}	Upper limit of the energy stored [MWh].
e^{MIN}	Lower limit of the energy stored [MWh].
η	Efficiency of the sale offers and the purchase bids.
γ	Loss efficiency of the energy stored.
$gw_{t,w}$	Power produced by the wind farm in period *t* and scenario *w* [MW].
OF^{MAX}	Upper limit of the sale offer [MW].
OF^{MIN}	Lower limit of the sale offer [MW].
$\lambda_{t,w}$	Day-ahead market price in period *t* and scenario *w* [€/MWh].
$\lambda^{-}_{t,w}$	Negative imbalance market price in period *t* and scenario *w* [€/MWh].
$\lambda^{+}_{t,w}$	Positive imbalance market price in period *t* and scenario *w* [€/MWh].
ρ_w	Probability of occurrence of scenario *w*.
WP^{MAX}	Maximum power capacity of the wind farm [MW].

Continuous Variables

bs_t	Power offer/bid in the day-ahead market associated to the storage system in period *t* [MW].
bid_t	Power purchase bid in the day-ahead market associated to the storage system in period *t* [MW].
bw_t	Power offer in the day-ahead market associated to the wind farm in period *t* [MW].
$\Delta w_{t,w}$	Imbalance between actual wind production and the offer associated to the wind farm in period *t* and scenario *w* [MW].
$\Delta w^{FINAL}_{t,w}$	Final positive imbalance between actual wind production, the wind power offer associated and the excess of energy sent to the storage system in period *t*, and scenario *w* [MW].
$\Delta w^{-}_{t,w}$	Negative imbalance between actual wind production and the offer associated to the wind farm in period *t* and scenario *w* [MW].
$\Delta w^{+}_{t,w}$	Positive imbalance between actual wind production and the offer associated to the wind farm in period *t* and scenario *w* [MW].
e_t	Energy stored in period *t* [MWh].
$e_{t,w}$	Energy stored in period *t* and scenario *w* [MWh].
e^{LOSS}_t	Energy loss of the energy stored in period *t* [MWh].
$e^{LOSS}_{t,w}$	Energy loss of the energy stored in period *t* and scenario *w* [MWh].
of_t	Power sale offer in the day-ahead market associated to the storage system in period *t* [MW].
PFS	Profit from sales and purchases of energy in the day-ahead market associated to the storage system [€].
PFW	Profit from sales of energy in the day-ahead market associated to the wind farm [€].

$ppw_{t,w}$	Energy sent through physical connection to reduce the wind positive imbalance and increase the energy level of the storage per period *t* and scenario *w* [MWh].
$tp_{t,w}$	Total energy incorporated in the storage per period *t* and scenario *w* [MWh].

Binary Variables

$j_{t,w}$	0/1 variable, that is equal to 1 if the imbalance in period *t* is negative, otherwise it is 0 for a positive imbalance, in period *t* and scenario *w*.

I. INTRODUCTION

The development of wind power started with the Kyoto protocol international agreement. After that, the wind power installed has grown, where wind power capacity has been increased from 17.5 GW in 2000 to 370 GW in 2014. Hence, new approaches of the production management are of vital importance, allowing the incorporation of energy with high uncertainty, like wind power.

This paper describes two kinds of models whose objective is to increase the profits of generators selling their energy in the day-ahead market and penalizing the imbalances in the balancing market. The coordination allows to reduce the imbalances through possible synergies, where lower imbalances imply a lower penalty.

Moreover, the coordination proposed is between a renewable technology and a storage system, reducing CO_2 emissions.

The renewable generation technology selected is wind power whose generation uncertainty is high. On the other hand, the generic storage system could reduce the effect of wind uncertainty.

Thus, the connection between both plants allows to evaluate the coordination of the wind and the storage systems, improving the profits due to the energy offer in the electricity market. The improvement of the profits is achieved reducing the wind positive imbalances through a physical connection.

The incorporation of wind renewable energy in electricity markets is presented in [1]. Wind power has stimulated a great interest for short-term trading [2], with a probabilistic forecast of wind power [3] and risk mitigation of a wind producer in an electricity market [4].

On the other hand, the high penetration of renewable energies is encouraging the participation of storage systems [5] to smooth the demand and the utility curve in the reserve market. Nevertheless, storage systems will be required for a future sustainable network [6] and the viability of balancing wind generation with energy storage [7].

Currently, a mature storage system is hydro-pump storage. The coordination between wind and hydro-pump storage is researched in [8]–[11].

This paper proposes two models to compare the improvement of the production management of both technologies. The main contributions are presented as follows:

- Modeling the coordination of wind and a generic storage system offering without/with physical connection through stochastic mixed integer linear programming.
- Evaluation of a new technology coordination to incorporate easily a high amount of wind energy in the electric system.
- A new kind of coordinated wind-storage offering to increase the profits of the generators, reducing the imbalances.

This paper is organized as follows: Section II describes the idea of coordination, Section III presents the stochastic mixed integer linear models with their objective functions and constraints, Section IV defines the case study to test the model, Section V shows the results and Section VI summarizes the relevant conclusions of the paper.

II. PROBLEM DESCRIPTION

In European electricity markets, the generators send their offers to the day-ahead market the previous day. When the real generation is known, the differences between the real wind generation and the wind power offer as a consequence of wind uncertainty are penalized in the settling of the balancing market.

The storage system needs to send the bid/offer the previous day, making the decision of the amount of energy to buy and sell in each hour of the next day. The energy stored is known in each hour, so a balancing market for the storage system model is not necessary.

The model of wind power and storage without a physical connection is explained in Section III-A. A diagram of this strategy to offer the energy is depicted in Fig. 1. The profit is the sum of trading both technologies separately in the day-ahead electricity market.

However, a physical connection is added to send the excess of wind generation to the storage system. The energy stored will be used when the storage losses and the difference between market prices increase the profit. The main idea of this model is portrayed in Fig. 2.

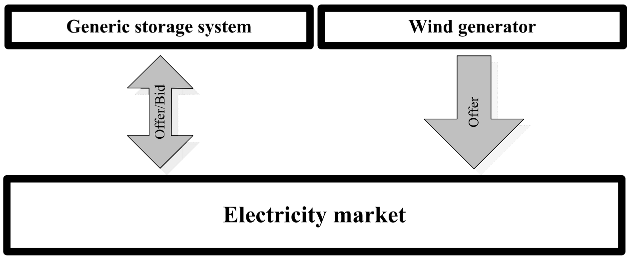

Fig. 1. Diagram of the wind power and generic storage system model without a physical connection.

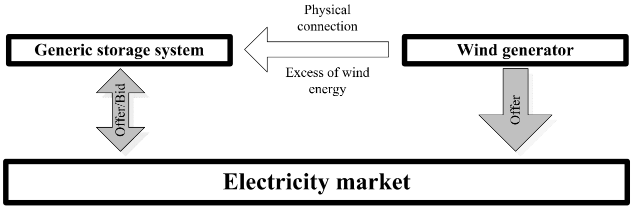

Fig. 2. Diagram of the wind power and generic storage system model with a physical connection.

III. MATHEMATICAL FORMULATION

Stochastic mixed integer linear programming is used to model the optimization problem. The objective maximizes the profits coming from selling energy in the electricity market for a period of 168 hours.

Next, the objective functions and the constraints are presented for the two models.

A. Wind power and generic storage system model without a physical connection

The model presents the objective function and the constraints needed to be evaluated and compared.

The objective function (1) is composed of the wind profit (2) and the storage profits (3).

$$max \;\; PFW + PFS; \tag{1}$$

where

$$PFW = \sum_{w} \rho_{w} \sum_{t} \Big[\lambda_{t,w} \cdot bw_{t} + \lambda^{+}_{t,w} \cdot \Delta w^{+}_{t,w} - \lambda^{-}_{t,w} \cdot \Delta w^{-}_{t,w} - c^{W} \cdot gw_{t,w} \Big]. \tag{2}$$

The revenues come from the energy sold in the day-ahead market and the positive imbalances of the balancing market. On the other hand, the costs come from the negative imbalance costs of the balancing market and the marginal costs. The marginal costs are calculated according to [12].

Therefore, the profits are the revenues minus costs as expressed in (2). The profits of the storage system are the revenues from offering the energy minus the marginal costs (3).

$$PFS = \sum_{w} \rho_{w} \Big[\sum_{t} \Big(\lambda_{t,w} \cdot bs_{t} - c^{STG} \cdot e_{t} \Big) \Big]. \tag{3}$$

Wind constraints (4)-(11) are divided into two blocks: the constraints needed to evaluate the offer (4)-(5) and the constraints needed to calculate the imbalances, (6)-(11).

Wind generators have to offer their energy in the day-ahead market at each hour and send their offers ranging between 0 and the maximum power, see (4) and (5).

$$bw_{t} \geq 0; \tag{4}$$

$$bw_{t} \leq WP^{MAX}. \tag{5}$$

Wind power imbalances can be positive or negative and they are calculated as the difference between generations and offers (6). When the generation is higher than the offer, the imbalance is positive. However, when the offer is higher than the generation, the imbalance is negative. The constraints calculate the value of the imbalance, either positive or negative (7). The positive and negative imbalances have the maximum wind power as their upper limit, see (8) and (9). The lower limit of the imbalances is zero, see (10) and (11).

$$\Delta w_{t,w} = gw_{t,w} - bw_{t}; \tag{6}$$

$$\Delta w_{t,w} = \Delta w^{+}_{t,w} - \Delta w^{-}_{t,w}; \tag{7}$$

$$\Delta w^{-}_{t,w} \leq WP^{MAX} \cdot j_{t,w}; \tag{8}$$

$$\Delta w^{+}_{t,w} \leq WP^{MAX} \cdot (1 - j_{t,w}); \tag{9}$$

$$\Delta w^{-}_{t,w} \geq 0; \tag{10}$$

$$\Delta w^{+}_{t,w} \geq 0. \tag{11}$$

Storage constraints are shown in (12)-(20). The limits of the sale offers are (12) and (13), and the limits of the purchase bids are fixed in (14) and (15), where BID^{MAX} is 0 and BID^{MIN} is a negative value, so bid_t is a negative value as well. Therefore, the sale offers are positive values and the purchase bids are negative values. Finally, (16) decides if the storage system buys or sells energy. Furthermore, the energy can be purchased and sold at the same time.

$$of_{t} \leq OF^{MAX}; \tag{12}$$

$$of_{t} \geq OF^{MIN}; \tag{13}$$

$$bid_{t} \leq BID^{MAX}; \tag{14}$$

$$bid_{t} \geq BID^{MIN}; \tag{15}$$

$$bs_{t} = of_{t} + bid_{t}. \tag{16}$$

A continuous variable, e_t, is used to determine the energy level in the storage system whose limits are (17) and (18). The balance of energy is calculated in (19) and the energy bought or sold has an efficiency η. The energy stored in period t is the energy stored in period $t-1$, minus the energy sold, plus the energy bought, with the addition of the parameter for energy loss. Because bid_t has a negative value, $bid_t \cdot \eta$ has a negative sign in (19). The losses are equal to the energy stored in each period multiplied by the loss parameter, γ.

$$e_{t} \leq e^{MAX}; \tag{17}$$

$$e_{t} \geq e^{MIN}; \tag{18}$$

$$e_{t} = e_{t-1} - (of_{t}/\eta) - (bid_{t} \cdot \eta) - e^{LOSS}_{t}; \tag{19}$$

$$e^{LOSS}_{t} = e_{t} \cdot \gamma. \tag{20}$$

B. Wind and generic storage system with a physical connection

The objective function and the constraints are similar to the previous model, but the model with a physical connection presents some differences. All the equations of the model are shown below.

The objective function (21) is composed of the wind profit (22) and the storage profit (23). The wind profit with a physical connection is different because the final wind positive imbalance $\Delta w_{t,w}^{FINAL}$ can be lower than or equal to the wind positive imbalance, $\Delta w_{t,w}^{+}$, in (22) due to the physical connection.

$$max \;\; PFW + PFS; \tag{21}$$

where

$$PFW = \sum_{w} \rho_w \sum_{t} \Big[\lambda_{t,w} \cdot bw_t + \lambda_{t,w}^{+} \cdot \Delta w_{t,w}^{FINAL} - \lambda_{t,w}^{-} \cdot \Delta w_{t,w}^{-} - c^{W} \cdot gw_{t,w} \Big]; \tag{22}$$

$$PFS = \sum_{w} \rho_w \left[\sum_{t} \left(\lambda_{t,w} \cdot bs_t - c^{STG} \cdot e_{t,w} \right) \right]. \tag{23}$$

Some constraints are similar to the ones in the previous model, see (24)-(40).

$$bw_t \geq 0; \tag{24}$$

$$bw_t \leq WP^{MAX}; \tag{25}$$

$$\Delta w_{t,w} = gw_{t,w} - bw_t; \tag{26}$$

$$\Delta w_{t,w} = \Delta w_{t,w}^{+} - \Delta w_{t,w}^{-}; \tag{27}$$

$$\Delta w_{t,w}^{-} \leq WP^{MAX} \cdot j_{t,w}; \tag{28}$$

$$\Delta w_{t,w}^{+} \leq WP^{MAX} \cdot (1 - j_{t,w}); \tag{29}$$

$$\Delta w_{t,w}^{-} \geq 0; \tag{30}$$

$$\Delta w_{t,w}^{+} \geq 0; \tag{31}$$

$$of_t \leq OF^{MAX}; \tag{32}$$

$$of_t \geq OF^{MIN}; \tag{33}$$

$$bid_t \leq BID^{MAX}; \tag{34}$$

$$bid_t \geq BID^{MIN}; \tag{35}$$

$$bs_t = of_t + bid_t. \tag{36}$$

As a consequence of introducing $tp_{t,w}$ in the model, the excess of wind energy can be sent to the storage. Therefore, wind uncertainty affects the energy level of the storage and the energy level variable is stochastic, depending on the scenario w, see (39).

$$e_{t,w} \leq e^{MAX}; \tag{37}$$

$$e_{t,w} \geq e^{MIN}; \tag{38}$$

$$e_{t,w} = e_{t-1,w} - (of_t/\eta) - (tp_{t,w} \cdot \eta) - e_{t,w}^{LOSS}; \tag{39}$$

$$e_{t,w}^{LOSS} = e_{t,w} \cdot \gamma. \tag{40}$$

In addition, the physical connection is modeled through (41)-(45). The physical connection determines the energy sent from the wind power to the generic storage system.

$$ppw_{t,w} \leq \Delta w_{t,w}^{+}; \tag{41}$$

$$ppw_{t,w} \geq 0; \tag{42}$$

$$tp_{t,w} = bid_t - ppw_{t,w}; \tag{43}$$

$$tp_{t,w} \geq -BID^{MIN}; \tag{44}$$

$$tp_{t,w} \leq 0. \tag{45}$$

Finally, the final wind positive imbalance is calculated in (46).

$$\Delta w_{t,w}^{FINAL} = \Delta w_{t,w}^{+} - ppw_{t,w}. \tag{46}$$

IV. CASE STUDY

The case study is composed of a wind farm and a storage system. The wind farm and storage system are located in Navarre, Northern Spain. The models are tested for selling the energy in the Spanish market for one week, 168 hours.

The wind farm has a total capacity of 50 MW and the wind marginal cost is equal to €17/MWh [12]. The storage system has a capacity of 50 MW. Hence, the storage parameters are OF^{MAX} =50 MW, OF^{MIN} =0 MW, e^{MAX} =50 MWh, e^{MIN} =0 MWh, BID^{MAX} =0 MW, BID^{MIN} =-50 MW, c^{STG} =€0.5/MWh, γ =0.5% and η =99%.

The parameters that introduce uncertainty are wind generation, market prices, positive market prices and negative market prices. Thus, the wind generation scenarios, the market price scenarios, the positive imbalance market price scenarios and the negative imbalance market price scenarios are obtained from real data ranging from July to September of 2014 in the Spanish electricity market [13], allowing us to test the model and to compare the strategies.

The scenario tree is divided into two types of nodes: price and wind generation nodes. The three types of prices comprise the first node type and wind generation the second one. Therefore, the total number of scenarios, 8 price scenarios and 12 wind power scenarios, is equal to 96 scenarios. The wind generation scenarios, price market scenarios, positive imbalance market price scenarios and negative imbalance market price scenarios are shown in Figs. 3-6.

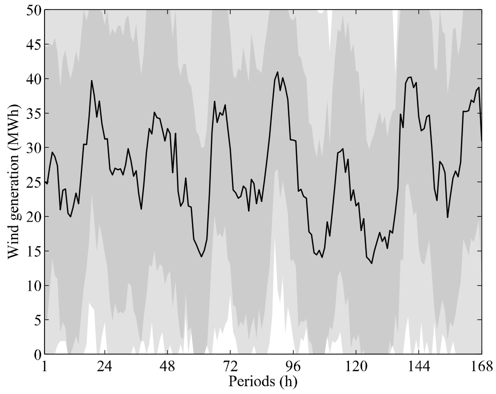

Fig. 3. The maximum, average+standard deviation, average, average-standard deviation and minimum of the wind generation scenarios from July to September of 2014.

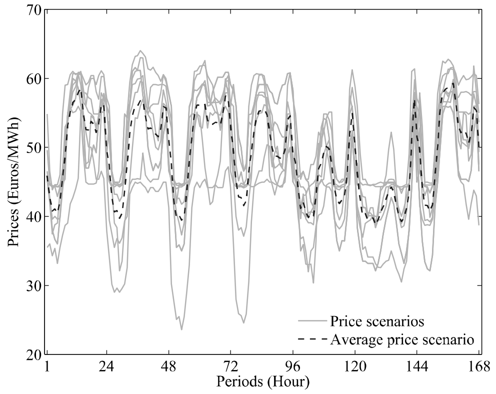

Fig. 4. Price scenarios and average price scenarios from July to September of 2014.

The model is programmed in MATLAB [14] and GAMS [15] in a computer with a Xeon E5-2687W processor at 3.1 GHz and 256 GB of RAM. The CPU time is different for each model due to the physical connection, where the CPU time without a physical connection is 16 seconds and roughly 3 hours with a physical connection. The different CPU times are a consequence of the intertemporal relationship of the physical connection constraints.

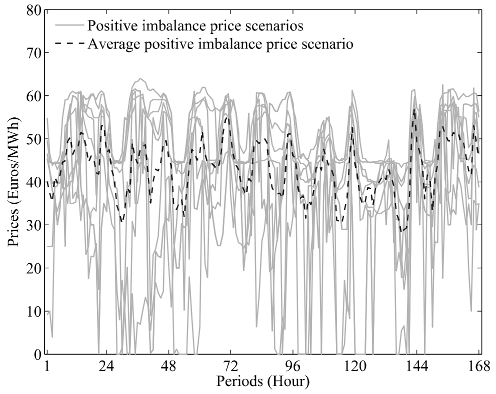

Fig. 5. Positive imbalance price scenarios and average positive imbalance price scenarios from July to September of 2014.

V. RESULTS

The main results are shown and discussed in this section. The wind power offer, the storage offer/bid and the wind power imbalances for both strategies, without and with physical connection are presented in Figs. 7-9.

The physical connection modifies the offers of the wind power and the storage system. The incorporation of a physical connection allows the storage of the excess of wind energy, reducing the purchase bids of the storage and increasing the coordinated profit. Those effects occur between the 48th hour and the 120th hour, as seen in Figs. 7-9.

The imbalances per period of both models are presented in Fig. 9 for scenario 1.

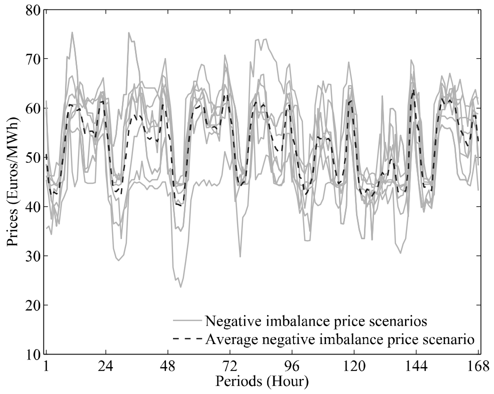

Fig. 6. Negative imbalance price scenarios and average negative imbalance price scenarios from July to September of 2014.

The wind power offer is different for both models due to the possibility of sending part of the positive imbalance to the storage, making the wind power offer lower for the physical connection model. The lower wind power offer of the physical connection model has a higher likelihood of a possible wind positive imbalance.

In fact, the physical connection takes advantage of the good regulation of the storage system. So, the model with a physical connection can increase the profit as a consequence of the volatility of market prices and the regulation.

The final wind positive imbalance can be higher than or lower than imbalances without physical connection as is presented in Fig. 9. However, the final wind positive imbalance is always equal to or lower than the imbalance with a physical connection.

The profit of the wind power is lower with a physical connection to increase the possible positive imbalances, as shown in Table I. Then, the wind generator can send more energy to the storage system, and next they can sell the excess of wind energy stored at a higher market price due to the regulation of the storage system. Hence, the volatility of the market prices makes the model more profitable with a physical connection. Moreover, the losses of the storage system and the storage marginal cost have to be lower than the possible differences between market price throughout several hours.

TABLE I
WIND PROFIT, STORAGE PROFIT AND TOTAL PROFIT WITHOUT/WITH PHYSICAL CONNECTION.

	Profits (€)		
	Wind power	**Storage system**	**Total**
No physical connection	136063.5	4610.6	140674.1
Physical connection	126654.6	14549.2	141203.9

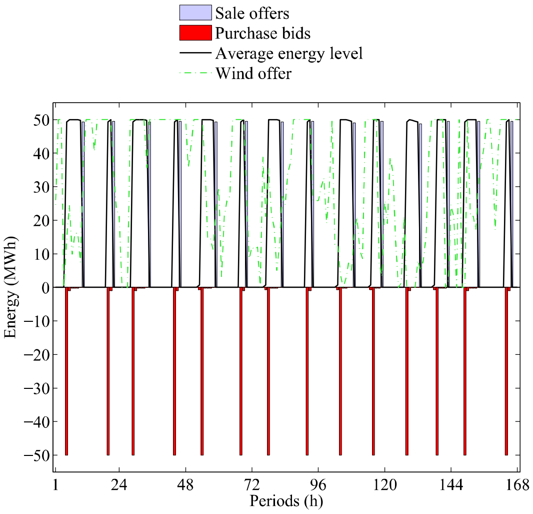

Fig. 7. Model without a physical connection.

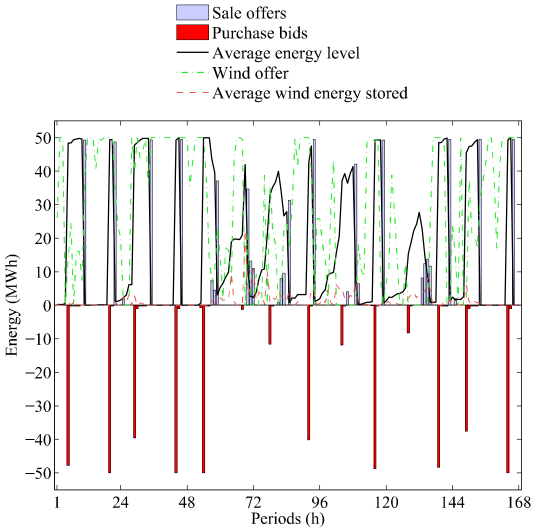

Fig. 8. Model with a physical connection.

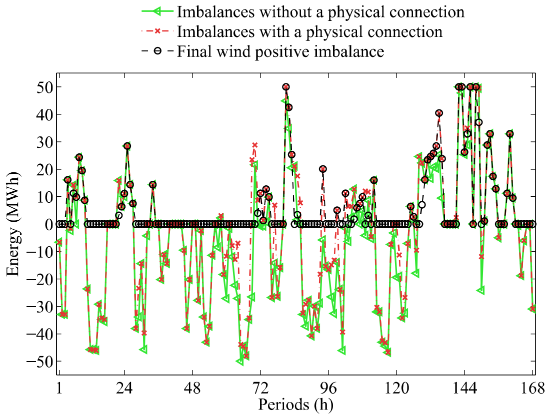

Fig. 9. Imbalance of the wind generator without/with a physical connection and the final wind positive imbalance with a physical connection.

VI. CONCLUSIONS

This paper has presented a stochastic mixed integer linear model, where an offer is optimized to maximize the profit of selling the wind production and trading the energy of the storage system in an electricity market.

The main conclusions are presented as follows:

- The highest profit occurs when the physical connection takes advantages of the volatility of the market prices.
- The wind profit is reduced by the physical connection, increasing the profit in the generic storage system three times more than without the physical connection.

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