Energy Storage Operation in the Day-Ahead Electricity Market

Hrvoje Pandžić and Igor Kuzle
Faculty of Electrical Engineering and Computing, University of Zagreb
Zagreb, Croatia
Hrvoje.pandzic@ieee.org; Igor.kuzle@fer.hr

***Abstract*—This paper considers market operation of an energy storage unit. The goal is to assess the potentials for revenue and impact of a profit-maximizing storage unit on market prices in the day-ahead electricity market. It also analyzes the impact of a storage unit on market performance of conventional generators. A bilevel profit maximization model is proposed in which the upper-level problem is a storage operation and bidding decision problem, while the lower level problem simulates market clearing. The proposed model is applied to the 24-bus IEEE test system.**

***Index Terms*—Bilevel Programming, Electricity Market, Energy Storage.**

I. INTRODUCTION

Energy storage has been used in power systems for many decades in the form of pumped hydro power plants. However, the main drawback of this technology are the geographical constraints, i.e. it requires the upper and the lower basin. Compressed air energy storage (CAES) technology has a similar limitation. Large-scale battery storage has several advantages over pumped hydro and CAES technologies: i) it can be installed at any substation; ii) its capacity is virtually unlimited; iii) it has low fixed cost, which makes the small installations viable, and iv) it can be moved from location to location. The main drawback of battery storage is its high price as compared to pumped hydro and CAES. However, with the development of new battery technologies and the increased production volume of the batteries, mostly due to the expanding electric vehicle market, their prices have dropped to reasonable levels [1].

Due to the geographical limitations, market interactions of an independently owned energy storage has not been in the focus of the scientific community. However, with the expected expansion of large-scale battery storage devices, this type of players could be much more common in electricity markets. For this reason, in this paper we focus on batter energy storage (BES), although the model can be applied to any other type of energy storage.

Energy storage is deemed to have an important role in the power system planning and operation in the near future. It has a key role in Europe's efforts towards the low-carbon future [2].

Large-scale grid deployment of batteries has a wide range of applications, ranging from arbitrage to frequency regulation, ramping, congestion relief, voltage support, transient stability and other benefits. The goal of this paper is to assess the role of the battery energy storage in a transmission network in terms of arbitrage. The operation of a BES depends on its ownership and the type of a power system (vertically integrated vs. market oriented). In case a BES is installed in a vertically integrated system, a single entity is operating the entire system. This means that storage operation is integrated in the unit commitment model of the entire system, e.g. [3]. Since the operation schedule and performance of a storage unit is co-optimized with other transmission assets, its operation is different than in the market environment. In market environment, energy storage can be considered passive, in case it is owned by a transmission company and treated as a transmission asset, or active, in case it is owned and operated by an independent entity [4]. A BES owned by an independent entity is the approach considered in this paper. Although the market participation rules of a BES are not yet clear and unified, this paper analyses the opportunities and roles of a BES in the market environment. We are trying to tackle the following questions: What size of a BES is suitable for a specific power system? How does it impact the LMPs? How does it impact the revenue of dispatchable generators? Should it be able to both submit buy and sell orders in the market?

A. *Literature Review*

Most of the literature regarding storage is oriented towards supporting the renewable generation, mostly wind farms. A dynamic programming algorithm is used in [5] to determine the optimal operation of a storage unit that supports a wind power producer. The authors consider only the transmission line connecting the wind farm/storage node to the rest of the system. Another example of optimal dispatch scheduling of wind farms and energy storage device is presented in [6], where the authors derive the optimal policy for advance energy commitment in a simple, analytical form, for a storage

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with an arbitrary round-trip efficiency, and when electricity prices are mean-reverting.

In [7] authors formulate a simple optimal power flow model that contains storage and focuses on the renewable resources integration issues. The model analyzes the effect that a single storage unit and a single generator have on the optimal power flow solution.

Authors in [8] model the optimal pumped hydro storage weekly schedule in price-taker and price-maker scenarios. Modes in whish pumped hydro storage unit operates in standalone and integrated in a portfolio of other generation assets are considered. Results show that the price-maker standalone pumped storage hydro plant will curtail more wind power in comparison to the price-taker mode. Moreover, when the PSH unit is integrated in a portfolio with a base load power plant, the role of the price elasticity of demand may completely change the operational profile of the pumped hydro storage unit.

Combined optimization of a wind farm and a pumped hydro storage unit in market environment is proposed in [9]. The problem is formulated as a two-stage stochastic programming problem with market prices and wind generation being random parameters. The results show that, for a specific test case, the profit for a joint optimization of the wind farm and the pumped hydro storage unit is up to 4% higher as compared to their uncoordinated operation.

Participation of a virtual power plant consisting of an intermittent source, a storage facility, and a dispatchable power plant in both day-ahead and balancing markets is considered in [10]. The offering problem is formulated as a two-stage stochastic mixed-integer linear program which maximizes the virtual power plant expected profit. The results show that the majority of the trading takes place in the day-ahead market, while the balancing market makes less than 2% of the revenue in the considered case study.

An insightful overview of the technical issues and proposed concepts of integrating energy storage into power markets is provided in [11].

II. Model

A. Structure

The owner of the BES is seeking the optimal time periods to perform arbitrage. The upper-level problem sets its bidding/offering schedule and the lower-level problems simulate market clearing procedure for each time period.

B. Nomenclature

The following sets and corresponding indices are used in the formulation: B is the set of generator offering blocks with indices b, H is the set of BES with indices h, I is the set of controllable generators with indices i, L is the set of lines with indices l, S is the set of buses with indices s, T is the set of time periods with indices t, and W is the set of wind farms with indices w.

1) Parameters

$\mathrm{ch}_h^{\max}$ Maximum BES charging capacity of BES h (MW).

$\mathrm{dis}_h^{\max}$ Maximum BES discharging capacity (MW).

$\mathrm{d}_{s,c}^{\max}$ Capacity of bidding block c of demand at bus s (MW).

$\mathrm{g}_{i,b}^{\max}$ Capacity of offering block b of generator i (MW).

$\mathrm{K}_w^{\max}(t)$ Available wind generation of wind farm w (MW).

$\mathrm{pf}_{s,m}^{\max}$ Capacity of line s-m (MW).

$\mathrm{soc}_h^{\max}$ Capacity of BES h (MWh).

sus_{sm} Susceptance of line s-m (S).

η_h^{ch} Charging efficiency of BES h.

η_h^{dis} Discharging efficiency of BES h.

λ_h^{ch} Charging bid of BES h (€/MW).

$\lambda_{s,c}^{\mathrm{D}}$ Bid block c of demand at bus s (€/MW).

λ_h^{dis} Discharging bid of BES h (€/MW).

$\lambda_{i,b}^{\mathrm{G}}$ Bid block b of generator i (€/MW).

2) Variables

$d_{s,c}(t)$ Power purchased by block c of demand at bus s (MW).

$g_{i,b}(t)$ Power sold by block b of generator i (MW).

$k_w(t)$ Power sold by wind farm w (MW).

$q_h^{\mathrm{ch}}(t)$ Power purchased by BES h (MW).

$q_h^{\mathrm{dis}}(t)$ Power sold by BES h (MW).

$pf_{s,m}(t)$ Power flow through line s-m (MW).

$soc_h(t)$ State-of-charge of BES h (MWh).

$x_h^{\mathrm{ch}}(t)$ Binary variable that enables bidding to BES h.

$x_h^{\mathrm{dis}}(t)$ Binary variable that enables offering to BES h.

$\theta_s(t)$ Voltage angle at bus s (rad).

C. Formulation

The problem is formulated as follows (for clarity, the dual variables of the lower-level problem are listed after the corresponding constraints following a colon):

$$\text{Maximize} \sum_{t\in T}\sum_{h\in H} -\alpha_{s(h)}(t)\cdot\left(q_h^{\mathrm{dis}}(t)-q_h^{\mathrm{ch}}(t)\right) \tag{1}$$

subject to:

$$soc_h(t) = soc_h(t-1) + q_h^{\mathrm{ch}}(t)\cdot\eta^{\mathrm{ch}} - \frac{q_h^{\mathrm{dis}}(t)}{\eta^{\mathrm{dis}}} \quad \forall h\in H, t\in T \tag{2}$$

$$0 \le soc_h(t) \le \mathrm{soc}_h^{\max} \quad \forall h \in H, t \in T \tag{3}$$

$$x_h^{\mathrm{dis}}(t) + x_h^{\mathrm{ch}}(t) \le 1 \quad \forall h \in H, t \in T \tag{4}$$

$$\left\{ \begin{array}{l} \underset{\Omega_{\mathrm{LP}}}{\text{Maximize}} \sum_{s\in S}\sum_{c\in C} \lambda_{s,c}^{\mathrm{D}} \cdot d_{s,c}(t) + \sum_{h\in H} \lambda_h^{\mathrm{ch}} \cdot q_h^{\mathrm{ch}}(t) - \\ - \sum_{i\in I}\sum_{b\in B} \lambda_{i,b}^{\mathrm{G}} \cdot g_{i,b} - \sum_{h\in H} \lambda_h^{\mathrm{dis}} \cdot q_h^{\mathrm{dis}}(t) \end{array} \right. \tag{5}$$

subject to:

$$\begin{aligned} &\sum_{w\in W^s} k_w(t) + \sum_{h\in H^s} q_h^{\mathrm{dis}}(t) + \sum_{i\in I^s}\sum_{b\in B} g_{i,b}(t) - \\ &- \sum_{\{s,m\}\in L^s} pf_{s,m}^{-}(t) + \sum_{\{s,m\}\in L^s} pf_{s,m}^{+}(t) = \\ &= \sum_{s\in S}\sum_{c\in C} d_{s,c}(t) + \sum_{h\in H^s} q_h^{\mathrm{ch}}(t) \qquad : \alpha_s(t) \quad \forall s \in S \end{aligned} \tag{6}$$

$$pf_{s,m}(t) = \mathrm{sus}_{s,m} \cdot \left(\theta_s(t) - \theta_m(t)\right) \;: \beta_{s,m}(t) \;\; \forall \{s,m\} \in L \tag{7}$$

$$pf_{s,m}(t) \le \mathrm{pf}_{s,m}^{\max} \quad : \kappa_l^{\max}(t) \quad \forall \{s,m\} \in L \tag{8}$$

$$pf_{s,m}(t) \ge -\mathrm{pf}_{s,m}^{\max} \quad : \kappa_l^{\min}(t) \quad \forall \{s,m\} \in L \tag{9}$$

$$g_{i,b}(t) \le \mathrm{g}_{i,b}^{\max} \quad : \gamma_{i,b}(t) \quad \forall b \in B, i \in I \tag{10}$$

$$d_{s,c}(t) \le \mathrm{d}_{s,c}^{\max} \quad : \chi_{s,c}(t) \quad \forall s \in S, c \in C \tag{11}$$

$$q_h^{\mathrm{dis}}(t) \le \mathrm{dis}_h^{\max} \cdot x_h^{\mathrm{dis}}(t) \quad : \varphi_h^{\mathrm{dis}}(t) \quad \forall h \in H \tag{12}$$

$$q_h^{\mathrm{ch}}(t) \le \mathrm{ch}_h^{\max} \cdot x_h^{\mathrm{ch}}(t) \quad : \varphi_h^{\mathrm{ch}}(t) \quad \forall h \in H \tag{13}$$

$$k_w(t) \le \mathrm{K}_w^{\max}(t) \quad : \vartheta_w(t) \quad \forall w \in W \tag{14}$$

$$\theta_s(t) \le \pi \quad : \mu_s^{\max}(t) \quad \forall s \in S \setminus s : \text{ref. bus} \tag{15}$$

$$\theta_s(t) \ge -\pi \quad : \mu_s^{\min}(t) \quad \forall s \in S \setminus s : \text{ref. bus} \tag{16}$$

$$\theta_s(t) = 0 \quad : \upsilon(t) \quad s : \text{ref. bus} \tag{17}$$

$$g_{i,b}(t) \ge 0 \quad \forall b \in B, i \in I \tag{18}$$

$$d_{s,c}(t) \ge 0 \quad \forall s \in S, c \in C \tag{19}$$

$$q_h^{\mathrm{dis}}(t), q_h^{\mathrm{ch}}(t) \ge 0 \quad \forall h \in H \tag{20}$$

$$\Big\} \forall t \in T$$

Profit maximization in objective function (1) is the overall revenue of the BES. Locational marginal price (LMP) at the bus to which a BES is connected is equal to the negative of $\alpha_s(t)$, the dual variable of the power balance equation (5). It multiplies the difference between the electricity sold and purchased in the market.

The objective function (1) is subject to storage operation constraints (2)-(4), and a set of lower-level problems (5)-(20) that simulate the market clearing procedure. Constraint (2) is used to set the state-of-charge of the storage at each hour. It considers both charging and discharging efficiencies. Constraint (3) imposes the BES energy limit, while constraint (4) allows a BES to either charge (submit bid in the market) or discharge (submit offer in the market) at each time period.

The objective function (5) of each lower-level problem (5)-(18) is the maximization of the social welfare. Constraint (6) is the power balance equation for each bus. Wind generation, energy discharged from BES, and line inflows need to be balanced with demand, energy charged to BES and line outflows at each bus. Power flows through the lines are calculated using equation (7). Constraints (8) and (9) impose line power flow limits. Constraint (10) imposes capacity limit for each generator *i* offering block *b*, while constraint (11) imposes capacity limit for each block *c* of the demand at bus *s*. Constraints (12) and (13) limit storage offering/bidding blocks, while constraint (14) limits the power sold by a wind farm to the available wind generation. Constraints (15) and (16) limit voltage angles, while constraint (17) sets the reference bus. Finally, constraints (18)-(20) declare generator, demand and storages offers/bids as non-negative variables.

D. Transformation to MPEC

Because of its bilevel structure, the problem formulated in the previous subsection cannot be solved using commercial solvers. Thus, it needs to be converted into a mathematical program with equilibrium constraints (MPEC). In other words, the set of lower-level problems needs to be converted to a set of constraints. Using the strong duality theorem, the equivalent of the lower-level problem consists of its primal constraints, its dual constraints and the strong duality equation.

Dual of the lower-level problem (5)-(20) is:

$$\begin{aligned} &\text{Minimize} \sum_{l\in L} \left(\kappa_l^{\max}(t) - \kappa_l^{\min}(t)\right) \cdot \mathrm{pf}_l^{\max} + \\ &+ \sum_{i\in I}\sum_{b\in B} \gamma_{i,b}(t) \cdot \mathrm{g}_{i,b}^{\max} + \sum_{s\in S}\sum_{c\in C} \chi_{s,c}(t) \cdot \mathrm{d}_{s,c}^{\max} + \\ &+ \sum_{h\in H} \varphi^{\mathrm{dis}}(t) \cdot \mathrm{dis}_h^{\max} \cdot x_h^{\mathrm{dis}}(t) + \sum_{h\in H} \varphi^{\mathrm{ch}}(t) \cdot \mathrm{ch}_h^{\max} \cdot x_h^{\mathrm{ch}}(t) + \\ &+ \sum_{w\in W} \vartheta_w(t) \cdot \mathrm{K}_w^{\max}(t) + \sum_{s\in S} \left(\mu_s^{\max}(t) - \mu_s^{\min}(t)\right) \cdot \pi \end{aligned} \tag{21}$$

subject to

$$\alpha_{s(i)}(t) + \gamma_{i,b}(t) \ge -\lambda_{i,b}^{\mathrm{G}} \quad \forall b \in B, i \in I \tag{22}$$

$$-\alpha_s(t) + \chi_{s,c}(t) \ge \lambda_{s,c}^{\mathrm{D}} \quad \forall s \in S, c \in C \tag{23}$$

$$\alpha_{s(h)}(t) + \varphi_h^{\mathrm{dis}}(t) \ge -\lambda_h^{\mathrm{dis}} \quad \forall h \in H \tag{24}$$

$$-\alpha_{s(h)}(t) + \varphi_h^{\mathrm{ch}}(t) \ge \lambda_h^{\mathrm{ch}} \quad \forall h \in H \tag{25}$$

$$\alpha_{s(w)}(t) + \vartheta_w(t) \ge 0 \quad \forall b \in B, i \in I \tag{26}$$

$$-\alpha_{s(o(l))}(t) + \alpha_{s(d(l))}(t) + \beta_l(t) + \kappa_l^{\max}(t) - \kappa_l^{\min}(t) = 0 \quad \forall l \in L \tag{27}$$

$$\begin{aligned} &- \sum_{l|\mathrm{o}(l)=s} \mathrm{sus}_l \cdot \beta_l(t) + \sum_{l|\mathrm{d}(l)=s} \mathrm{sus}_l \cdot \beta_l(t) + \mu_s^{\max}(t) + \\ &+ \mu_s^{\min}(t) = 0 \qquad \forall s \in S / \text{ref. bus} \end{aligned} \tag{28}$$

$$-\sum_{l|o(l)=s} \text{sus}_l \cdot \beta_l(t) + \sum_{l|d(l)=s} \text{sus}_l \cdot \beta_l(t) + \upsilon(t) = 0 \quad s = \text{ref. bus} \tag{29}$$

$$\alpha_s(t), \upsilon(t) \quad \text{free variables} \tag{30}$$

$$\kappa_l^{\max}(t), \gamma_{i,b}(t), \chi(t), \mu_s^{\max}(t) \geq 0 \tag{31}$$

$$\kappa_l^{\min}(t), \mu_s^{\min}(t) \leq 0 \tag{32}$$

Strong duality equality of the lower-level problem is:

$$\begin{aligned}&\sum_{h\in H} \lambda_h^{\text{ch}} \cdot q_h^{\text{ch}} + \sum_{s\in S}\sum_{c\in C} \lambda_{s,c}^{\text{D}} \cdot d_{s,c}(t) - \sum_{h\in H} \lambda_h^{\text{dis}} \cdot q_h^{\text{dis}} - \\ &-\sum_{i\in I}\sum_{b\in B} \lambda_{i,b}^{\text{G}} \cdot g_{i,b}(t) = \sum_{l\in L}\left(\kappa_l^{\max}(t) - \kappa_l^{\min}(t)\right) \cdot \text{pf}_l^{\max} + \\ &+\sum_{i\in I}\sum_{b\in B} \gamma_{i,b}(t) \cdot \text{g}_{i,b}^{\max} + \sum_{s\in S}\sum_{c\in C} \chi_{s,c}(t) \cdot \text{d}_{s,c}^{\max} + \\ &+\sum_{h\in H} \varphi^{\text{dis}}(t) \cdot \text{dis}_h^{\max} \cdot x_h^{\text{dis}}(t) + \sum_{h\in H} \varphi^{\text{ch}}(t) \cdot \text{ch}_h^{\max} \cdot x_h^{\text{ch}}(t) + \\ &+\sum_{w\in W} \vartheta_w(t) \cdot \text{K}_w^{\max}(t) + \sum_{s\in S}\left(\mu_s^{\max}(t) - \mu_s^{\min}(t)\right) \cdot \pi \quad \forall t \in T\end{aligned} \tag{33}$$

Since it is assumed that wind farms bid at 0 €/MW, the left-hand side of the strong duality equality does not contain the wind farm term.

The final MPEC is formulated as:

$$\begin{gathered}(1) \\ \text{subject to: } (2)-(4), (6)-(20), (22)-(33)\end{gathered} \tag{34}$$

E. Linearized Problem

Problem (34) is not linear because the objective function (1) contains multiplication of dual variable $\alpha_s(t)$ and the storage operation variables $q_h^{\text{dis}}(t)$ and $q_h^{\text{ch}}(t)$. In order to use a linear solver, this term needs to be linearized using some of the Karush-Kuhn-Tucker optimality conditions. Details on this procedure may be found in [12] and [13]. This resulting linear objective function is:

$$\begin{aligned}&\text{Maximize} \sum_{t\in T}\sum_{h\in H} \lambda_h^{\text{dis}}(t) - \lambda_h^{\text{ch}}(t) + \\ &+\text{dis}_h^{\max} \cdot (\varphi_h^{\text{dis}}(t) - \varphi_h^{\text{dis-}}(t)) + \text{ch}_h^{\max} \cdot (\varphi_h^{\text{ch}}(t) - \varphi_h^{\text{ch-}}(t))\end{aligned} \tag{35}$$

that needs to be accompanied by the following constraints:

$$-x_h^{\text{dis}}(t) \cdot M \leq \varphi_h^{\text{dis}}(t) - \varphi_h^{\text{dis*}}(t) \leq x_h^{\text{dis}}(t) \cdot M \quad \forall h \in H \tag{36}$$

$$-(1 - x_h^{\text{dis}}(t)) \cdot M \leq \varphi_h^{\text{dis*}}(t) \leq (1 - x_h^{\text{dis}}(t)) \cdot M \quad \forall h \in H \tag{37}$$

$$-x_h^{\text{ch}}(t) \cdot M \leq \varphi_h^{\text{ch}}(t) - \varphi_h^{\text{ch*}}(t) \leq x_h^{\text{ch}}(t) \cdot M \quad \forall h \in H \tag{38}$$

$$-(1 - x_h^{\text{ch}}(t)) \cdot M \leq \varphi_h^{\text{ch*}}(t) \leq (1 - x_h^{\text{ch}}(t)) \cdot M \quad \forall h \in H \tag{39}$$

The newly added variables $\varphi_h^{\text{dis*}}(t)$ and $\varphi_h^{\text{ch*}}(t)$ are used for linearization purposes only and work in the way described in [14]. Constraints (36)-(39) also serve for linearizing the multiplication of binary and continuous variables in (33), whose final form is:

$$\begin{aligned}&\sum_{h\in H} \lambda_h^{\text{ch}} \cdot q_h^{\text{ch}} + \sum_{s\in S}\sum_{c\in C} \lambda_{s,c}^{\text{D}} \cdot d_{s,c}(t) - \sum_{h\in H} \lambda_h^{\text{dis}} \cdot q_h^{\text{dis}} - \\ &-\sum_{i\in I}\sum_{b\in B} \lambda_{i,b}^{\text{G}} \cdot g_{i,b}(t) = \sum_{l\in L}\left(\kappa_l^{\max}(t) - \kappa_l^{\min}(t)\right) \cdot \text{pf}_l^{\max} + \\ &+\sum_{i\in I}\sum_{b\in B} \gamma_{i,b}(t) \cdot \text{g}_{i,b}^{\max} + \sum_{s\in S}\sum_{c\in C} \chi_{s,c}(t) \cdot \text{d}_{s,c}^{\max} + \\ &+\sum_{h\in H}\left(\varphi_h^{\text{dis}}(t) - \varphi_h^{\text{dis*}}(t)\right) \cdot \text{dis}_h^{\max} + \\ &+\sum_{h\in H}\left(\varphi_h^{\text{ch}}(t) - \varphi_h^{\text{ch*}}(t)\right) \cdot \text{ch}_h^{\max} + \\ &+\sum_{w\in W} \vartheta_w(t) \cdot \text{K}_w^{\max}(t) + \sum_{s\in S}\left(\mu_s^{\max}(t) - \mu_s^{\min}(t)\right) \cdot \pi \quad \forall t \in T\end{aligned} \tag{40}$$

Finally, the linear MPEC of the original problem is:

$$\begin{gathered}(35) \\ \text{subject to: } (2)-(4), (6)-(20), (22)-(32), (36)-(40)\end{gathered}$$

III. CASE STUDY

The proposed model is tested on IEEE RTS-24 expanded with nine wind farms to replicate modern power systems. Figure 1 shows the output of these wind farms. All the data corresponds to the western subsystem from [3]. A single BES with the following parameters is connected to bus 120: offering price is set to 0 €/MW, bidding price to 100 €/MW, storage capacity is 50 MWh, both charging and discharging capacities are 10 MW, and both charging and discharging efficiencies are 0.9, resulting in the roundtrip efficiency 0.81.

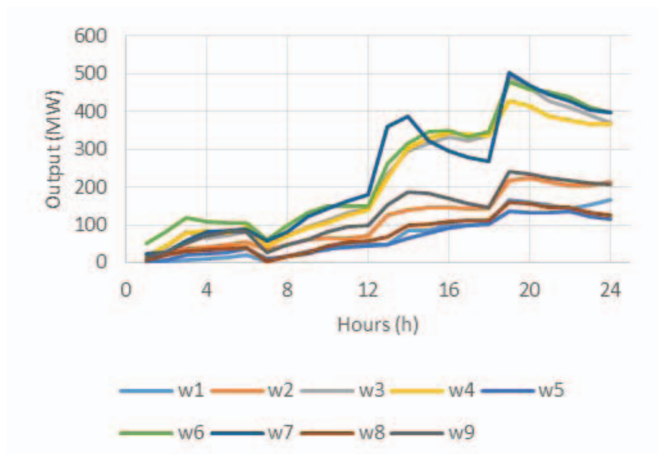

Figure 1. Wind farm outputs

The overall BES profit throughout the day is only 42.4 €. Cumulative profit throughout the day is given in Figure 2.

Figure 3 compares the LMPs at bus 120 (where the BES is connected) to the base case where there is no storage in the system. All the LMPs are identical, which implies that the BES does not benefit if its actions change the LMPs. For instance, when the BES acts as a load, its market bid could increase the corresponding LMP, which would result in high purchase price of electricity. On the other hand, when the BES injects electricity into the grid, if its offer decreases the LMP, there is no economic viability to such action.

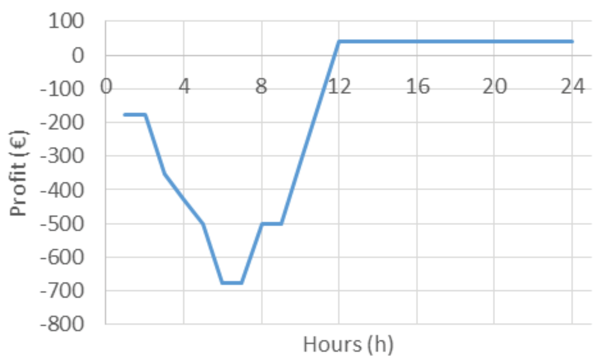

Figure 2. Cumulative profit of the BES throughout the day

BES operation throughout the day is shown in Figure 4. Charging occurs in hours 1, 3-6 and 16, while discharging in hours 8 and 10-12. Maximum SoC is 45 MWh, which is the result of a 5 hour charging at 10 MW and the charging efficiency 0.9. It is interesting to see that the final SoC is not zero, but 9.6 MWh (there is no final SoC assigned in the model). The reason is that the BES charges in hour 16 at price 0 €/MW, i.e. at no cost. However, this energy is never discharged as the BES discharge would cause slightly negative LMP at bus 120. The primary reason for that is increased wind generation in the second part of the day, as shown in Figure 1.

The overall generation of dispatchable generators is shown in Figure 5. Due to the relatively low capacity of the BES, the difference is barely visible in the figure. However, the dispatchable generators produce more electricity when the BES is charging, and less electricity when the BES is discharging.

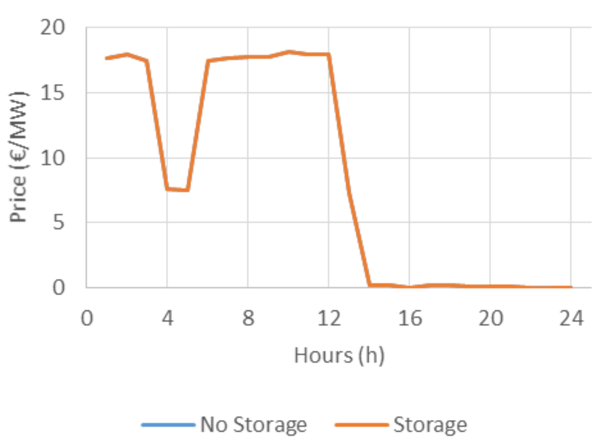

Figure 3. Comparison of LMPs at bus 120 with and without the BES

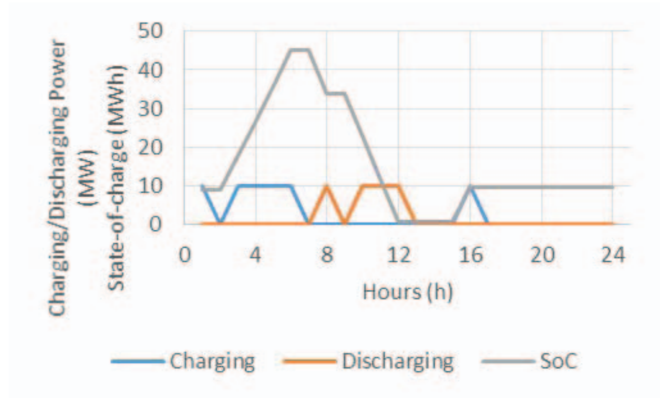

Figure 4. BES operation: charging, discharging, and SoC during the day

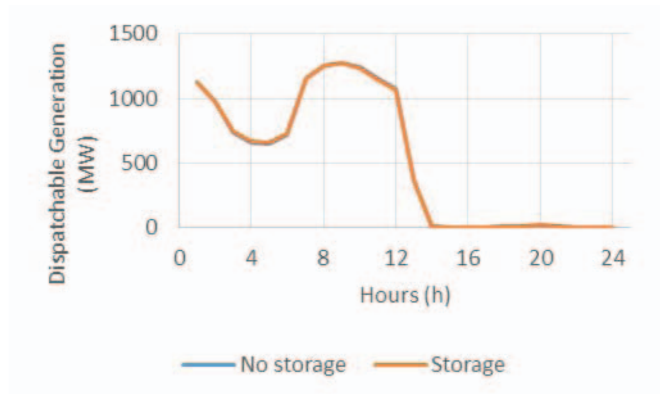

Figure 5. Overall generation of dispatchable generators

IV. CONCLUSIONS

This paper proposes a framework for the assessment of an independently owned BES and its operation in the day-ahead market. The following conclusions are derived:

1. The location of a BES should be carefully planned. The ideal node to connect a BES to is the one where the BES does not cause large changes in LMPs when submitting offers/bids in the market. Otherwise, the BES operation may not be profitable.
2. The sizing of the BES is also important. Submitting large block for selling and purchasing electricity will definitely alter the LMPs, thus decreasing the profit of a BES.
3. BES investment attractiveness highly depends on the configuration of the power system. Generally, the most promising power systems are the ones with large penetration of intermittent renewables, such as wind, and the ones with high occasional congestion.
4. The system in the presented test case contains large amount of renewable resources and the daily profit while performing arbitrage is merely 42.4 €. This means that the streams of value of a BES need to be multifold and added up together in order to create a convincing economic case for private investors. These

streams of value, besides arbitrage, include primary and secondary reserve, voltage support, load shifting and others.

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