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Dispatch of a wind farm with a battery storage

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Abstract The combination of a wind farm with a battery storage allows to schedule the system in a more balanced way, alleviating natural wind power fluctuations. We present a mathematical model that optimizes the contribution margin (CM) of a system that consists of a wind farm and a lithium-ion battery storage from an operator's perspective. We consider the system to take part in the electricity stock exchange. We discuss adaptions of the model when additional participation at the minute reserve market is possible. We construct a test instance for the model for Germany and compare the optimal solutions to two reference cases. We evaluate if the gain of an integrated wind battery system compensates the investment and operating costs for the storage and we derive target prices for the battery system.

1 Introduction

Since 2012, the German renewable energy act (EEG) incentivizes direct marketing (DM) of electricity generated by renewable energies. Until July 2014, wind farm operators could choose between fix feed-in-tariffs (FIT) and DM, where a market premium was paid for the spread between average trading revenues and the FIT. By the end of 2013, more than 80% of the electricity generated by wind power was traded through the direct marketing mechanism. An integrated wind battery system

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can be scheduled in a more balanced way and avoid throttling of the wind turbines due to grid bottlenecks. Furthermore, generation levelling facilitates additional revenue generation. This paper analyzes a 2013 installed wind battery system that takes part in different DM options and compares the results with two reference cases:

- Reference case 1: Average fix EEG FIT for wind energy
- Reference case 2: Revenues for wind energy from DM
- Wind farm with battery storage: Revenues are generated through the DM mechanism, where first the sole participation in the day-ahead market of the European energy exchange is considered (i), and second additional participation in the tertiary control market with minute reserve is possible (ii).

We present a mixed-integer linear program (MILP) that optimizes the CM for the direct marketing options (i) and (ii). We construct test instances and compare the optimal solutions to the reference cases. We evaluate whether the additional revenues in (i) and (ii) justify investing in the storage by a net present value (NPV) analysis.

2 Problem formulation and solution approach

There are mainly two different approaches for an economic assessment of wind storage systems. MILP [1, 2] and stochastic dynamic programming models [3, 4]. Our MILP does not consider battery operating cost that we define to be fix, which allows a subsequent profitability analysis for different battery prices. Moreover, we assume perfect foresight on prices and wind power generation. The neglect of stochastics tends to result in an overestimation of the profitability. On the other hand, other model simplifications, such as excluding e.g. the intraday market and arbitrage through purchasing electricity, could influence the results in the opposite direction. Below, we describe the model (i) in detail and only explain the objective function and the most important changes in the constraints for the advanced model. The following notations for decision variables and parameters are used in model (i).

Decision variables:

X_t^{Spot}:	Energy that is sold on the spot market in period t [MWh]
P_t^c, P_t^d:	Battery charging and discharging power in period t [MW]
C_t:	Available battery capacity in period t [MWh]
W_t^u:	Wind power used for trading and battery charging in period t [MW]
$B_t^c, B_t^d \in \{0,1\}$:	indicates if the battery is charged or discharged in period t

Parameters:

C_{min}, C_{max}:	Minimum and maximum battery capacity [MWh]
$P_{min}^{c/d}, P_{max}^{c/d}$:	Minimum and max. battery charging and discharging power [MW]
D:	Duration of one time period t [h], here 0.25 hours

η^c, η^d: Battery charging and discharging efficiency [%]
p_t^{Spot}, p_t^{MP}: Spot market price and market premium in period t [€/MWh]
W_t^a: Available power of the wind farm in period t [MW]
$c_t^{W,var}$: Specific operating costs of wind farm in period t [€/MWh]

The formulation looks as follows:

$$\max CM = \sum_{t \in T} (p_t^{Spot} + p_t^{MP}) \cdot X_t^{Spot} - c_t^{W,var} \cdot W_t^u \cdot D \tag{1}$$

$$\text{s.t.} \quad \frac{X_t^{Spot}}{D} + P_t^c = P_t^d + W_t^u \quad \forall t \tag{2}$$

$$0 \leq W_t^u \leq W_t^a \quad \forall t \tag{3}$$

$$X_{t+1}^{Spot} = X_t^{Spot} \quad \forall t, z \leq t \leq z + 4D, \; z \in \{t \bmod 4 \neq 1\} \tag{4}$$

$$C_t = C_{t-1} + D \cdot (P_t^c \cdot \eta^c - P_t^d \cdot \frac{1}{\eta^d}) \quad \forall t \tag{5}$$

$$C_{min} \leq C_t \leq C_{max} \quad \forall t \tag{6}$$

$$P_{min}^{c,d} \leq P_t^{c,d} \leq P_{max}^{c,d} \cdot B_t^{c,d} \quad \forall t \tag{7}$$

$$B_t^c + B_t^d \leq 1 \quad \forall t \tag{8}$$

$$B_t^{c,d} \in \{0, 1\} \quad \forall t \tag{9}$$

$$X_t^{Spot} \geq 0 \quad \forall t \tag{10}$$

The target function (1) maximizes the CM. While energy is balanced at all times (2), the generated wind power can remain unused (3). Equation (4) ensures that energy offered on the spot market remains constant within each 1 hour block. The battery charging state is modelled in (5). Moreover, there are boundaries for the battery size (6) and power rating (7). The constraints in (7) also ensure that the battery is only charged or discharged if the binary variable (9) is selected accordingly. The battery cannot be charged and discharged at once (8).

In a next step, we extended the model in order to enable additional participation in the minute reserve market. The battery can now be charged, when the system delivers negative minute reserve, and discharged, when the system delivers positive minute reserve. In order to allow for reservation of battery capacity for minute reserve, additional variables must be introduced. The target function of model (ii) is

$$\begin{aligned} \max CM = & \sum_{t \in T} (p_t^{Spot} + p_t^{MP}) \cdot X_t^{Spot} + \sum_{t \in T} X_t^{pos} \cdot (\tfrac{1}{16} \cdot p_t^{C,pos} + d_t^{pos} \cdot p_t^{E,pos} \cdot D) \\ & + \sum_{t \in T} X_t^{neg} \cdot (\tfrac{1}{16} \cdot p_t^{C,neg} + d_t^{neg} \cdot p_t^{E,neg} \cdot D) - c_t^{W,var} \cdot W_t^u \cdot D \end{aligned} \tag{11}$$

Here, $X_t^{pos/neg}$ is the reserved power for positive and negative minute reserve [in MW], $p_t^{C,pos/neg}$ is the capacity price [in €/MW] for reserved balancing power, and $p_t^{E,pos/neg}$ is the price for delivered energy [in €/MWh]. Parameter $d_t^{pos/neg}$ indicates the actually delivered minute reserve [in %].

3 Computational results

In the following section, we present the input data and briefly describe and compare the results computed by the MILP with the reference cases.

3.1 Data

The test instance is created with 2013 data. The wind generation data from the transmission system operator 50Hertz is scaled to a wind park of 50 MW and yearly output of 2,700 kWh/kW. The usable battery size is set to 100 MWh; the battery can be charged and discharged at 50 MW [1, 2]. Due to the current progress in development and price decline, two lithium-ion batteries are chosen with a charging and discharging efficiency of 92.5 %, a depth of discharge of 80 % and cost of 600 and 1,000 €/kWh respectively. In the presented models, self-discharge as well as battery degradation are neglected. A lifetime of 20 years is assumed for both the battery and the wind farm. Yearly warranty cost of the battery is set to 2% of the investment. The NPV is calculated with an interest rate of 6 % [3]. The wind farm is assumed to have investment cost of 1,000 €/kW and operating costs of 1.8 €-ct/kWh (maintenance and repair) [5]. Transaction costs for DM, taxes, EEG-levies, and grid fees are neglected. Spot and minute reserve market prices are available on [6] and [7].

3.2 Results for wind-battery system

When solely participating in the day ahead spot market, yearly revenues of 9.2 mn € can be realized. With variable operating cost of the wind farm, the CM is 6.8 mn €. However, taking into account investment and operating cost of the lithium-ion battery, the NPV is strongly negative between -142.4 and -80.2 mn € (Table 1).

Table 1 Comparison of revenues, CM, and NPV

	Wind farm only		Combined wind and battery system			
	Ref. case 1	Ref. case 2	Spot market only (i)		With minute reserve (ii)	
Battery price in €/kWh	-	-	600	1,000	600	1,000
Yearly revenues in mn €	7.8	8.2	9.2		11.1	
Yearly CM in mn €	5.4	5.9	6.8		8.9	
NPV in mn €	4.3	9.6	-80.2	-142.4	-55.2	-117.4

Figure 1 shows generated wind power, electricity sold over the spot market, and the battery charging state, as well as spot market prices and revenues over the course of a day. Wind power generated during periods of low spot market prices or before periods of high spot market prices is used for charging the battery, whereas the battery is discharged at high spot market prices or before periods of low spot market prices. Through additional participation in the minute reserve market, yearly revenues increase to 11.1 mn €, the CM is 8.9 mn €, whereas the NPV is between -117.4 and -55.2 mn €. The maximum target battery price for a positive NPV is 80 €/kWh if electricity is traded on the spot market only, and increases to up to 240 €/kWh in case of additional participation in the minute reserve market.

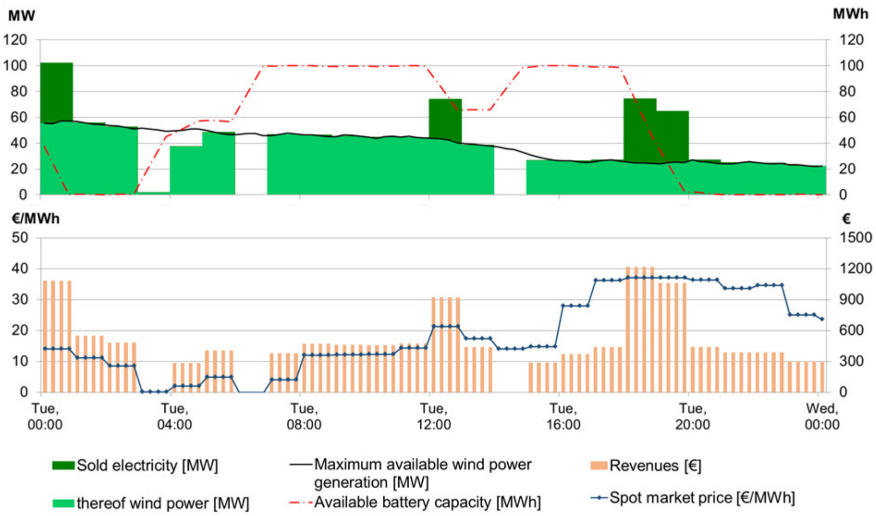

Fig. 1 Dispatch of the wind battery system and the dependency on spot market prices

3.3 Results for reference scenarios

The first reference case is a fix FIT for a 2013 installed 50 MW wind farm. The wind farm is assumed to apply for the energy system services bonus. The average FIT over 20 years is 5.83 €-ct/kWh. Compensation is calculated for 100% of the generated electricity. The average yearly revenues would reach 7.8 mn €, the NPV is 4.3 mn €. Within the second reference scenario, the wind energy is traded over the day-ahead spot market. Assuming perfect foresight, as much energy as possible is sold, given that prices and market premium exceed the operating costs. Yearly revenues reach 8.2 mn €, the NPV is 9.6 mn €. With a market premium of zero, yearly revenues would reach 4.2 mn €, the NPV would be negative at -47 mn €.

3.4 Comparison

Through adding a lithium-ion battery system to a wind farm, the CM can be increased by 15% to 50%. Taking battery investment into account, the NPV is strongly negative for lithium-ion battery prices between 600 - 1,000 €/kWh. This shows that trading electricity of a wind battery system was not economically viable in Germany in the year 2013. At hypothetical lithium-ion battery prices of 80 - 240 €/kWh, the market integration of wind battery systems might be more close to profitability.

4 Conclusions and recommendations for further research

The profitability of batteries e.g. in combination with residential photovoltaic systems has been shown by recent publications [8, 9]. However, an economic viability of a wind battery system could not be shown with 2013 data. The results generated by the two MILP are mainly limited by perfect foresight. Yet, a further battery price decrease as well as the expected increasing market price fluctuations caused by a rising share of volatile renewable energy generation are indicating a future profitability of wind battery systems. Moreover, the latest EEG amendments will make alternative subsidy schemes become more attractive. In a next step, we will take into account uncertainties in wind forecasts and future price development and add other marketing options in order to deeper assess the profitability of the battery storage.

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