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Application of Battery Storage for Compensation of Forecast Errors of Wind Power Generation in 2050

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Abstract

Transmission system operators have to buy control power to cover deviations in energy production of wind power plants due to prediction errors. The risk of errors is immanent to any prediction. This leads to financial risks, especially for the unexpected large deviations. Therefore large-scale integration of wind power could oblige the system operator to allocate more spinning and supplemental energy reserve. This would cause more operation costs, in order to balance wind power prediction errors in a certain time period. Battery storage technology can be used to supply backup power for wind power plants. However, the high cost of battery storage systems (BESS) is the major drawback for their commercial applications. Gradually decreasing costs of batteries can bring BESS in a competitive position for balancing wind prediction errors. By analyzing the application of BESS as means to balance prediction errors, the resulting cost associated with wind generation prediction errors in a liberalized electricity market in the year 2050 is assessed. The result shows, that BESS is an outstanding alternative for short-term balancing in order to reduce the cost of prediction uncertainties.

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1. Introduction

Wind turbines will contribute to European future electricity generation to a high degree. Due to the intermittent nature of wind power (WP), the importance of accurate forecasts is increasing. In order to deal with imperfect wind power prediction, system operators have to face additional cost as a result of increasing reserve levels. The

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unexpected large forecast deviations would cause more operating costs, because it requires more balancing energy to balance the wind power forecast errors (WPFEs) and the cost of balancing energy will be calculated with balancing energy price. Previous studies have presented different ways to minimize the cost of balancing energy. A sophisticated trading strategy can avoid more cost caused by short-time forecast errors [1]. Virtual power plants can be also an alternative to reduce the cost for balancing energy [2]. Some studies have investigated that a BESS can serve as a backup energy resource in combination with wind power plants. An optimal operation strategy of a battery energy storage system can not only support the physical safety of the power system but can also be economically profitable trading at the electricity market [3-4].

In this paper, an improved efficiency and a sinking cost of different types of batteries in the year 2050 were assumed. The relationship between the spot price of electricity in day-ahead market and the residual load was researched in order to get a simple model to forecast the spot price in the year 2050. In addition an operation strategy of the BESS is proposed, which depends on the spot price for electricity.

In section II, the model used to characterize day-ahead spot price of electricity in the year 2050 is presented and the balancing energy price is assessed. In section III, an operation strategy of a BESS associated with balancing energy price is proposed. In section IV, two simulations aimed on balancing WPFEs without the BESS in year 2011-2012 and with the BESS in year 2050 is presented, the economic benefit with applications of different battery types is discussed. Finally, section V presents the conclusions of this study.

Nomenclature

BEP	balancing energy price
BESS	battery energy storage system
EPEX	European Power Exchange
FWP	forecasted wind power
SMP	spot market price
TSO	transmission system operator
WP	wind power
WPFEs	wind power forecast errors
WPP	wind power plants

2. Modeling spot market pricing

2.1. German power market

The European Power Exchange (EPEX SPOT) is a spot market for power. It operates day-ahead power markets and intraday power markets. The day-ahead markets are organized by an auction process and closed on 12:00 p.m. one day before the respective delivery day. The intraday markets are organized by continuous trading. The intraday markets open on 3:00 p.m. one day before the respective delivery day and close up to 45 minutes before physical delivery. The control reserve is utilized in order to balance the forecast errors until the real-time operation. Furthermore, the day-after-market can be considered as the last chance to change the delivery plan. It closes 4:00 p.m. one day after the delivery day. The transmission system operator (TSO) is responsible for the physical balance between production and consumption. Based on the cost of the control reserve, the TSOs will publish the price of the balancing energy each month for the previous month, when the up-regulations increase generation or reduce consumption and the down-regulations decrease generation or increase consumption.

In order to simplify the marketing process, only the day-ahead markets and the payments for balancing energy due to WPFEs will be considered in the following simulations presented in this paper.

2.2. Day-ahead spot price and residual load

The main determinants for the day-ahead spot market price are the power plant fleet, the fuel prices and the load [5]. In this section, a simple linear trend line for the year 2012 to 2014 between day-ahead spot market price and the residual load is established. The TSOs in Germany publish the time series data for the consumption, wind power and photovoltaic energy production for each 15 minutes. The residual load profiles P_{RL} could be built as follows.

$$P_{RL}(t) = P_L(t) - P_W(t) - P_{PV}(t) \tag{1}$$

Where $P_L(t)$ is the consumption in Germany for each time step t . $P_W(t)$ and $P_{PV}(t)$ represent the wind and photovoltaic power in Germany for each time step t . Figure 1 shows the normalized spot market price over the residual load in the year 2013. Because the marginal costs of gas and coal power plants determine the spot market price [5], the spot market price was normalized by dividing it by the actual average natural gas price of 21 €/MWh.

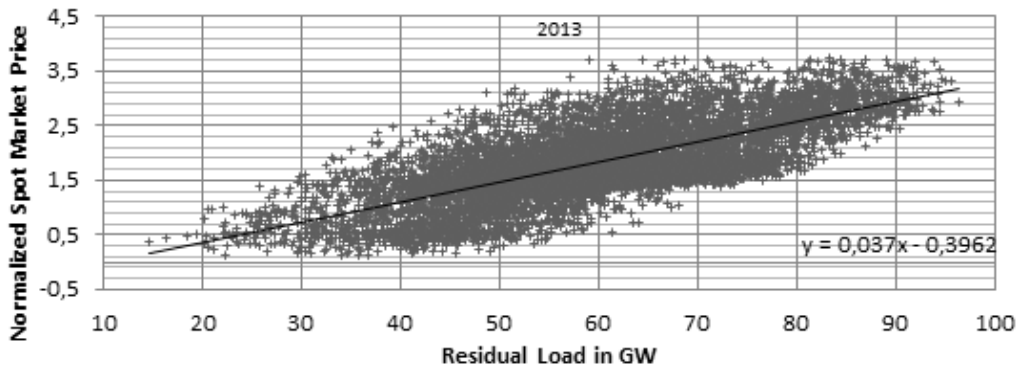


Fig. 1. Normalized spot market price over residual load 2013

Table 1. Overview of R^2 and slopes of regression analysis

	R^2			Slope		
	2012	2013	2014	2012	2013	2014
$P_L - P_W - P_{PV}$	0.51	0.52	0.56	0.036	0.037	0.031
$P_L - P_W$	0.63	0.64	0.66	0.043	0.045	0.037
$P_L - P_{PV}$	0.40	0.40	0.39	0.033	0.034	0.027

A linear regression line with its formula is illustrated in the diagram. Similar evaluations for the spot market price have been done for two more variants of residual load, one without regarding PV as must run power plant, the other one without regarding Wind. Thus the residual load is then calculated as the consumption subtracted by wind power ($P_L - P_W$) or PV power ($P_L - P_{PV}$) respectively. The coefficient of determination R^2 indicates how well the data match the linear regression lines. In Table 1, the R^2 and slopes of the linear regressions in the different years are summarized. Here the ($P_L - P_W$) version has the best coefficient of determination, so the “Load- Wind” can provide the most accurate base to predict the spot market price.

According to [6], it can be assumed that there will be no big changes in the consumption in year 2050. The installed capacity of wind power will increase up to 90 GW until 2050 compared to 35 GW in 2014 [7], and the average price of natural gas will double in the next 35 years up to 42 €/MWh. The time series data for wind power in

2050 was scaled from the dataset in 2014 according to this assumption. The spot market price (SMP) for 2050 can be calculated according to:

$$SMP_{2050} = (P_{RL} \cdot 0.0369 - 0.6508) \cdot Price_{gas_2050} \tag{2}$$

2.3. Assessment of balancing energy price

The price of balancing energy depends on different factors, such as the forecasting errors of wind or PV power, the trading volume in intraday-market, the concrete working price of negative or positive control reserve and so on. A simple model which describes the price of balancing energy correctly is hard to find. Table 2 shows the statistic data of the electricity price in different years. According to the standard deviations, the price of balancing energy has a relative larger variation compared with the spot market price. The difference between maximum and minimum value in year 2014 is even more than 3000 €/MWh.

Table 2. Statistic data of the electricity price

	Balancing Energy Price			Spot Market Price		
	2012	2013	2014	2012	2013	2014
Minimum [€/MWh]	-404	-633	-1492	-220	-100	-65
Maximum [€/MWh]	633	457	1630	210	130	88
Mean [€/MWh]	46	34	25	43	38	33
Standard deviation [€/MWh]	63	52	72	19	16	13

3. An operation strategy of BESS associated with balancing energy price

3.1. The relationship between energy production and price

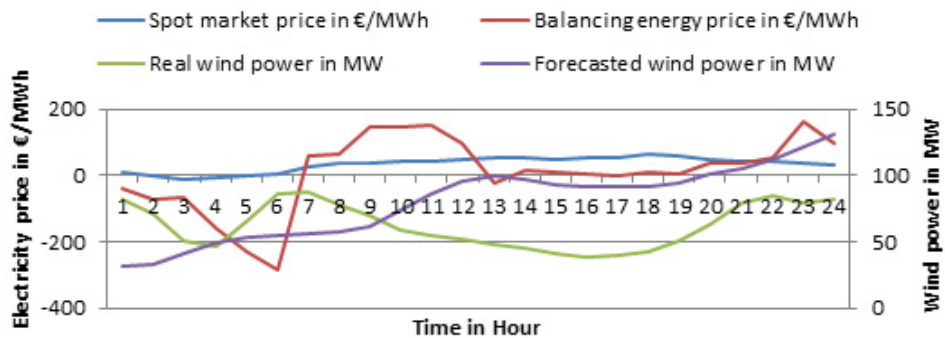


Fig. 2. The trend of wind power and electricity price in one day

In Fig.2, the forecasting and real wind power data for one exemplary day is shown, which was taken from a pool of wind power plants with a total combined nominal output power of approximately 238 MW in Germany. The time series dataset of the wind power covers the period from June 2011 to May2012. The deviations between the day-ahead forecast P_{DA} and real wind power P_{IS} are referred to as forecasting errors in the following.

$$Error = P_{is} - P_{DA} \quad (3)$$

The day-ahead electricity price and the price of balancing energy are shown in Fig.2 for the same time period. A positive day-ahead price means that the wind power plants can profit when they sell their power production. A negative day-ahead price can appear in at times throughout one year, as can be seen for example in Fig.2 (the blue line) during the time period between 03:00-05:00 a.m. This can be explained by a much lower demand compared to the energy production. In such situations, the wind power plants have to pay the electricity consumer (TSO) for feeding their produced energy into the power system. Compared with the day-ahead price, the price of balancing energy has larger variations and can be negative on much more occasions. The overview of the direction of pay for balancing energy is indicated in Table 3.

Table 3. Statistic data of the electricity price

	Underproduction	Overproduction
Positive price	WPP* pays TSO	TSO pays WPP*
Negative price	TSO pays WPP*	WPP* pays TSO

*WPP means wind power plants

Because of the dynamic characteristic of the electricity price and the huge variation of the price of balancing energy, the BESS can be used to compensate the off-peak price and achieve more profit at the on-peak price.

3.2. Operation strategy of BESS

The BESS can be built as a backup energy resource for the wind power plants. It is assumed that the BESS can offer not only positive but also negative control reserve. Thus the discharging or charging energy for providing balancing energy can be calculated in the following simulations depending on the operation strategy. In order to design the operation strategy, a reference price is proposed, which determines if the BESS should charge or discharge. When the price of balancing energy BEP_i at hour i is higher than the reference price, the BESS is discharging firstly to balance underproduction of the wind power plants and then serves as control reserve continuing to discharge into the grid in order to maximize the income. When the reserve energy price BEP_i at hour i is lower than the reference price, the underproduction of the wind power plants can be balanced by the control reserve from the power system and then the BESS is charged by offering negative reserve energy into grid. The energy stored in the BESS is expressed as follows. When the BESS is charging at hour i ($P_i > 0$),

$$E_{i+1} = E_i + \eta_{Batt} \cdot \eta_{Inv} \cdot P_i \cdot (1 \text{ hour}) \quad (4)$$

and when the BESS is discharging at hour i ($P_i < 0$),

$$E_{i+1} = E_i + P_i \cdot (1 \text{ hour}) / \eta_{Batt} \cdot \eta_{Inv} \quad (5)$$

where E_i , E_{i+1} are the energy stored in the BESS at hour i and hour $i + 1$, respectively, P_i is the power output of the BESS at hour i , η_{Batt} and η_{Inv} are the efficiencies of battery and inverter unit. In addition, the limitations of the BESS with respect to power and stored energy have to be considered as follows:

$$-P_{max} \leq P_i \leq P_{max} \quad (6)$$

$$0 \leq E_i \leq E_{\max} \quad (7)$$

Where P_{\max} , E_{\max} are the maximal power generation and energy capacity of the BESS.

4. Calculation of total profit associated with the wind power forecast errors

To show the potential of BESS utilization in comparison with non-BESS system to balance WPFEs, two simulations have been implemented. The first simulation represents the case, that the overproduction or underproduction is balanced only by the control reserve from the power system in the scenario of year 2011-2012. The second simulation represents the case with BESS as a backup operation unit for the wind power plants applying the proposed operation strategy in the scenario of year 2050. The achievable gain which is composed by the income for the day-ahead market and the income or cost for balancing is calculated for each simulation.

The system which is simulated as basis for the presented results in this paper is assuming wind power plants with the rated capacity of 238 MW. The backup BESS is assumed with a rated capacity of 20 MWh and 10 MW for the maximal power generation. The spot market price in year 2050 is generated by approach mentioned before. For the price of balancing energy no changes between the scenario in year 2011-2012 and in year 2050 is assumed.

4.1. Simulation without BESS in year 2011-2012

Due to the limited capacity of the wind power plants, no effect on the price is assumed and the wind power plants act always as so-called "Price-Taker". The income of the day-ahead market associated with the forecasted wind power for a certain period of time T can be calculated as follows.

$$Income_{day-ahead} = \sum_{i=1}^T FWP(i) \cdot Price_{day-ahead}(i) \quad (8)$$

Where $FWP(i)$ is the forecasted wind power in time i . The income and the cost associated with WPFEs for a certain period of time T can be calculated as follows.

$$Income_{balance} = \sum_{i=1}^T (|WPF E_p(i) \cdot BEP_p(i)| + |WPF E_n(i) \cdot BEP_n(i)|) \quad (9)$$

$$Cost_{balance} = \sum_{i=1}^T (|WPF E_p(i) \cdot BEP_n(i)| + |WPF E_n(i) \cdot BEP_p(i)|) \quad (10)$$

$$Gain = Income_{day-ahead} + Income_{balance} - Cost_{balance} \quad (11)$$

Where WPF E and balancing energy price BEP have the positive value when the subscript is p, and have the negative value when the subscript is n at the time point i .

4.2. Simulation with BESS in year 2050

In this paper, the BESS is only utilized to balance the forecasting errors and operate as balancing energy source. The income at day-ahead market is the same with the formula (8). The income and the cost for balancing forecast errors are calculated as follows:

$$Income_{balance} = \sum_{i=1}^T (|BP_p(i) \cdot BEP_p(i)| + |BP_n(i) \cdot BEP_n(i)|) + \sum_{i=1}^T (|WP_p(i) \cdot BEP_p(i)| + |WP_n(i) \cdot BEP_n(i)|) \quad (12)$$

$$Cost_{balance} = \sum_{i=1}^T (|BP_p(i) \cdot BEP_n(i)| + |BP_n(i) \cdot BEP_p(i)|) + \sum_{i=1}^T (|WP_p(i) \cdot BEP_n(i)| + |WP_n(i) \cdot BEP_p(i)|) \quad (13)$$

$$Gain = Income_{day-ahead} + Income_{balance} - Cost_{balance} - Cost_{Batt} \quad (14)$$

Where BP and WP mean the direct trading of power generation into the power system from the BESS and wind power plants at time point i , respectively. The subscript p means positive values. The subscript n means negative values. Three different types of batteries have been analyzed: lead-acid, Sodium-Sulphur (NaS) and Lithium-ion batteries. The annual cost $Cost_{Batt}$ of each BESS using different battery types can be calculated with the parameters shown in Table 4. The assumptions for the characteristic parameters for BESS in year 2050 are based on the study in [6].

Table 4. Characteristic parameters of different batteries for BESS in year 2050

Characteristic parameters	Lead-acid		NaS		Lithium-ion	
	B.U.	I.U.	B.U.	I.U.	B.U.	I.U.
Investment cost (€/kWh)	133	75	111	75	333	75
Life time (Year)	15	30	25	30	20	30
Maintenance cost (% of Inv./year)	1.5					
One-way efficiency (%)	92.2	98	89.4	98	97.5	98
Interest rate (%)	8					

B.U. means Battery Unit and I.U. means Inverter Unit

The annual cost of the BESS utility can be calculated as followed.

$$C_{Batt_annuity} = E_{Batt} \cdot I_{Batt} \cdot (\mu_{Batt} + m_{Batt}) \quad (15)$$

$$C_{Inv_annuity} = P_{Inv} \cdot I_{Inv} \cdot (\mu_{Inv} + m_{Inv}) \quad (16)$$

$$\mu = \frac{r(1+r)^Y}{(1+r)^Y - 1} \quad (17)$$

Where E_{Batt} and P_{Inv} are the BESS energy and power capacities, respectively, I_{Batt} and I_{Inv} are specific investment costs of the BESS for energy and power capacity, m_{Batt} and m_{Inv} are cost coefficients of maintenance, r is the annual banking interest rate and Y is the life time for the different components.

4.3. Results

The operation strategy of the BESS which was mentioned before is used in the simulations. The reference price which is associated with the operation strategy of the BESS has been assumed as the average price of balancing

energy. In Fig.3, the green line is the reference price. From 01:00 to 02:00 a.m., the forecasting error is positive. This means that the wind power plants have an overproduction compared with the forecast. The gray line showing the balancing energy price is lower than the reference price, thus the BESS is charging during that period. From 05:00 to 06:00 a.m., the balancing energy price is higher than the reference price. The BESS is discharging by offering positive control reserve in order to get more revenue, even though the wind power plants show an overproduction. From 6:00 to 7:00 p.m., the BESS is discharging because of the underproduction of the power plants. From 9:00 to 10:00 p.m., the BESS is charging by offering negative control reserve, storing energy from the power system, even though the wind power plants are in underproduction. Fig.4 shows the difference of the day-ahead market incomes for the years 2011-2012 and 2050. The difference could be explained by the higher gas price in 2050 increasing the spot market price.

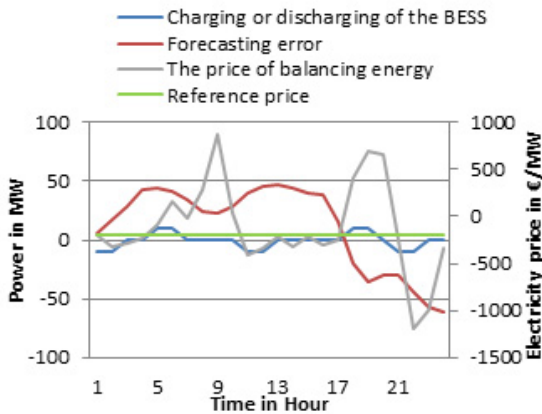


Fig. 3. The operation process of the BESS associated with balancing energy price

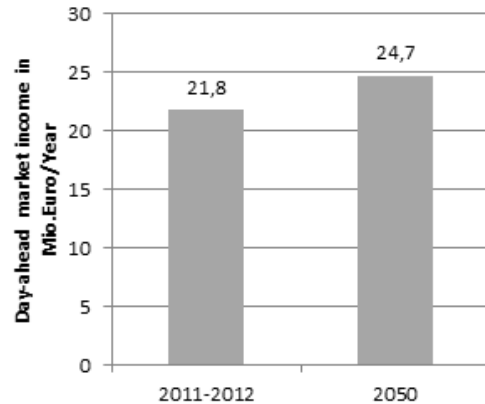


Fig. 4. The income of day-ahead market in the scenario of years 2011-2012 and year 2050

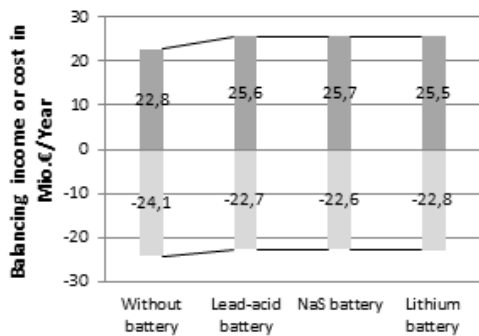


Fig. 5. The income and cost due to balancing energy

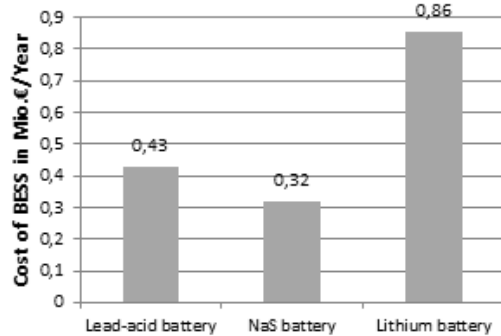


Fig. 6. The cost of different types of batteries

Fig.5 shows that the income from balancing increases significantly and the cost from balancing decreases when a BESS is operated, because the BESS can not only balance the prediction errors but also serve as a supplemental supplier to provide balancing energy in the power system. For example of the NaS battery system, the balancing income increases by 12.7 % and meanwhile the balancing cost decrease by 5.8 % compared with the scenario without BESS in the years 2011-2012. Due to similar efficient charging and discharging operation, there is no big difference for different types of BESS. Nevertheless, Fig.6 shows the cost of the BESS for different types of batteries according to the assumptions. The NaS battery system presents relatively cheaper annual cost. The income, cost and gain for different scenarios can be found as shown in the following Table 5. The gain of the wind power

plants can be improved by operation of a joint BESS. Compared with the scenario in the years 2011-2012 for the wind power plants, the gain per MW could increase by approximately 33 % in year 2050.

Table 5. Summary of different scenes

	Without BESS in 2011	Lead-acid Battery in 2050	NaSBattery in 2050	LithiumBattery in 2050
Day-ahead income (Mio.€/year)	21.8	24.7	24.7	24.7
Balancing income (Mio. €/year)	22.8	25.7	25.7	25.5
Balancing cost (Mio. €/year)	24.1	22.7	22.6	22.8
Battery cost (Mio. €/year)	-	0.429	0.319	0.856
Gain (Mio. €/year)	20.5	27.3	27.5	26.5
Gain per wind power (€/MW)	41.0	54.6	55.0	53.0

5. Conclusion

In this paper, a general trading process for the electricity in Germany was introduced. A simple linear relationship between the day-ahead spot market price and the residual load was found. This model is useful to forecast the spot market price in the future. The result indicates that it is sufficient to model the residual load by the consumer load subtracted by the feed-in wind power for price correlation analysis. The slope of the normalized spot market price over residual load is about 0.037 per GW residual load. This means that 1 GWh feed-in wind power leads to a spot market price reduction of 0.78 €/MWh (assuming the average natural gas price in 2014 of 21 €/MWh). An operation strategy of the battery energy storage system under consideration of a reference price has been designed. It has been shown that such a battery energy storage system can achieve an economical benefit by balancing wind power forecast errors and providing balancing energy. However, the simulations results show that some types of battery such as lead-acid and lithium can increase the revenue, even though they have relatively shorter life times or higher investment cost compared with NaS battery systems in the assumed scenario.

Furthermore, due to the diversification of the effects on the spot market price and balancing energy, more precise models should be implemented. The aging performance affects the cost of batteries. In this paper, the aging effect was not considered in the simulations. This will be another key point for future works.

Acknowledgement

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